Politechnika Wrocławska

FIELD OF SCIENCE: Engineering and Technical Sciences

DISCIPLINE OF SCIENCE: Environmental Engineering, Mining and Energy

DOCTORAL DISSERTATION

Intermittent water spray in non-porous dewpoint indirect evaporative cooler

mgr inż. Łukasz Stefaniak

Supervisors:
prof. dr hab. inż. Jan Danielewicz

Assistant supervisor: dr inż. Krzysztof Rajski

Keywords: evaporative cooling, GWP, HVAC, energy efficiency,

WROCŁAW 2025

Contents

Abstract

The doctoral dissertation is based on a series of articles devoted, in the most general sense, to evaporative cooling. Initial theoretical studies focused on refrigerants have shown that water (R-718) and air (R-729) are promising in terms of application in cooling. This is related to the pursuit of using refrigerants with the least negative impact on the environment.

The literature review allowed for the identification of current trends in evaporative cooling. It was shown that one of the directions of development of evaporative cooling technology is the use of porous materials for the construction of exchangers or for covering their surfaces. These materials, due to their ability to store water in their structure, allow for the introduction of non continuous water supply to the exchanger. Thanks to this phenomenon, intermittent water spraying of the exchanger was introduced to evaporative cooling, which allows for reducing the operating time of the water supply system. However, the result of the literature review turned out to be a research gap - the use of intermittent water spraying on non-porous exchangers.

The experimental part, which allowed for providing results filling the research gap, was carried out on a test rig prepared for these purposes. The first part of the research focused on the operation of the non-porous Dewpoint Indirect Evaporative Cooler (DIEC) after stopping the water supply. In this way, the drying phases of the exchanger were determined. In addition to the experiment, a mathematical description was also proposed using non-linear regression. It was shown that immediately after turning off the spraying, a period of 4–6 minutes occurs, during which an increase in cooling power was noted (due to the drop in the temperature of the treated air). Therefore, an experiment was planned in which, with a spraying break of 7 minutes, 3 spraying times (30, 60, 90 seconds) were used, as well as continuous spraying. In order to compare the effect of the application of time to continuous spraying of the non-porous exchanger, the effect was described using the cooling power and the Coefficient Of Performance (COP) indicator.

The results of the work are supplemented by a description of the microbiological hazard occurring in evaporative coolers. This is an inherent problem that occurs in these devices due to the use of water and air as refrigerants.

The results of the work allowed us to state that it is possible to use timed spraying on non-porous evaporative heat exchangers (DIEC). By limiting the operating time of the water supply system, the consumption of electricity was reduced. The effect of using such a spraying strategy is not only the improvement of its efficiency, but also an increase in cooling power.

Streszczenie

Rozprawa doktorska oparta jest na cyklu artykułów poświęconych, w najbardziej ogólnym rozumieniu, chłodzeniu wyparnemu. Wstępne badania teoretyczne skupione wokół czynników chłodniczych wykazały, że woda (R-718) i powietrze (R-729) są obiecujące w kwestii wykorzystania ich w obszarze chłodzenia. Związane jest to z dążeniem do stosowania czynników chłodniczych o jak najmniejszym negatywnym wpływie na środowisko.

Przegląd literaturowy pozwolił na identyfikację obecnych trendów w chłodzeniu wyparnym. Wykazano, że jednym z kierunków rozwoju technologii chłodzenia wyparnego jest zastosowanie materiałów porowatych do konstrukcji wymienników lub do pokrywania ich powierzchni. Materiały te poprzez zdolność do magazynowania wody w swojej strukturze pozwalają na wprowadzenie nieciągłego dostarczania wody do wymiennika. Dzięki temu zjawisku, do chłodzenia wyparnego zostało wprowadzone czasowe zraszanie wymiennika, które pozwala ograniczyć czas pracy układu dostarczającego wodę. Jednak wynikiem przeglądu literaturowego okazała się luka badawcza – zastosowanie czasowego zraszania na wymiennikach nieporowatych.

Część eksperymentalna, która pozwoliła na dostarczenie wyników uzupełniających lukę badawczą, została wykonana na stanowisku badawczym przygotowanym do tych celów. Pierwsza część badań skupiła się wokół zachowania chłodnicy wyparnej punktu rosy (DIEC) o powierzchni nieporowatej po zatrzymaniu dostarczania wody. W ten sposób określono fazy wysychania wymiennika. Oprócz eksperymentu zaproponowano także opis matematyczny przy użyciu regresji nieliniowej. Wykazano, że tuż po wyłączeniu zraszania, następuje okres 4–6 minut, w którym odnotowano wzrost mocy chłodniczej (na skutek spadku temperatury powietrza uzdatnianego). Dlatego zaplanowano eksperyment, w którym przy czasie przerwy zraszania 7 minut, zastosowano 3 czasy zraszania (30, 60, 90 sekund), a także zraszanie ciągłe. W celu porównania efektu zastosowania czasowego do ciągłego zraszania wymiennika nieporowatego opisano efekt przy pomocy mocy chłodniczej oraz wskaźnika Coefficient Of Performance (COP).

Uzupełnieniem wyników pracy jest opis zagrożenia mikrobiologicznego występującego w chłodnicach wyparnych. Jest to nieodłączny problem, który występuje w tych urządzeniach w związku z użyciem wody i powietrza jako czynników chłodniczych.

Wyniki pracy pozwoliły na stwierdzenie, że istnieje możliwość zastosowania czasowego zraszania na nieporowatych wymiennikach wyparnych (DIEC). Poprzez ograniczenie czasu pracy systemu dostarczania wody, ograniczone zostało zużycie energii elektrycznej. Efektem zastosowania takiej strategii zraszania jest nie tylko poprawa jego sprawności, ale także zwiększenie mocy chłodniczej.

Doctoral series

Doctoral series consists of 6 articles with the total of MNiSW: 830; IF: 23,0

1. S. Szczęśniak and Ł. Stefaniak. ”Global Warming Potential of New Gaseous Refrigerants Used in Chillers in HVAC Systems”. In: *Energies* 2022, vol. 15, no. 16, art. 5999, p. 1-20., DOI: 10.3390/en15165999 – P1
MNiSW: 140 (2019–2022); IF: 3,2 (2022)

2. Ł. Stefaniak, K. Rajski, J. Danielewicz. „Przegląd zastosowania nanopłynów oraz materiałów porowatych w pośrednim chłodzeniu wyparnym”. In: *Ciepłownictwo, Ogrzewnictwo, Wentylacja* 2023, vol. 54, no. 12, p. 33-40, DOI: 10.15199/9.2023.12.5 – P2
MNiSW: 70 (2023); IF: -

3. Ł. Stefaniak, A. Grabka, J. Walaszczyk, K. Rajski, J. Danielewicz, W. Jaskóła, M. Wochniak, W. Żyta. „Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review” In: *Energies* 2025, vol. 18, no. 9, art. 2296, p. 1-24., DOI: 10.3390/en18092296 – P3
MNiSW: 140 (2024); IF: 3,0 (2023)

4. Ł. Stefaniak, S. Szczęśniak, J. Walaszczyk, K. Rajski, K. Piekarska, J. Danielewicz. „Challenges and future directions in evaporative cooling: balancing sustainable cooling with microbial safety”. In: *Building and Environment* 2025, vol. 267, Pt. A, art. 112292, p. 1-12, DOI: 10.1016/j.buildenv.2024.112292 – P4
MNiSW: 200 (2024); IF: 7,1 (2023)

5. Ł. Stefaniak, J. Walaszczyk, M. Karpuk, K. Rajski, J. Danielewicz. „The possibility of intermittent water spray implementation in a non-porous indirect evaporative cooler*”*. In: *Energies* 2025, vol. 18, no. 4, art. 882, DOI: 10.3390/en18040882 – P5
MNiSW: 140 (2024); IF: 3,0 (2023)

6. Ł. Stefaniak, J. Walaszczyk, J. Danielewicz, K. Rajski. „Experimental performance analysis of non-porous indirect evaporative coolers under intermittent water spraying conditions”. In: *Journal of Building Engineering* 2025, vol. 105, art. 112585, p. 1-16, DOI: 10.1016/j.jobe.2025.112585 – P6
MNiSW: 140 (2024); IF: 6,7 (2023)

I Introduction

1. Introduction

With the inevitable global climate change, the time of the year in which cooling systems are used is increasing [1,2]. At the same time, climate policy is forcing the implementation of technologies that are consistent with the idea of sustainable development, underlining aspect of cooling [3]. The pursuit to reduce the impact of refrigerants used in refrigeration and cooling systems on climate change is causing an increase in interest in refrigerants with a low impact on the atmosphere. The development of this demand will follow in two directions. In countries where there is already a high demand for cooling, existing air conditioning systems will be increasingly expanded. On the other hand, in regions that have not previously required cooling, air conditioning systems will need to be built from the very beginning. The mentioned situation is presented in Figure 1, where the disparities between different regions of world in AC use in households is clearly visible.

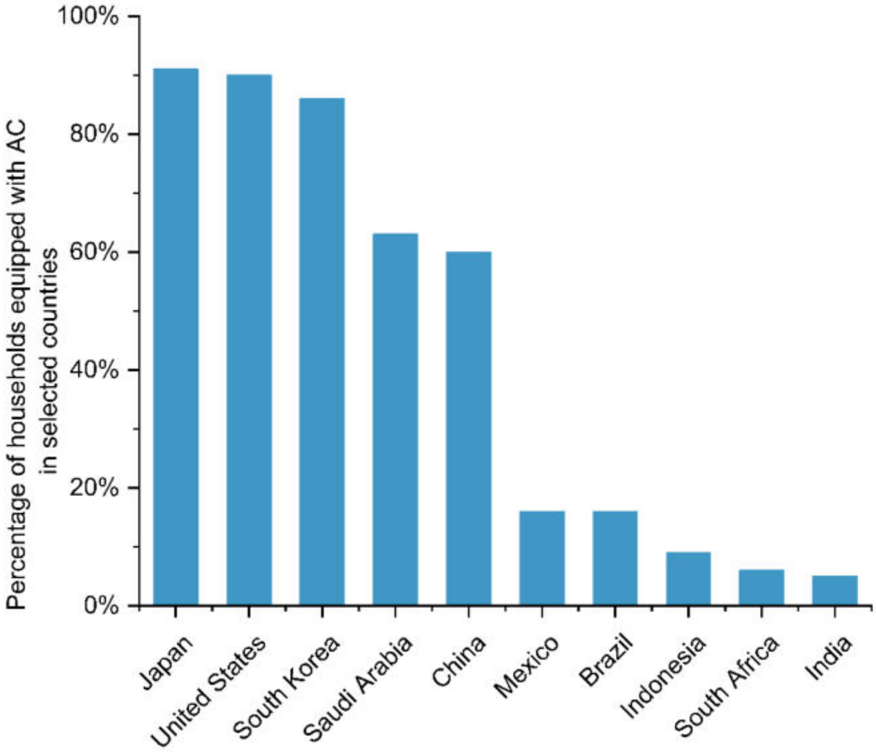


Figure 1. Percentage of households equipped with AC in selected countries [4]

Compressor refrigeration units are often used for air conditioning solutions, which are able to provide cooling coil surface temperature lower than the dew point temperature of the ambient air. The use of such units allows both the reduction of the air temperature (cooling) and moisture content (condensate dehumidification). However, the compressor units that are available and popular in the market commonly use gaseous refrigerants in their working cycle, which can have a negative impact on the environment and increase the greenhouse effect [5].

1.1. Ventilation and air conditioning systems – functions

Ventilation is usually called the exchange of indoor state air to fresh outside air which can be provided by natural or mechanical way. This process is responsible for supplying the appropriate amount of fresh air which can guarantee proper indoor air quality. This fresh air replaces the stale air that has become contaminated with pollutants. As an effect indoor contaminants are removed from rooms. Ventilation can be natural, mechanical or hybrid. Natural ventilation occurs in the building as there is always an air exchange through buildings' envelopes. It is due to wind force and gravitational pressure (difference in density between indoor and ambient air.

Ventilation, as defined by ASHRAE [6], is "the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space. Such air may or may not have been conditioned". In practice, a ventilation system draws outdoor air through intake dampers and filters, uses fans to overcome system resistance, and distributes or exhausts the air via ductwork. By exchanging or diluting indoor air, these systems are primarily used for maintaining acceptable indoor air quality (IAQ) and provide a basic level of pollutants, thermal, and moisture control.

The system that allows more complex control of air parameters is comfort air conditioning. According to ASHRAE [7] and Pełech [8] comfort air conditioning is "treating air to control its temperature, relative humidity, cleanliness, and distribution to meet the comfort requirements of the occupants of the conditioned space". The devices that may be included into the system are: cooling coils, heating coils, heat recovery exchangers, humidifiers, and dehumidifiers.

1.2. Evaporative cooling

Evaporative cooling (EC) is an old concept that has found ingenious applications in modern, environmentally friendly engineering. At its core, it capitalizes on the simple principle that, when transitioning from a liquid to a gas, water absorbs heat from its surrounding. The heat exchange between water and the air in contact with its surface takes place in two ways: either by convection, or simultaneously with mass transfer i.e., concurrently with the evaporation of water or the condensation of vapor from the air whereby the air gains the latent heat of evaporation or loses the latent heat of condensation of the water vapor deposited on the water's surface. Water can be supplied from the water supply system continuously or can be stored in a water tank and circulate in a closed circuit with the water refilling system.

This mechanism is currently widely investigated to create a sustainable and energy-efficient cooling solution for the increasingly demanding building sector [9,10]. This type of cooling became an alternative to traditional air conditioning devices. As these are mainly based on a compressor cycle with gaseous refrigerants, they are not perceived as a sustainable solution for the future, especially in terms of the aspect of global warming [5].

1.2.1. Fundamentals

The EC technology can be divided into two main types: Direct Evaporative Cooling (DEC) (air is in direct contact with water) and Indirect Evaporative Cooling (IEC) (wet and dry channel are part of heat exchanger). IEC can be further divided into regular IEC and Dewpoint Indirect Evaporative Cooling (DIEC) (where part of supply air is returned to the wet channels by perforation in heat exchanger walls). Schemes of all types of EC technology are shown in (Figure 2).

In DEC inlet air (1) is directly in contact with water therefore the outlet air (2) is cooled and can be humidified if the water temperature is the same as air wet bulb temperature. It means that water is in the closed circuit without any additional treatment. Therefore, this type of cooling is limited to the wet bulb temperature. In IEC and DIEC inlet air (1) is cooled by indirect contact with water. There are separated wat and dry channels. Heat transfer occurs through the heat exchanger wall. However, in IEC the outlet air (2) is cooled without moisture addition and cooling is limited to the wet bulb temperature. In DIEC part of outlet air is returned to the wet channel. Therefore, cooling is limited to the dewpoint temperature.

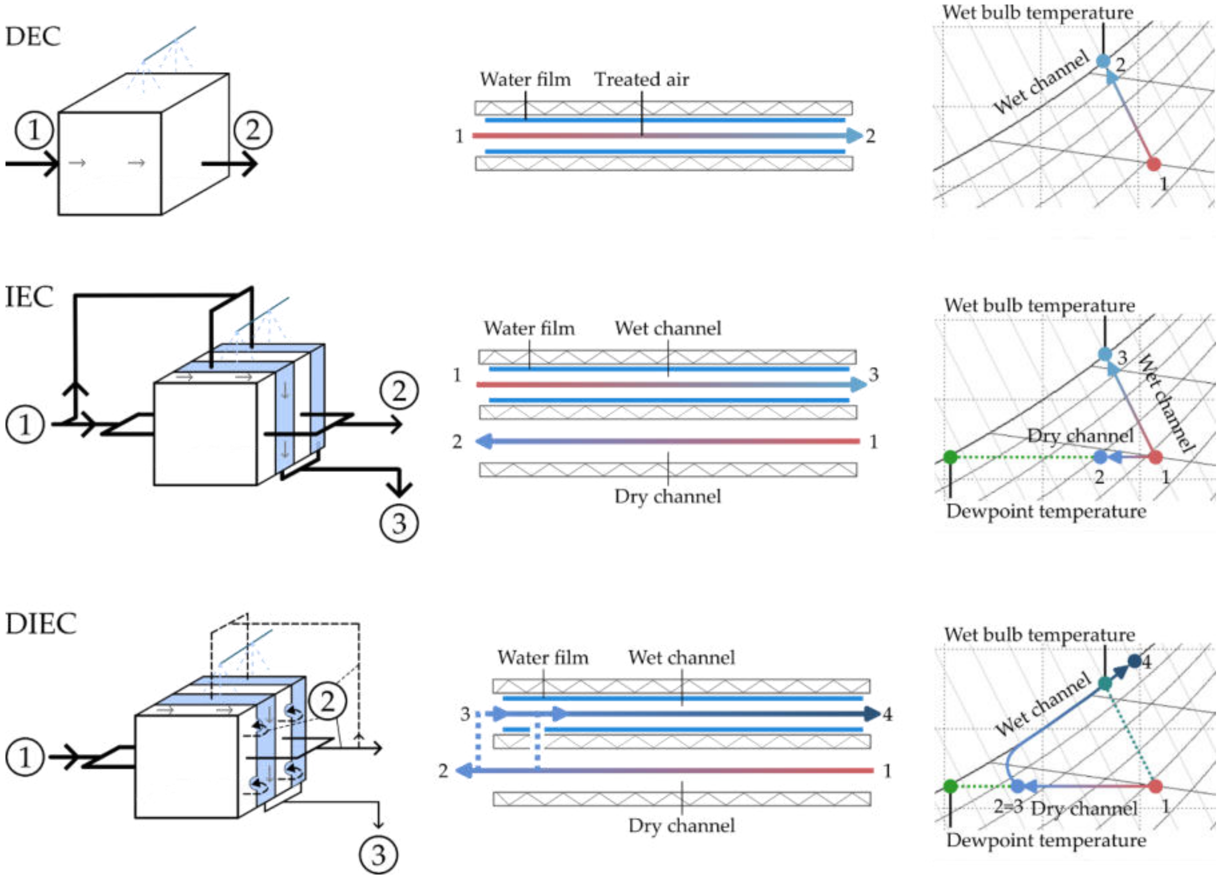


Figure 2. Types of EC technology (DEC, IEC, DIEC) schemes, working principles, and psychometric representation

1.2.2. Key considerations

Ambient air parameters, in which the device is working, play a crucial role in the effectiveness of evaporative cooling (which is mainly dependent on a meteorological parameters [11]). In dry or semi-arid regions, where the air contains less moisture than in humid climate, DEC systems are often used because the additional moisture they introduce is insignificant [12]. The significant temperature difference between dry-bulb and wet-bulb temperature in these areas greatly enhances the cooling potential. In contrast, in humid climates, DEC is problematic because direct contact of air and water generate direct moisture increase. Thus, IEC or DIEC systems are better choice since they cool the air indirectly, thereby preserving a comfortable indoor environment without significantly increasing moisture content [13]. This is with the exception of situation when in DEC, water used for spraying has lower dewpoint temperature that the cooled air.

One of the greatest advantages of evaporative cooling is its high energy efficiency and minimal environmental impact. Unlike conventional air conditioning systems, which uses compressors and additional components such as pumps and condensers for refrigerant, evaporative coolers simply spray water into the airflow. The only energy used is the energy required to pump water (the refrigerant side). As a result, operating costs remain low (especially in large scale or continuously running installations), and greenhouse gas emissions are significantly reduced. Moreover, because no high GWP refrigerants are used, evaporative cooling offers a much cleaner, more environmentally friendly alternative to traditional compressor based systems.

The complexity of the system is another important factor when selecting the right evaporative cooling solution. DEC systems are generally simply and cheap to install, though their inherent moisture addition may not suit every environment. In contrast, IEC and DIEC systems involve more complex components, such as heat exchangers and additional air ducting. The best system choice depends on the specific application an location of evaporative cooler. Direct evaporative cooling (DEC) may serve as an ideal solution for cooling the refrigerant on the high-pressure side, for example through the use of open cooling towers. Whereas IEC and DIEC systems are better suited for cooling supply air delivered to indoor spaces such as offices or data centers.

Water, as the most important part of both evaporative cooling devices and human environment (as it is necessary to live), must be used wisely and responsibly. This is crucial in regions with limited water resources. Therefore, most projects aim to minimize water consumption while ensuring high cooling performance [14]. By managing water use carefully, these systems become both cost-effective and environmentally sustainable [12], reducing waste and diminishing the need for additional water treatment as even seawater can be used instead of freshwater [15].

Long-term reliability also depends on proper maintenance and operation. Since water is a key element in these systems, regular maintenance is necessary to prevent issues such as mineral buildup or microbial growth that could degrade performance [16]. Routine cleaning and preventive maintenance are crucial for sustaining efficiency, and many modern systems use real-time monitoring and control features to detect and address potential problems early, thereby extending the lifespan of the equipment and reducing overall maintenance costs.

1.2.3. Water supply

As the device discussed in this dissertation is a DIEC, water supply will be described with regards to this type of device. Water can be delivered to the heat exchanger with the pumping system, in gravitational way or by wicking. When system is equipped with pumps the water is circulating in a closed circuit and it is refilled when needed. Distribution system is based on pumps that transport water to the nozzles, which distribute the water onto the heat exchanger. Generally, the system works in a continuous way, so the heat exchanger is sprayed all the time. In case of gravitational water supply or wetting by wicking, there is no need for the pumps presence in the device. Still, water must be somehow delivered to the water supply system.

Nozzle based systems atomize water into fine droplets, forming a water film on heat exchanger walls. Water is supplied to the nozzles by pumps that delivers water from the water tank which is most commonly a part of cooler itself. For gravitational systems water is stored in an upper water tank and distributed via gravity through channels or drippers. As the pumps are eliminated from the system, the energy consumption is lowered, when compared to system with pumps. In case of wicking systems porous membranes or fabrics (which are the material that the heat exchanger is made of) transport water via capillary action, ensuring uniform distribution without pumps.

The other topic of consideration is the water temperature that is supplied to the heat exchanger. Air of parameters A can be cooled with constant enthalpy when water temperature is equal to the air (A) wet bulb temperature (t_{wb}). Sector 1 represents the situation when water temperature has the temperature between wet bulb and dewpoint temperature (t_{dp}) of the treated air (A) (the enthalpy and temperature decreases but the moisture content increases). Further, when water is of the t_{dp} of the treated air (A), the cooling occurs without moisture content change. Eventually, Sector 2 represents the situation when water has lower temperature than t_{dp} and the air can be dehumidified while cooling.

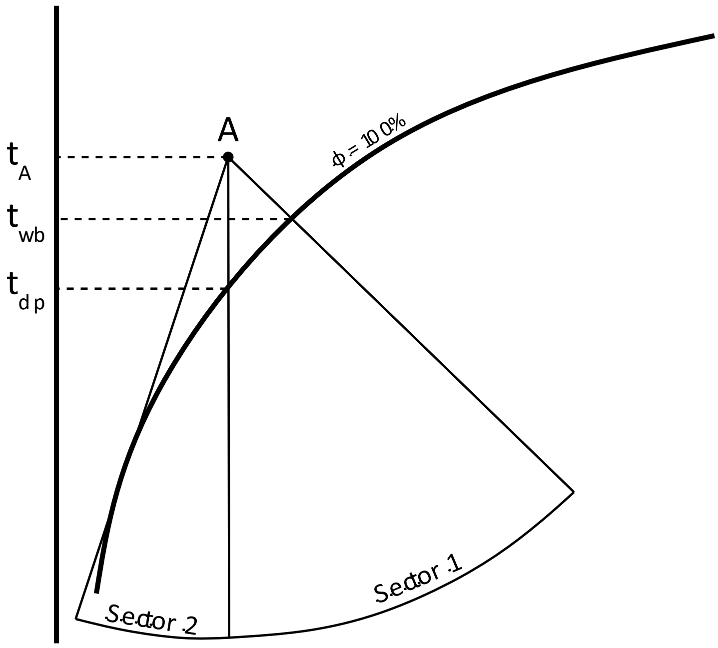


Figure 3. Air and water contact process direction

1.2.4. The idea of intermittent water spraying of the evaporative heat exchanger

Intermittent spraying in evaporative cooling is described in literature for IEC and DIEC. It involves the controlled supply of water to the cooling system in an intermittent manner, rather than continuously. It can reduce water consumption, which is crucial in areas with limited water resources. Third, intermittent spraying can increase cooling efficiency because it provides more uniform water evaporation, which can lead to more effective temperature reduction.

It is also worth noting that intermittent spraying can be used in existing evaporative cooling systems (only water system can be upgraded to intermittent control). The key here is to properly design the control system to adjust the frequency and intensity of water spraying to the current operating conditions of the system and the cooling requirements.

1.2.5. The operating time in intermittent water spraying systems

Based on the literature review concerning the applied spray intervals of air-cooling evaporative heat exchangers, a comparison was made of the pump and evaporative exchanger operating times without spraying.

As presented in Figure 4, the spraying time ranges from 1 second to 6 minutes. On the other hand, the pause time ranges from 1 second to just over 100 minutes. This discrepancy may result from the fact that all the publications (beside publication K) cited in the Figure 3 concern porous heat exchangers with different sprayed surfaces. The spraying time, therefore, depends on the ability of the given material from which the wet channel is made to absorb moisture. The operating time without spraying is related to the ability of the given material to store water. The more water is stored in the material, the longer the exchanger can operate without further spraying. Generalizing the results, it is worth noting that the ratio of pause time to operating time ranges from 1:1 to 20:1. The effect is to limit the operating time of the sprinkler system even to 3 minutes per hour of operation of the device.

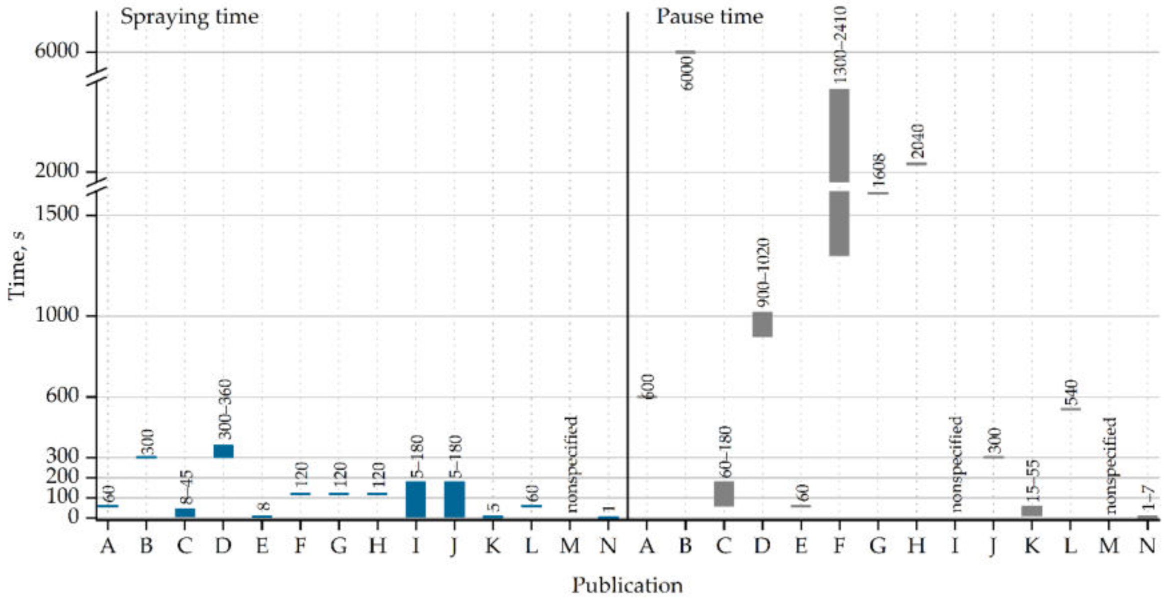


Figure 4. Water system operation intervals for publications: A [17], B [18], C [19], D [20], E [21], F [22], G [23], H [24], I [25], J [26], K [27], L [28], M [29], N [30]; [31]

A short summary of the objective and scope is presented graphically in Figure 5. Evaporative cooling (EC) broadly refers to temperature-lowering technology but is limited by added moisture. Indirect evaporative coolers (IEC) address this by separating air streams, cooling without introducing humidity, though they cannot surpass the outside air's wet bulb temperature. To enhance efficiency, dewpoint indirect evaporative cooling (DIEC) was developed. Unlike IEC, DIEC uses pre-cooled air in wet channels to enable both sensible and latent heat transfer, allowing supply air temperatures to drop below the wet bulb threshold, significantly improving performance. In every type of EC, the porous and non-porous heat exchanger surfaces were investigated. However, in DIEC type intermittent water supply was firstly coupled with porous surfaces. The non-porous type combined with intermittent water spraying has been skipped. Thus, it is a branch underlined in red in Figure 5, that has been identified to be missing in research.

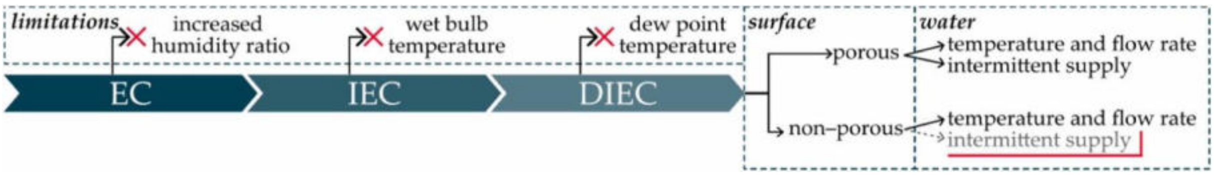


Figure 5. Evaporative cooling development with its limitations and research gaps [32]

2. Aim and research question

Based on the previously presented research the aim and thesis for the doctoral dissertation was formulated.

2.1. Aim

Determination of the energy effect of intermittent water spraying in the non-porous dewpoint indirect evaporative cooler.

2.2. Thesis

Use of intermittent water spraying in the non-porous indirect evaporative cooler allows to increase its efficiency.

3. Methods

As the articles included in this doctoral series vary in type and focus, the methodological details are presented within each individual article where relevant. A separate, unified methods section is therefore not provided, and readers are encouraged to refer to the specific articles for detailed descriptions of the methods used.

4. Test rig development

In order to investigate the thesis, the tests were done on the existing test rig, which photos and diagram are shown in Figure 6. The test rig were in need of underwent series of modifications fundamental to the proper experimental part.

4.1. First version

The first part of modification was the air ducting. Part of the outlet air is returned to the heat exchanger as a returned air. It can be seen that outlet air flows through a tee made of rectangular to round transition. Due to very close distance to the heat exchanger, stratification of temperature of outlet air was observed. Due to that, returned air and outlet air parameters were significantly different. Therefore the tee for returned air needed to be placed further from the heat exchanger.

Connection of returned air with heat exchanger also needed to be modified due to the space restrictions (test rig was to high to place it in the final position). In first version it was made out of rectangular to round transition and rectangular reducer. Eventually, it needed to be replaced with one piece of duct. The first version of the test rig is presented in Figure 7.

Figure 6. Existing Test rig (before modification and measurements)

4.2. Second version

The first version of the test rig is presented in Figure 7. Air ducting was improved as described earlier. The tee that splits outlet and returned air was placed further from the heat exchanger. The connection of the returned air duct with the heat exchanger was replaced with one rectangular to round transition. The water distribution system was also fitted to the new ducting piece including power supply for water pumps. At this stage it was possible to connect the device with existing ventilation system. Further work focused on measuring sensors installation.

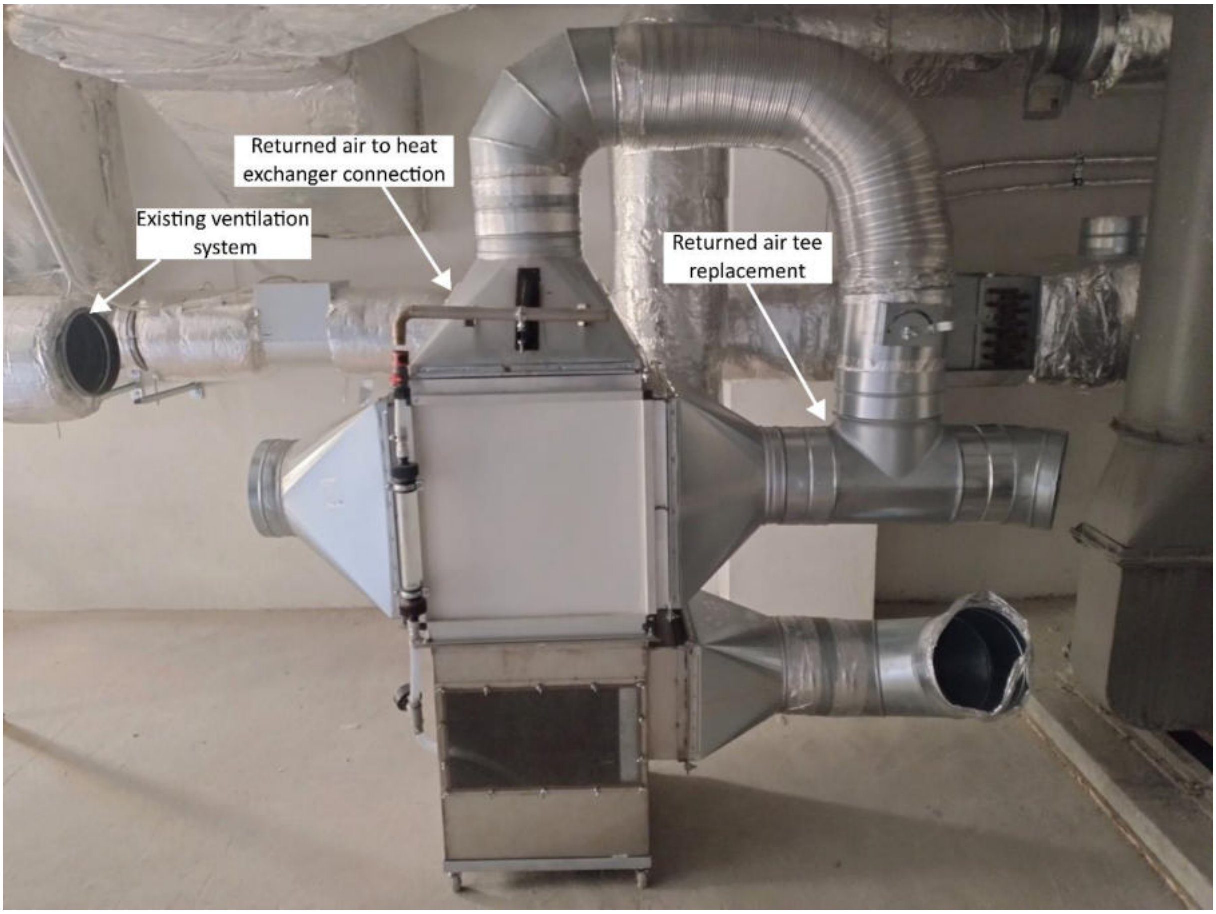


Figure 7. Test rig after first modifications of air ducting

4.3. Third version

Test rig connected to the existing system, with installed measuring devices, and pumping system is presented in Figure 8. There is a visible change in tee for returned air position. It was necessary to relocate it as far as possible from the heat exchanger as the temperature stratification was still observed. At the same time flexible ducts were replaced with insulated flexible ducts in order to reduce heat exchange between induct air and the environment.

The effect of above modifications is visible in Figure 9, where (a) represents the measured temperatures of outlet and returned air for test rig as in Figure 7. There is a steady difference between those values (around 2K). While for the third version of the test rig, the differences do not exceed 0.5K as visible in Figure 9 (b). At this stage the aim was achieved and no more further modifications to the construction of air ducts were done.

Figure 8. Complete test rig

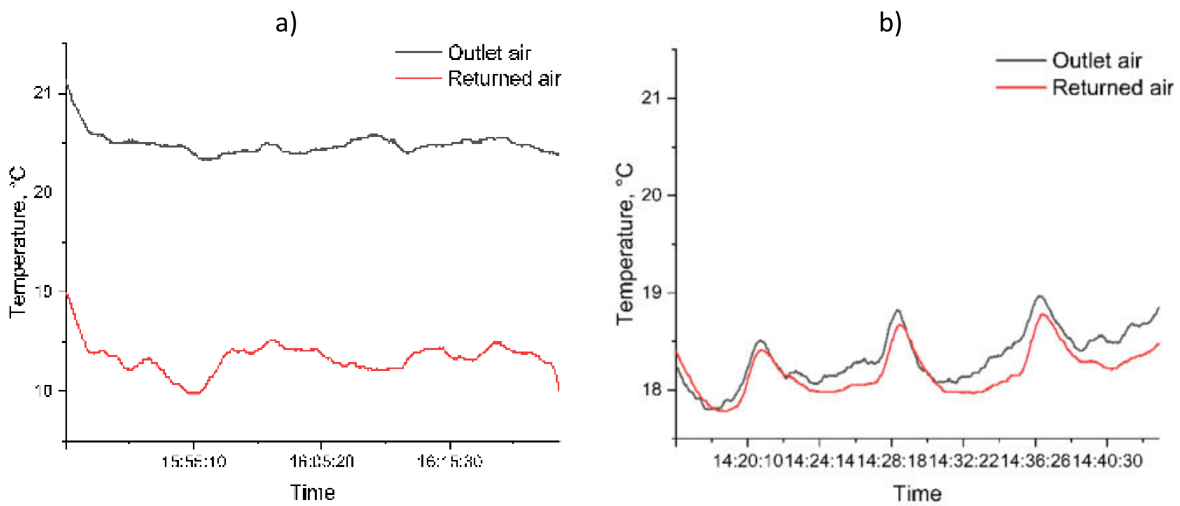


Figure 9. Outlet air and returned air temperature for: (a) second version of test rig; (b) third version of test rig

4.4. Final version

The last version of the test rig is presented in Figure 10. The main change is that it is fully insulated. In order to control inlet air parameters two modifications were implemented. Firstly, humidifier was added to keep humidity ratio at a constant level during the experiments.

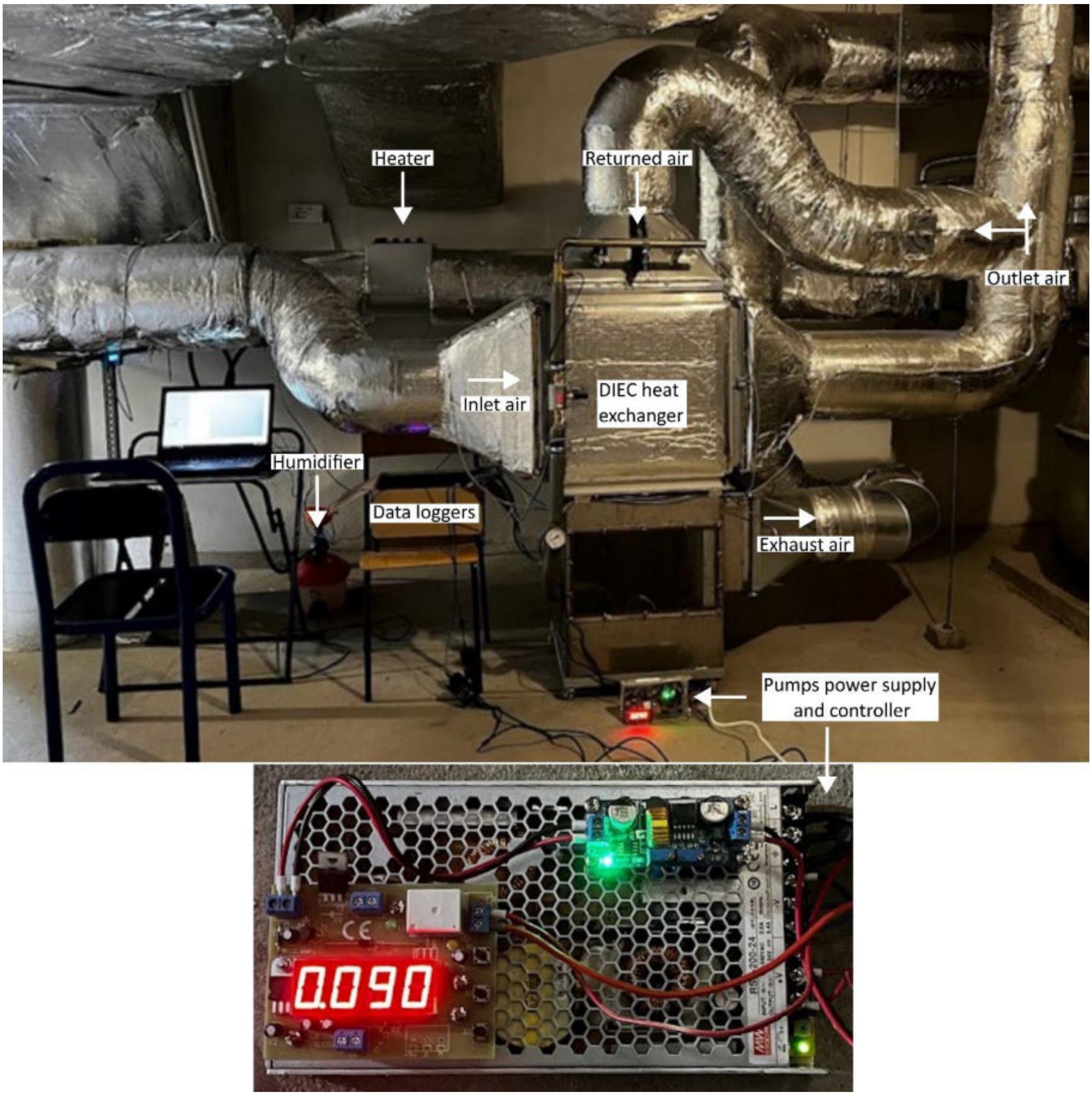


Figure 10. Test rig final version with detailed photo of pumps power supply and controller

Secondly, the existing heater control system was modified. The original control system consist of a heater, control module, and a temperature sensor. However, as the heater is of relatively high power 5 kW (to the air streams that were investigated), when operating the hysteresis was exceeding 2K. This is why the new control system has to be implemented. As the heater consist of 5 coils, each coil was separated electrically by switch (as visible in Figure 11. Therefore, manual control was possible to keep the inlet air temperature at the constant level with significantly lower hysteresis. Test rig also consist of cooling coil, however it was not used during the experiments.

Figure 11. Heater with modified control switches

Figure 10 presents also the detail photo of pumps power supply and controller. As the pumps operate at 24 V the separate power supply was needed. It is directly connected with the control module that allows to program the time of pump operation and pause time. It was necessary to evaluate the intermittent water spraying as manual turning on and off of pumps could results in non precise time periods.

Once the test rig was completed, the schematic configuration was prepared and it is presented in Figure 12. Temperature (T), relative humidity (H) and volumetric flow (V) are measured in the places specified in Figure 12. Additionally, pressure drop was measured manually for the heat exchanger (P) with instrument nozzles and impulse lines installed in points (P). Fans inverters are marked as (F) and adjustable timer for pumps control system as (CZ).

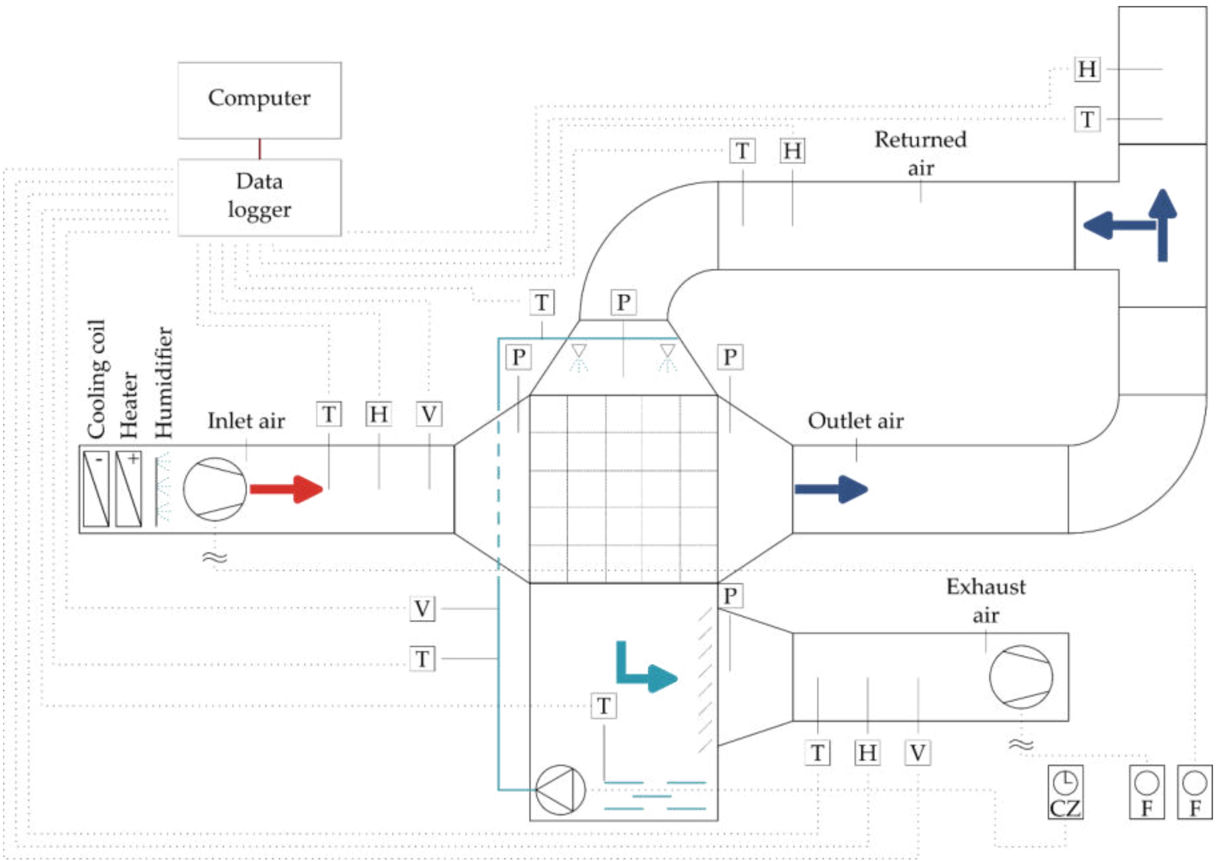


Figure 12. Schematic diagram of the test rig

6. Key findings of the dissertation

This dissertation consist of six papers. They are presenting both, the general knowledge on the topic and the path towards finding the answer for the thesis. All of them are connected to the evaporative cooling. The papers are assigned by the symbols from P1 to P6. Please find graphical summary of the dissertation below.

Intermittent water spray in non-porous dewpoint indirect evaporative cooler

Pre-research

P1

- Refrigerants used in HVAC systems identification
- Metrics on refrigerant impact on the environment evaluation
- Refrigerants impact on the environment assessment
- Switch towards natural refrigerants with low environmental impact
- **Water (R-718) and air (R-729) as latest generation of refrigerants**

Review

P2

- **Recent innovations in evaporative cooling identification**
- Nanofluids as spraying fluid implementation evaluation
- Porous surfaces in wet channels evaluation

P3

- **Intermittent water spraying in non-porous DIEC research gap identification**
- Spray-pause time regime evaluation in intermittent water spraying cases
- Water delivery and spraying control strategies discussion

Experiment

P5

- **DIEC operation after water spraying turn off investigation**
- Supply air temperature drop (5.9–11.1 K) after water spraying turn off
- Supply air temperature and relative humidity regression model

P6

- Three spraying times (30, 60, 90s) and pause (420s) experimentally tested
- **Enhanced effectiveness due to intermittent water spraying**
- 2–5 times higher Coefficient Of Performance
- 6–85% cooling power increase

Complementary research

P4

- Evaporative cooling poses microbial risks comparable to vapor compression systems
- **Porous materials in wet channels influences microbial contamination in evaporative coolers**
- Standard maintenance guidelines for evaporative coolers are insufficient
- *Legionella* sp. is well-researched, but other microbial risks need more attention

6.1. Global Warming Potential of New Gaseous Refrigerants Used in Chillers in HVAC Systems – P1

Results were published in S. Szczęśniak and Ł. Stefaniak. "Global Warming Potential of New Gaseous Refrigerants Used in Chillers in HVAC Systems". In: *Energies* 2022, vol. 15, no. 16, art. 5999, p. 1-20., DOI: 10.3390/en15165999.

The paper focuses on the refrigerants used in HVAC systems. The evaluation is made not only based on the impact that the specific refrigerants can have on the environment, but also how long are they present in the atmosphere once released.

The article underscores the global shift toward sustainable refrigerants in HVAC systems, driven by mounting environmental concerns and stringent international regulations aimed at mitigating climate change and ozone depletion. Historically, refrigerants such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) were phased out under the Montreal Protocol due to their high ozone-depleting potential (ODP). Subsequent generations, including hydrofluorocarbons (HFCs) like R134a and R410A, emerged as alternatives but were later scrutinized for their high global warming potential (GWP). This led to the Kyoto Protocol, which emphasized reducing greenhouse gas emissions, prompting the development of newer, low-GWP refrigerants such as hydrofluoroolefins (HFOs), hydrocarbons (e.g., R290), and natural refrigerants (e.g., CO_2, ammonia). These advancements align with global climate goals, emphasizing the need to transition from environmentally harmful substances to sustainable alternatives.

GWP that is mainly given and discussed in international policy is GWP 100 which means that the time horizon of the described impact on the environment is in 100 years. On the other hand, there is also GWP 20 (with time horizon of 20 years), that is more likely to be used in case of refrigerants that do not stay in the atmosphere for 100 years but much shorter. Lately GWP* has been introduced as it does not only represent equivalent of CO_2 but rather CO_2 warming equivalent that is suitable for short-lived climate pollutants.

The push for sustainable refrigerants is connected to their reduced direct environmental impact. Newer refrigerants, such as R1234ze, R513A, and R454B, have significantly lower GWP values compared to their predecessors. For instance, R1234ze has a GWP 100 of 1, contrasting with R134a (GWP 100 = 1360) or R410A (GWP 100 = 2100). Natural refrigerants like propane (R290) and CO_2 (R744) offer even greater sustainability, with negligible GWP and ODP. However, their adoption involves some trade-offs. R290, while environmentally benign (GWP 100 = 1), is highly flammable (A3 safety class), necessitating robust safety protocols in system design. Similarly, ammonia (R717), though efficient and non-ozone-depleting, is toxic, limiting its application to industrial settings. These examples highlight the balance required between environmental benefits and practical implementation challenges.

Regulatory frameworks and industry standards have been pivotal in driving this transition. The European Union's F-Gas Regulation and the Kigali Amendment to the Montreal Protocol mandate the phasedown of high-GWP HFCs, accelerating the adoption of alternatives. Manufacturers now prioritize refrigerants with lower GWP, such as R32 (GWP 100 = 704) and R454B (GWP 100 = 490), which serve as "drop-in" replacements for older systems. However, the article cautions that some substitutes, like R513A, are mixtures containing legacy refrigerants (e.g., R134a), which may undermine long-term sustainability goals. This underscores the importance of holistic evaluations that consider not only GWP but also factors like atmospheric lifetime, toxicity, and flammability.

The study emphasizes that sustainable refrigerants must be assessed in two ways: short-term (GWP 20) and long-term (GWP 100) climate impacts (Figure 13). While newer refrigerants reduces cumulative emissions over centuries (GWP 100), their short-term effects (GWP 20) can be significant. For example, R1234ze's GWP 20 is four times its GWP 100, reflecting its rapid atmospheric degradation but concentrated near-term impact. Similarly, R32 and R454B exhibit GWP 20 values 3.5 times higher than their GWP 100, illustrating the trade-offs between immediate and delayed climate effects. These findings favor for policies that integrate both metrics, ensuring that refrigerant choices address both urgent and protracted environmental challenges.

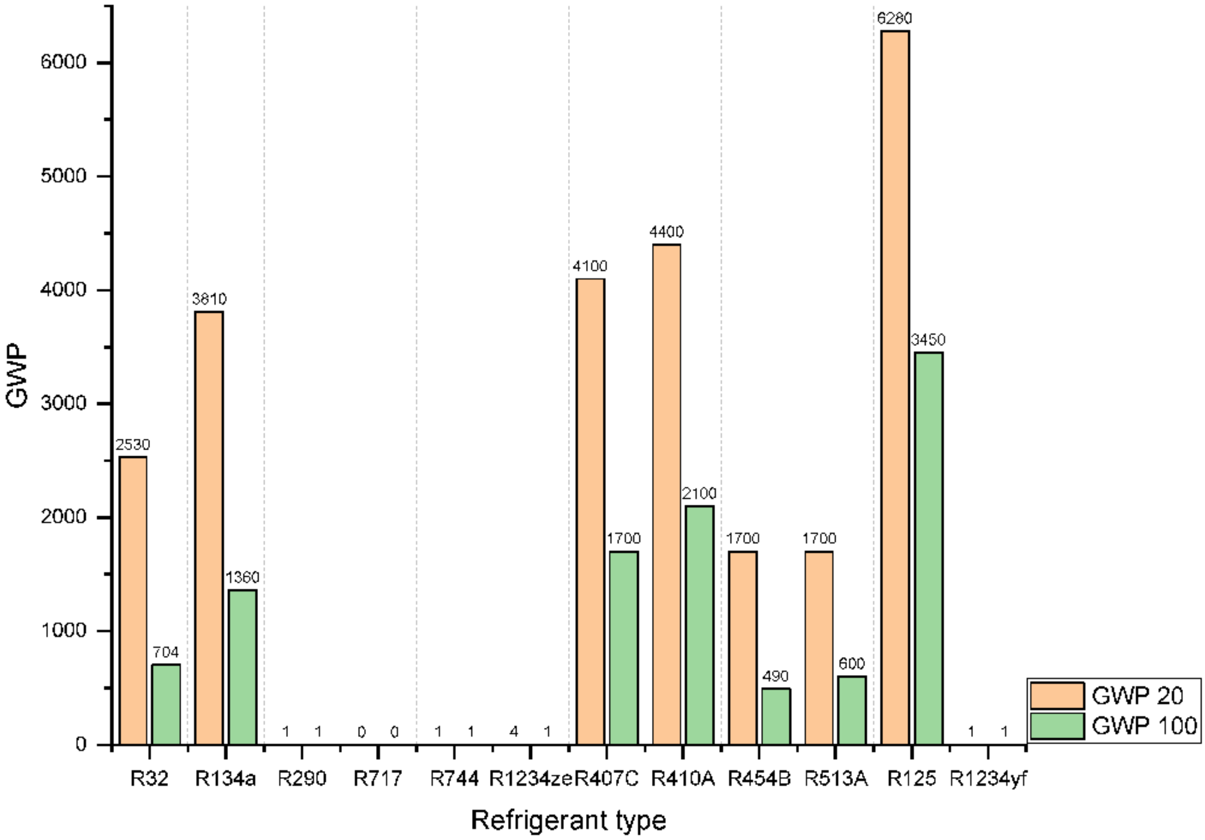


Figure 13. GWP 20 and GWP 100 index values for selected refrigerants and their components

Despite progress, barriers to widespread adoption persist. Flammable or toxic refrigerants require enhanced safety measures, increasing installation and maintenance costs. System retrofitting, particularly for natural refrigerants like CO_2, demands specialized equipment due to higher operating pressures. Additionally, the lack of standardized data on practical concentration limits for newer refrigerants complicates risk assessments. The article stresses the need for updated safety standards, such as ASHRAE 34 and ISO 817, to address these gaps and foster confidence in sustainable alternatives.

Multidimensional approach to refrigerant sustainability should be the main focus in future. Life cycle climate performance (LCCP) metrics, which account for direct emissions and indirect energy-related CO_2 output, should complement GWP evaluations. Furthermore, emerging indices like GWP*, which link cumulative CO_2 emissions to short-lived pollutants, could refine climate impact assessments. Policymakers are urged to mandate transparent reporting of GWP 20 and GWP 100 values, enabling informed decision-making.

In conclusion, the trend is directed towards refrigerants with negligible environmental impact. Some of the recently used refrigerants fit into the trend. However, they have some restrictions like flammability or toxicity. Air and water also have some limitations, but they are generally not perceived as a refrigerants itself. Due to their lack of negative impact on the environment, they can become a promising alternative for the future.

6.2. Przegląd zastosowania nanopłynów oraz materiałów porowatych w pośrednim chłodzeniu wyparnym (A review of nanofluids and porous materials application for indirect evaporative cooling) – P2

Results were published in Ł. Stefaniak, K. Rajski, J. Danielewicz. „Przegląd zastosowania nanopłynów oraz materiałów porowatych w pośrednim chłodzeniu wyparnym". In: *Ciepłownictwo, Ogrzewnictwo, Wentylacja* 2023, vol. 54, no. 12, p. 33-40, DOI: 10.15199/9.2023.12.5.

This paper focuses on recent advances in evaporative cooling. The use of nanofluids and porous materials in wet channel were identified to be the recent paths of development in this topic. Each was discussed in the details. Both approaches aim to make the heat-and-mass transfer more efficient, so the cooler can deliver more cold air for the same amount of energy.

Nanofluids, composed of water with suspended nanoparticles such as Al_2O_3, TiO_2, CuO, SiO_2, or hybrid and ternary combinations, enhance thermal conductivity by 1.6% to 32.3%, depending on nanoparticle type and concentration. These fluids improve evaporative cooling through a three-phase process: initial evaporation dominated by water, a critical phase where nanoparticles boost heat flux due to their high thermal conductivity, and a final phase leaving a nanoparticle residue. Numerical studies on cross-flow (CrF) and counter-flow (CoF) heat exchangers demonstrate performance improvements. For instance, at higher inlet air temperatures (e.g., 35°C), performance enhancement ratios (PER) reach tens of percent. Hybrid and ternary nanofluids, such as CuO-MgO, show marginal gains in exergetic efficiency but face challenges in preparation complexity and cost. However, the lack of experimental validation for these numerical results raises questions about real-world applicability, particularly regarding long-term stability and nanoparticle accumulation in systems.

The second innovation involves modifying wet channel surfaces with porous materials to ensure uniform, thin water films and reduce thermal resistance. Four material categories are evaluated: porous ceramics, natural fibers, polymer fibers, and textile fibers. Porous ceramics increases water retention and extended air-water contact but suffer from brittleness. Natural fibers, like those derived from pineapple leaves or hemp, are cost-effective but prone to delamination and microbial growth. Polymer fibers, often used in composites with materials like polystyrene or polypropylene, offer corrosion resistance and structural flexibility, enabling compact, lightweight heat exchangers. Textile fibers, while highly absorbent, require rigid construction due to their low durability. Commercial applications, such as Seeley's Coolerado HMX (polymer-based) and AOLAN's Wind Domination (cellulose-paper composite), highlight practical implementations, with reported cooling capacity increases of up to 20% and reduced pump operation.

The study concludes that porous materials should be prioritized in new heat exchanger designs due to their structural impact and immediate performance benefits, while nanofluids offer retrofit potential for existing systems. Both innovations align with global sustainability goals by minimizing carbon footprints and energy use. Indirect evaporative cooling's simplicity, combined with these advancements, positions it as a viable complement to conventional HVAC systems, particularly in regions transitioning to drier climates. However, challenges remain, including the need for experimental validation of nanofluids, optimization of material durability, and adaptation to local environmental conditions. Overall, the paper underscores the ecological and economic potential of these innovations, advocating for continued exploration to address current limitations and maximize their contribution to sustainable cooling solutions.

6.3. Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review – P3

Results were published in Ł. Stefaniak, A. Grabka, J. Walaszczyk, K. Rajski, J. Danielewicz, W. Jaskóła, M. Wochniak, W. Żyta. „Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review" In: *Energies* 2025, vol. 18, no. 9, art. 2296, p. 1-24., DOI: 10.3390/en18092296.

This paper offers a review focused directly on intermittent water spraying in DIEC. Previously the topic has not been discussed. Thus, the review tackles also the topic of materials that the heat exchanger is made of, and evaluates to what extent it can limit the use of intermittent water spraying.

Continuous-spray systems are achieving impressive energy savings and the researchers investigate various variables influencing the effectiveness of those coolers. Consequently, researchers have begun investigating intermittent spraying, in which water is cycled on and off at set intervals. However, most work to date has explored this only in porous heat exchangers that store water between sprays, leaving conventional finned-tube or plate exchangers largely unexamined. This review therefore spotlights both porous and non-porous surfaces under intermittent operation, aiming to chart a path toward retrofit-friendly, water-efficient DIEC units .

In case of intermittent spraying, the choice of material is crucial. Porous ceramics, fiber mats and hydrophilic coatings can absorb and hold water in their microstructure, releasing it steadily during spray pauses. For example, a cellulose/PET fiber medium demonstrated an evaporation rate of 4.34×10^{-4} kg/(m²·s) and supported non-spray cooling periods up to τ=2410 seconds, reducing pump runtime by over 95 % compared to continuous flow. Likewise, a bilayer structure combining hydrogel and SiO_2 aerogel extended cooling duration eleven-fold versus a single layer, showing that material design can dramatically boost water use efficiency under cyclical spraying.

Water delivery itself varies from nozzle-based atomization to passive, nozzle-free schemes. Gravity-fed systems, using an elevated reservoir to drip water via wicking channels, eliminate pumps altogether and halve water consumption, but with lower peak cooling capacity (when compared to nozzle based systems). Equally critical are the control strategies governing spray timing. Continuous spraying delivers steady output but at high water and pump energy cost. Intermittent modes, where spray and pause durations are preset, can reduce water use significantly, yet demand reliable timing control. Adaptive approaches, triggered by real-time temperature or humidity feedback, promise the best balance, dynamically matching water to cooling needs and further optimizing the water-energy trade-off.

Beyond core spray mechanics, practical deployments must consider water quality, source and regulatory context. Scale buildup can be mitigated with softeners, while reclaimed or rainwater harvesting can supply spray pumps in water-stressed locations. Studies show feed-water temperature has minimal effect on performance, and connecting to existing air-handler condensate can yield additional savings. Nonetheless, local water scarcity and legislation may still limit adoption, underscoring the value of systems that maximize rainwater use or integrate greywater harvesting.

Looking ahead, four priorities were identified for bringing intermittent spray DIEC to market readiness: (1) rigorously evaluating spray–pause dynamics on non-porous exchangers to enable retrofits without full hardware replacement; (2) developing next-generation coatings and composites that combine high wettability with long-term stability and low microbial risk; (3) refining adaptive control algorithms that link environmental sensors to spray cycles across diverse exchanger geometries;

and (4) assessing alternative water sources alongside renewable energy integration, such as solar-powered pumps, to align DIEC systems with broader sustainability goals.

6.4. Challenges and future directions in evaporative cooling: balancing sustainable cooling with microbial safety – P4

Results were published in Ł. Stefaniak, S. Szczęśniak, J. Walaszczyk, K. Rajski, K. Piekarska, J. Danielewicz. „Challenges and future directions in evaporative cooling: balancing sustainable cooling with microbial safety”. In: *Building and Environment* 2025, vol. 267, Pt. A, art. 112292, p. 1-12, DOI: 10.1016/j.buildenv.2024.112292.

This article is a complementary part of any evaporative cooling technology. It touches the risk of microbial risk in evaporative coolers. This is crucial in terms of safety of usage in wide spectrum of application.

The study addresses the dual challenges of promoting evaporative cooling (EC) as a sustainable alternative to traditional vapor compression systems while mitigating microbial risks. However, its reliance on air-water interaction creates moist environments conducive to microbial growth, posing significant health risks. While *Legionella pneumophila* is the most studied pathogen in these systems, the article emphasizes the need to address broader microbial threats, including fungi, molds, and other bacteria, which are often overlooked in guidelines and research.

Direct evaporative cooling (DEC), where air directly contacts water, poses the highest risk due to potential contamination of supply air. IEC and DIEC reduce this risk by separating wet and dry channels via division to wet and dry channels, though air leakage between channels remains a concern. The study highlights that microbial contamination can originate from outdoor air, water sources, or biofilm formation on heat exchanger surfaces. Biofilms, composed of bacteria, fungi, or protozoa, thrive on materials with moderate hydrophobicity and can detach into aerosols, contaminating indoor air.

The choice of heat exchanger materials significantly influences microbial safety. Porous materials like metal wicks or ceramics enhance water distribution but risk biofilm formation due to concealed pores. Non-porous materials, while easier to clean, may reduce cooling efficiency. Recent advancements focus on surface modifications, such as hydrophilic or hydrophobic coatings, to balance performance and safety. For instance, superhydrophilic surfaces reduce bacterial adhesion but require precise engineering to maintain thermal efficiency. The study critiques current maintenance practices, which often prioritize *Legionella spp.* control while neglecting other pathogens. Inadequate drainage, irregular cleaning, and insufficient monitoring exacerbate risks, particularly in systems using alternative water sources like rainwater or greywater.

Mitigation strategies include UV water treatment, biocides (e.g., bronopol), and operational adjustments such as maintaining water temperatures below 20°C to inhibit *Legionella spp.* growth. UV treatment effectively reduces microbial loads but requires integration with filtration to address symbiotic organisms like amoebae. The article also explores alternative water sources to address freshwater scarcity, noting that rainwater and greywater, when treated, can be viable but may introduce contaminants if improperly managed. Saline water, though abundant, risks corrosion and scaling. Condensate water, a byproduct of dehumidification, emerges as a promising supplement due to its low contamination risk.

In conclusion, the article positions EC as a sustainable solution with untapped potential, contingent on improved microbial safety measures. Key recommendations include adopting UV treatment, optimizing heat exchanger materials, and expanding maintenance guidelines to encompass non-*Legionella* pathogens. By addressing these challenges, any EC system can achieve a balance between energy efficiency and public health safety, aligning with global sustainability goals. Future research should focus on long-term material performance, hybrid systems integrating dehumidification, and standardized protocols for alternative water use, ensuring EC’s viability in diverse climatic and operational contexts.

6.5. The possibility of intermittent water spray implementation in a non-porous indirect evaporative cooler – P5

Results were published in Ł. Stefaniak, J. Walaszczyk, M. Karpuk, K. Rajski, J. Danielewicz. „The possibility of intermittent water spray implementation in a non-porous indirect evaporative cooler". In: *Energies* 2025, vol. 18, no. 4, art. 882, DOI: 10.3390/en18040882.

This study evaluates the very first test on the performance of the DIEC under intermittent water spraying. The investigation focused on the long period of time (over 40 minutes) without spraying to see how the system will work. It provides an original results that allow to provide a mathematical model on the behavior of the investigated DIEC.

DIEC enhance performance by recirculating precooled air. However, prior research has predominantly focused on porous heat exchanger surfaces for intermittent water spraying, leaving non-porous materials unexplored. This study bridges this gap by investigating the feasibility of intermittent water spray in non-porous IEC systems, aiming to optimize energy efficiency and cooling performance without structural modifications.

The experimental setup involved a cross-flow DIEC system with a non-porous polymer plate heat exchanger comprising 115 plates (500 × 500 mm dimensions, 2 mm channel height). Airflow parameters were regulated using adjustable dampers, cooling coils, heaters, and humidifiers. Water was sprayed via BETE WL-½ 120 BSP nozzles and recirculated from a reservoir. Temperature, humidity, and flow rates were monitored using Sensirion SHT25 sensors and flow meters, ensuring steady-state conditions (±1% temperature and ±5% humidity stability over 5 minutes). Tests were conducted across three inlet air temperatures (20, 25, 30 °C) and relative humidities (40, 45, 50 %), reflecting temperate European climates. After achieving steady-state cooling with continuous spraying, the water supply was stopped, and system performance was tracked for over 40 minutes. A regression model combining exponential decay (for initial temperature drop) and logistic functions (for subsequent temperature rise) was developed to predict outlet air temperature (T2) and relative humidity (RH2) as functions of time (τ), inlet temperature (T1), and humidity (RH1). The model demonstrated high accuracy, with determination coefficients R^2=0.980 for T2 and R^2=0.907 for RH2, validated by statistically significant parameters.

Key findings revealed distinct temperature dynamics after water shut-off: T2 initially dropped sharply (5.9–11.1 K reduction), stabilized at a minimum value within 4–6 minutes, and gradually returned to pre-shutoff levels. The main finding for exemplary parameters is presented in Figure 14. It can be divided by 4 points:

1. Turnoff of the water system;
2. Lowest T2 value is achieved;
3. T2 value starts to increase;
4. T2 is equal to the T2 in τ = 0 s.

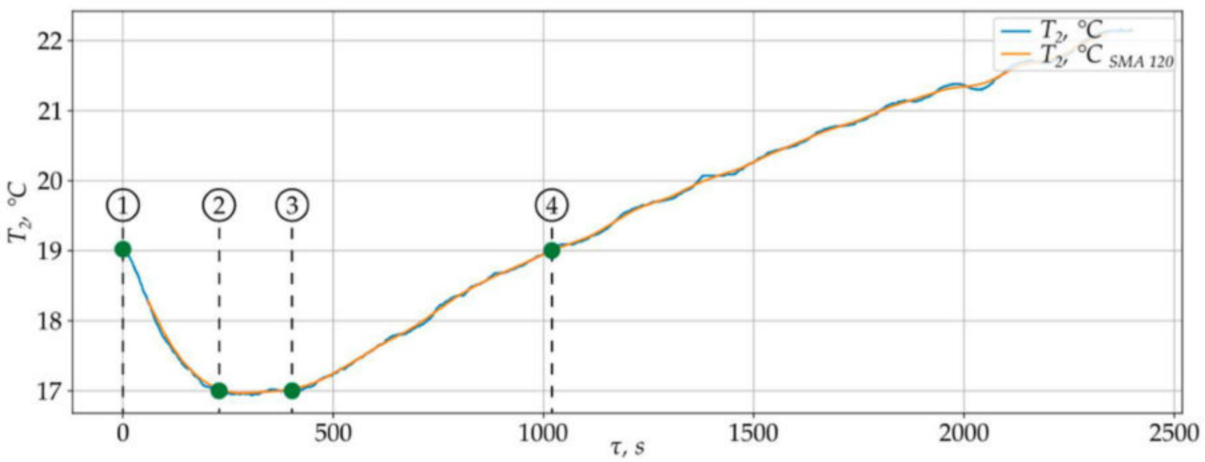


Figure 14. Supply air temperature after water system turnoff, example for inlet air temperature 25 °C and inlet air relative humidity 45%

This transient phase significantly enhanced cooling capacity. For instance, at T1=30°C and RH1=40%, the maximum cooling capacity (Q2) reached 1100 W, surpassing the steady-state capacity (Q1=800W). The average cooling capacity (Q3) during the drying phase consistently exceeded Q1, underscoring the potential of intermittent spraying. Notably, non-porous surfaces, despite lacking the water retention of porous materials, enabled effective intermittent operation, reducing pump operation time.

The study introduces a novel operational strategy for optimizing existing IEC systems through intermittent water management rather than structural changes. By identifying a 4–6 minute pause interval after achieving minimum T2, energy savings and cooling efficiency can be maximized. The regression model serves as a predictive tool for T2 and RH2 under varying conditions, aiding in system control optimization. Additionally, non-porous materials offer reduced microbial risks compared to porous alternatives, aligning with HVAC safety standards.

In conclusion, this research validates intermittent water spraying in non-porous IEC systems as a viable pathway toward energy-efficient cooling. Future directions include developing adaptive control systems for automated spray cycles, exploring hybrid systems integrating desiccants or renewable energy, and assessing long-term material durability. By bridging the gap between porous and non-porous material research, this work expands the applicability of evaporative cooling, offering a scalable solution to reduce HVAC energy demand across diverse climates.

6.6. Experimental performance analysis of non-porous indirect evaporative coolers under intermittent water spraying conditions – P6

Results were published in Ł. Stefaniak, J. Walaszczyk, J. Danielewicz, K. Rajski. „Experimental performance analysis of non-porous indirect evaporative coolers under intermittent water spraying conditions". In: *Journal of Building Engineering* 2025, vol. 105, art. 112585, p. 1-16, DOI: 10.1016/j.jobe.2025.112585.

This paper is a continuation of the P5. As previously the intermittent water spray was proved to be applicable in examined DIEC, the experiment was done for set up spraying and pause times.

Prior research has predominantly explored porous heat exchangers with intermittent water spraying, demonstrating significant energy savings and improved coefficients of performance (COP). Non-porous systems, however, remain understudied despite their advantages, including reduced susceptibility to bacterial growth and lower manufacturing complexity. This study experimentally evaluates the performance of a non-porous DIEC system under intermittent water spraying conditions, testing three spray intervals τ (30 s, 60 s, and 90 s with 420 s pauses) and varying inlet air velocities v (1.6, 2.0, and 2.5 m/s). The objective is to optimize water management strategies to enhance energy efficiency without compromising cooling capacity, thereby advancing sustainable cooling technologies.

The experimental setup was the same as in the P5. Key performance metrics evaluated included wet bulb effectiveness, dew point effectiveness, COP, and cooling power. Steady-state conditions were ensured by stabilizing temperature (±1%) and humidity (±5%) fluctuations, with uncertainty analysis following BIPM guidelines, yielding standard deviations of 2.6–3.7% for effectiveness metrics and 5.3–10.4% for COP.

Results revealed that intermittent spraying significantly enhanced cooling performance compared to constant operation. For instance, at an air velocity of 2.0 m/s, the average outlet temperature drop reached 10.4 K with 30 s spraying, surpassing the 8.5 K achieved under constant spraying. Cooling power for intermittent modes ranged from 937–1289 W, consistently exceeding the 598–1215 W observed in constant operation. Dew point effectiveness values for intermittent spraying (0.59–0.72) outperformed constant operation (<0.60), while wet bulb effectiveness peaked at 1.04 (30 s spraying) versus 0.85 for continuous spraying. Energy efficiency gains were particularly striking: COP values for intermittent spraying (50–107) were 2–5 times higher than those for constant operation, with the shortest spray interval (30 s) yielding the highest COP due to minimized pump runtime (4–10.5 minutes per hour). The most informative findings are presented in Figure 15. These improvements stemmed from reduced pump energy use and optimized heat transfer during dry intervals, where latent cooling dominated. Air velocity also played a role, with higher velocities (2.5 m/s) reducing effectiveness but maintaining competitive cooling power, aligning with literature recommendations to limit velocities to ≤2.5 m/s.

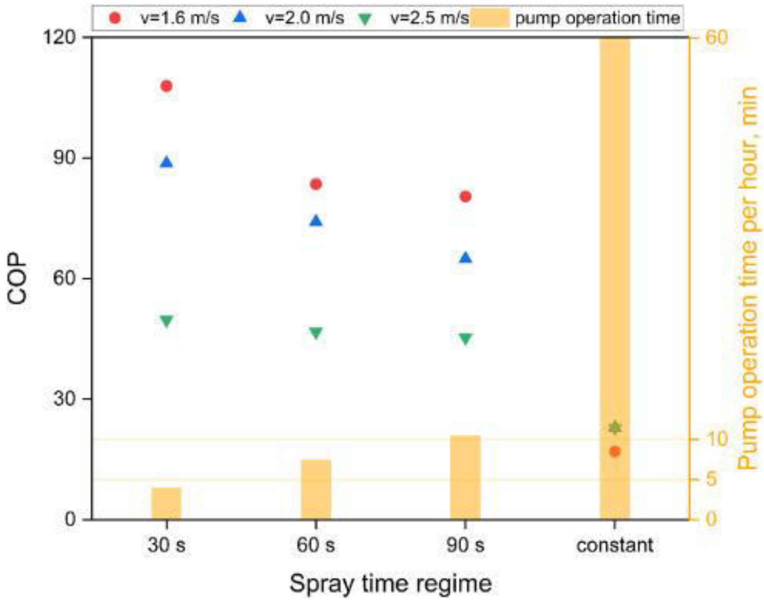


Figure 15. COP and the pump operation time per hour for dry channel air velocity 1.6, 2.0, 2.5 m/s

The discussion emphasizes that intermittent spraying mitigates key limitations of non-porous systems, such as excessive water film thickness and elevated water temperatures. During dry intervals, secondary air absorbs latent heat more efficiently, enhancing the temperature gradient between dry and wet channels. This contrasts with constant spraying, where continuous water flow increases thermal resistance and pump energy consumption. The findings align with those from porous systems but underscore the viability of non-porous designs, which avoid microbial risks associated with porous materials and simplify manufacturing.

In conclusion, the study demonstrates that intermittent water spraying in non-porous DIEC systems markedly improves energy efficiency and cooling performance. Key implications include electrical consumption reductions exceeding 80%, COP values up to 107, and avoidance of microbial growth risks. The proposed strategy requires minimal retrofitting, focusing solely on optimizing water pump control. While the study's scope was limited to specific inlet conditions (30°C, 40% RH) and a single heat exchanger design, the findings provide a foundational framework for advancing DIEC technology. Future research should explore diverse climatic conditions, materials, and spray algorithms to further validate and refine these systems. Ultimately, this work highlights the potential of optimized water management in non-porous DIEC systems to meet escalating cooling demands sustainably.

energies

Article

Global Warming Potential of New Gaseous Refrigerants Used in Chillers in HVAC Systems

Sylwia Szczęśniak * and Łukasz Stefaniak *

Faculty of Environmental Engineering, Wroclaw University of Science and Technology, 50377 Wroclaw, Poland
* Correspondence: sylwia.szczesniak@pwr.edu.pl (S.S.); lukasz.stefaniak@pwr.edu.pl (Ł.S.)

Abstract: Due to the global warming and resulting problems, attention has been paid to greenhouse gases released into the atmosphere since the 1980s and 1990s. For this reason, the Montreal Protocol and the Kyoto Protocol have tightened regulations on the use of gaseous refrigerants in both HVAC systems and industrial refrigeration. Gradually, new generations of gaseous refrigerants, that theoretically have much less negative environmental impact than their predecessors, are introduced into the market. The key parameter describing environmental impact is the GWP index, which is most often defined on a time horizon of 100 years. The long-term use of new generations of gaseous refrigerants in HVAC systems reduces CO_2 emissions into the atmosphere; however, given that new generation gases often have a short lifetime, it seems that the adopted assessment may not be applicable. The aim of the article was to show how emissions of CO_2 equivalent to the atmosphere differs in the short and long time horizon. The article presents the results of calculations of equivalent CO_2 emissions to the atmosphere caused by the operation of compressor cooling devices used in HVAC systems, where cooling is done with the use of water or a water-glycol solution. The analysis was carried out for 28 commonly used devices on the world market. The analyzed devices work with refrigerants: R513A, R454B, R290, R1234ze, R32, R134a, R410A. The equivalent emissions values for GWP 100 and GWP 20 were analyzed in relation to the unit power of the devices depends on refrigerant mass and number of fans. The study showed that in the case of new generation refrigerants with a very short lifetime, the use of GWP 100 indicators is misleading and does not fully reflect the effects of environmental impact, especially in the area of refrigeration equipment application. The article shows that the unit value of the cooling load related to the number of fans or the unit would be helpful in assessing the environmental impact of a cooling device.

Keywords: Global Warming Potential (GWP); Ozone Depletion Potential (ODP); air cooling; air pollutant; CO_2 equivalent; climate change; sustainable development

Citation: Szczęśniak, S.; Stefaniak, Ł. Global Warming Potential of New Gaseous Refrigerants Used in Chillers in HVAC Systems. *Energies* **2022**, *15*, 5999. https://doi.org/10.3390/en15165999

Academic Editor: Donato Morea

Received: 15 July 2022
Accepted: 16 August 2022
Published: 18 August 2022

1. Introduction

1.1. The Idea of Determining the Impact of Different Substances on the Climate

There has been a debate [1–9] about the impact of pollutants emitted into the atmosphere for decades about when changes in typical weather patterns began to be noticed. Substances that are able to retain the Sun's energy within the Earth's atmosphere as a result of their physical and chemical properties are called greenhouse gases. They have a direct impact on the temperature rise observed on the globe, as they absorb the infrared radiation emitted from our planet. Because it cannot be released into space, the resulting energy enters the atmosphere, causing its temperature to rise, which in turn increases the temperature of the Earth's surface. Greenhouse gases include: water vapor, carbon dioxide (CO_2), CFCs, refrigerant gases (HCFCs, HFCs), halons, methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and various industrial gases (e.g., perfluorocarbons (PFCs)). One of the primary pollutants that have a great impact on the increase in the temperature of the Earth's surface and atmosphere are gaseous refrigerants [10–16].

It was not until the 1970s that an attempt was made to determine to what extent greenhouse gases of different chemical compositions affected the temperature of the atmosphere and thus the Earth's surface. The use of refrigerants with the potential to destroy the ozone layer (OL) and create the greenhouse effect has been done in the nineteenth century [17]. Figure 1 shows the development of refrigerants in a historical context. Refrigerants are illustrated here with reference to their successive generations from 1 to 5. The introduction of each successive generation of refrigerants is related to a reduction in CO_2 equivalent emissions into the atmosphere.

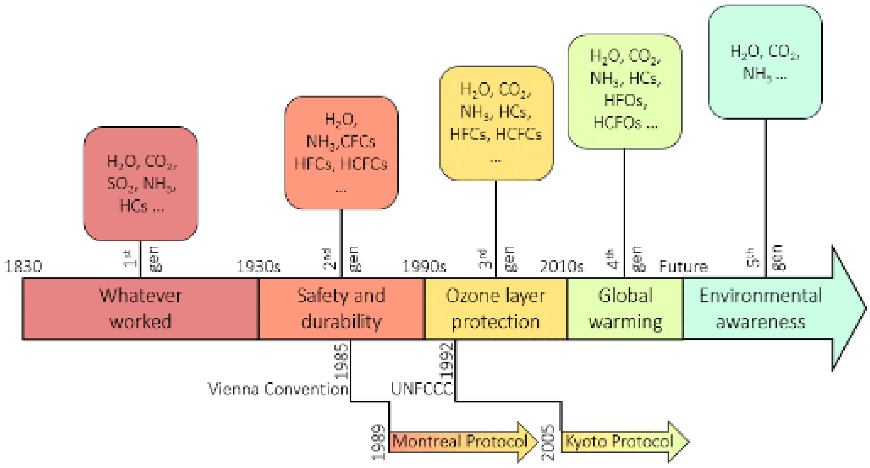


Figure 1. Historical development of refrigerants [17].

The growing awareness of environmental issues has led the World Meteorological Organization (WMO) to conduct an international assessment of the OL on a global scale [12]. As a result, the need arose to organize measures to protect the Earth by protecting the OL. It was established in 1985 in the Vienna Convention, which dealt with the issue of protecting the OL. The Convention was signed by 28 countries at the time and currently has 198 members [18]. The convention resulted in the Montreal Protocol on substances that contribute to the so-called depletion of the OL, which entered into force in 1989. According to the idea of protecting the OL, 8 substances with a high Ozone Depletion Potential (ODP) were controlled [14]. The gaseous refrigerants were then divided into two groups: chlorofluorocarbons (group I) and halons (group II). This breakdown is shown in Table 1. This was also the time when the next third generation of refrigerants appeared, for which the ODP index takes the value of 0 (group III—refrigerants analyzed in the paper).

Table 1. Controlled substances with ODP values based on Annex A of the Montreal Protocol [14] and analyzed refrigerants.

Group	Substance	Ozone Depletion Potential
I *	R11	1.0
	R12	1.0
	R113	0.8
	R114	1.0
	R115	0.6
II *	CF2BRCl (halon-1211)	3.0
	CF2BR (halon-1301)	10.0
	C2F4Br2 (halon-2402)	6.0 **

Table 1. *Cont.*

Group	Substance	Ozone Depletion Potential
III ***	R32 R134a R290 R717 R744 R1234ze R407C R410A R454B R513A R125 R1234yf	0

* Groups implemented by Montreal Protocol. ** Value assumed under the Decisions of the Meetings of the Parties to the Montreal Protocol—Decision I/9: ODP for halon 2402 [19]. *** Analyzed refrigerants.

The second study that indicated that anthropogenic factors affect not only the OL but also climate change was a report published in 1990 by the Intergovernmental Panel on Climate Change (IPCC) [10]. The purpose of the report was to assess the negative impact of human activities on the climate [10,20]. In response to the results of this assessment, the United Nations Framework Convention on Climate Change was adopted in 1992 [16]. The most important protocol of this convention became the Kyoto Protocol, negotiated in 1997, which introduced specific provisions on, among other things, the emission of greenhouse gases, including gaseous refrigerants, into the atmosphere [15]. This protocol did not enter into force until 2005 and with it the next fourth generation of refrigerants is presented in Figure 1. Article 5 of the Kyoto Protocol uses the Global Warming Potential (GWP) value introduced in 1990 by the IPCC. The use of the GWP index was to allow the determination of the impact of various greenhouse gases on the climate in relation to the equivalent of carbon dioxide accumulated in the atmosphere [10,21].

1.2. Indicators for Assessing the Impact of Different Refrigerants on Climate

One of the most popular indicators of environmental pollutants is the Global Warming Potential (GWP). The use of the GWP index was to allow determination of the impact of various greenhouse gases on the climate in relation to the equivalent of carbon dioxide accumulated in the atmosphere [10,21]. The GWP index describes the change in the quotient of the global mean surface temperature for a given time horizon (TH) after a number of years caused by the emission of the substance related to the reference substance. The introduction of the GWP index was innovative and interesting because it takes into account both global mean Radiative Forcing (RF), a so-called disturbance in the radiation balance of the Earth's climate system [22], and the length of time that a substance remains in the atmosphere [10]. It has become the default measure for converting the emissions of different gases into an equivalent emission value of a reference gas (usually CO_2) into the atmosphere [22]. The following periods have been established by default as TH: 500, 100 or 20 years [22]. The GWP index relating to the equivalent emission of CO_2 in the atmosphere was introduced in 1990 and was already considered in terms of climate policy on a 100-year time horizon, which was written as GWP 100 [23]. The IPCC [10] indicated that long time horizons are adequate for evaluating sea level rise, while for terrestrial areas, where the effects of changes in energy emissions from the atmosphere are much faster, short time horizons are much more important. For gaseous refrigerants with a long atmospheric life, it was reasonable to consider GWP 100 [21]. Meanwhile, with the introduction to the market of gaseous refrigerants with a short life (VSL) in the atmosphere (with a life of less than a month [11]), the use of GWP 100 is no longer justified.

This long time period (TH = 100) ignores the fact that it has an effect on RF disturbance at short intervals [24], especially at the local scale. Effective mixing with air at a global level for refrigerants of short lifetime is impossible, and thus their distribution in the troposphere is uneven. As a result, one needs to consider the real three-dimensional distribution of refrigerants in the atmosphere at the local level. Combining this knowledge with the infrared absorption value for a given refrigerant makes it possible to calculate the GWP in the local area. These data depend, among other things, on the composition of the atmosphere in the emission area at a given time [21] and are not popularized and easily accessible, making it difficult to standardize them on a global scale. However, it is certain that global GWP values for short-lived refrigerants will be significantly lower compared to those with long-life refrigerants, because, despite the local impact, this index has a global reference. Therefore, the article attempts to determine the actual differences in these values of CO_2 equivalent emissions for cooling devices filled with stock refrigerants.

Due to the need to assess the risk of global warming and the more commonly used substances with a very short life, a new approach to GWP was presented in 2018 [25]. Crucial is that in 2016 [7] and in 2019 [26] it was mentioned that the long-term GWP index does not relate cumulative CO_2 emissions to date with the current rate of emission of short-lived climate pollutants (SLCPs). Allen [7] proposed a new, broader GWP index, designated as GWP*. It relates the CO_2 emissions accumulated so far to the current stream of refrigerants with a short lifetime. Studies [25–27] confirmed that the new idea of GWP* is better on assessing the impact on the climate in both long- and short-term modes. Therefore, it is suitable to show the effect of greenhouse gas emissions on radiative forcing and temperature for long- and short-lived refrigerants in the atmosphere [23,27]. This also applies to the refrigerants used in compressor systems. Potentially, the GWP* values will be presented in the Sixth IPCC Report of 2022, which already exists but cannot be cited and distributed. The part that is possible to cite does not contain any GWP* values, thus no further consideration of GWP* is performed. Nevertheless, the article compares the values of CO_2 equivalent emissions for GWP 100 and GWP 20.

Climate reports and scientific articles include alternative indicators of the impact of greenhouse gases on climate. Shortly after the GWP, in 1991, the Total Equivalent Warming Impact (TEWI) index was proposed [28]. It is a measure of the direct and indirect effects of the device during operation and later during storage and processing [29]. It also includes fossil fuels energy used during device operation. The TEWI is dedicated for installations or systems and depends on the GWP index value, the annual percentage rate of leakage from the system, the lifetime of the system and the energy consumed during the year, equivalent of emission CO_2 (g CO_2 kWh^{-1}) and system uptime [30]. Due to the fact that the TEWI index does not take into account the emissions related to the production of refrigerants and refrigeration equipment, in 1999, the United Nations Environment Program (UNEP) presented the Life Cycle Climate Performance Index (LCCP) [31]. It takes both direct and indirect emissions during the life cycle of the device and its components into account.

In summary, the GWP index is used to evaluate the environmental impact of e.g., refrigerants used in HVAC devices in a global meaning. To determine the environmental impact of refrigeration systems or installations, the TEWI and LCCP indicators are more applicable. This is due to considering not only the influence of the refrigerant emitted to the atmosphere, but also, e.g., energy consumption in the working cycle [30,32,33]. No indicators take the environmental impact caused by the use of various materials in the production process, e.g., metals, into account.

1.3. *Refrigerants Used in Air Conditioning and Space Cooling*

The increasing quality of life has forced the widespread use of air conditioning systems in both Europe and the United States, in which cold air or cold surfaces in Thermally Activated Building Systems (TABS) are obtained through the operation of direct or indirect cooling devices. The common denominator for these devices, installations, and systems is always a gaseous refrigerant, which have a crucial influence on the climate of the Earth. They are one of the basic factors that contribute to climate change. In the case of single-component refrigerants, the entire mass of substances undergoes the same processes and cycles of changes in the atmosphere. In the case of multicomponent mixtures, the behavior of each component in the atmosphere should be considered individually.

The introduction of substitutes is, of course, aimed at reducing the negative impact of emissions on the climate. It should be related to an environmentally and energetically rational and justified decision. As understood by the widely used GWP 100, the introduced substitutes significantly reduce threats to the human environment. When switching from R410A with a GWP 100 of 2100 to R454B with a GWP 100 of 490, the decrease in GWP 100 is 1610. For comparison, the change of the R134a refrigerant with GWP 100 = 1360 to R513A, for which GWP 100 = 600, the decrease is 760. Although this is a good direction of change in terms of climate policy, the opposite is true for the transformation processes of the constituent substances in the atmosphere. For example, as mentioned, by changing refrigerant R134a to R513A, both components (R134a and R1234yf) are decomposed, among others, into Trifluoroacetic acid (TFA). After decomposition in the atmosphere, up to 92–100% of R1234yf mass emissions will become TFA, and for R134a this percentage is only 7–20% of mass [29]. In the case of R1234ze, the formation of TFA does not occur [34].

There are a number of replacements for old generation refrigerants (because of high GWP and ODP). There is a visible tendency to change refrigerants in the A1 class to other refrigerants that are more dangerous in terms of flammability. This is directly related to the shorter decay time in the atmosphere. It allows to obtain a lower GWP index, but at the same time promotes easier decomposition in contact with ignition sources [29,35]. Table 2 presents the substitutes for selected refrigerants commonly used in air conditioning systems and compressor refrigeration devices with their safety classes. For those substances, all calculations were done in this article (excluding R123, R22, R404A and R507). Table 3 presents the method of classification of refrigerants in terms of flammability and toxicity according to ASHRAE Standard 34 [36] and ISO 817:2014 [37].

Table 2. Substitutes for selected refrigerants commonly used in air-conditioning systems and in compressor refrigeration devices with their safety classes [38,39].

Substitute	Current Refrigerant
R513A (A1)	R134a (A1)
R454B (A2L)	R410A (A1)
R32 (A2L)	R410A (A1)
R1234ze (A1)	R134a (A1), R123 (B1)
R290 (A3)	R22 (A1), R404A (A1), R507 (A1)

Table 3. Safety classes for refrigerants according to ASHRAE Standard 34 [36] and ISO 817:2014 [37].

Flammability	Lower Toxicity	Higher Toxicity
Higher Flammability	A3	B3
Lower Flammability	A2 A2L *	B2 B2L *
No Flame Propagation	A1	B1

* Refrigerants with maximum burning velocity of ≤10 cm/s.

1.4. *Which GWP Index Should Be Used to Assess the Real Impact on Local and Global Environment*

As can be seen from the above considerations, it seemed that a better alternative to the 100-year period is the 20-year period, for which GWP 20 is considered [40]. It should be noted that the use of shorter time periods results in an increase of GWP value of gases with a short lifetime in the atmosphere [41] and in a decrease of safety classes. For gases with a long atmospheric lifetime, such a treatment reduces the GWP value and provides greater toxic safety. This is closely related to the uniformity of the distribution of the concentration of a given refrigerant in a narrow emission area and a wide spreading area. This observation is widely used in the refrigeration equipment and plant market. Unfortunately, there is no clear indication of which time horizon GWP index should be used and for what purposes [42,43]. This choice should depend on the negative short-term or long-term effects on the environment that are to be shown. GWP 20 is suitable for use in understanding climate policy, where the timescale covers the next decades, not centuries. Using GWP 20 together with GWP 100 can give a broader view of the environmental impact of greenhouse gases (especially short-lived ones) [44] with regard to short-term and long-term effects. It seems that a balance should be struck with regard to both short-term and long-term impact.

To illustrate differences in the lifetime of each refrigerant and to emphasize where the discussion on their local accumulation in the atmosphere came from, in Figure 2, the lifetime of selected gaseous refrigerants are shown.

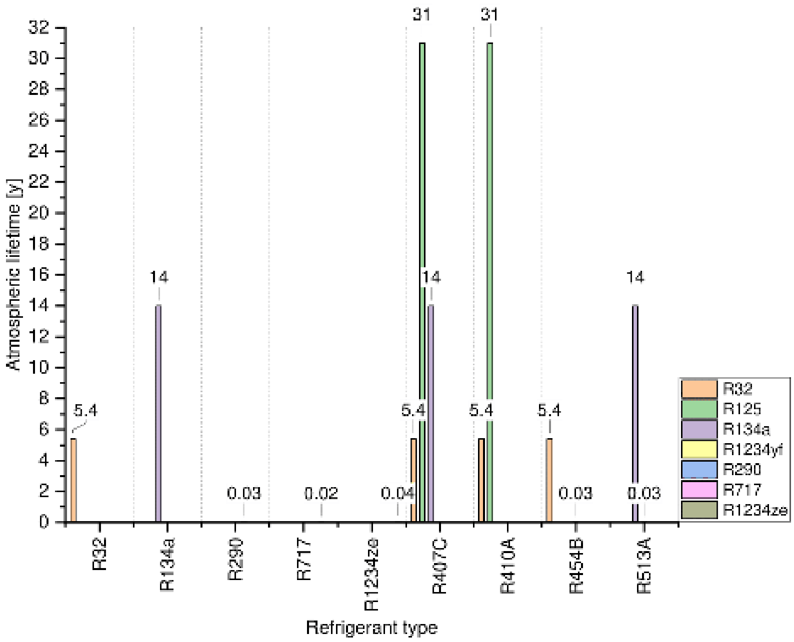


Figure 2. Lifetime in the atmosphere of selected refrigerants [29].

The graph shows how significantly different lifetimes of the next generations of gaseous refrigerants are. The longest-lived refrigerant is R125 (component R407C and R410A) with an atmospheric life of 31 years. For the shortest time, live R717 (less than 7 days) and R1234yf (10.5 days). Therefore, considering the GWP 100 index for refrigerants that remain in the atmosphere for several or several dozen years has logical justifications. However, for refrigerants that are degraded in the atmosphere in several days or even hours, such a long time horizon is no longer relevant.

Despite all criticism and discussions around the GWP index [1–9] it is continuously used in the field of climate policy [45] and in trade. The assumed time horizon is crucial, as it is always considered over a 100-year time horizon. Recent studies indicate uncertainties in the GWP 100 value of the order of ±50% for methane and short-lived gases in the atmosphere and ±40% for non-CO_2 gases with a longer lifetime (in particular, this applies to gases with a lifetime of more than 20 years) [46]. Despite these discrepancies, it remains the primary tool for reporting emissions within the meaning of the United Nations Framework Convention on Climate Change.

One must remember that 100 year time horizon affects at least one generation, thus values of the GWP index are mainly based on calculations and simulations instead of experimental data. Taking the rapid growth of cooling systems in warm or moderate climate and illegal refrigerant markets into account, an examination of the GWP index is needed in terms of short and long time horizons.

The literature and policy review in the article present recent data on the GWP index and its assumptions that are crucial for understanding the implementation of the GWP index and which are not widely presented in the literature. Results based on theoretical review reveal that, along with placing new gaseous refrigerants with VSL on the market, it requires revision and update of the approach to emissions reports.

1.5. The Basic Framework of Work

In this paper, we present a significant difference in GWP 100 and GWP 20 values and further influence on actual CO_2 equivalent emissions to the atmosphere by the implementation of GWP 20/GWP 100 index. Actual masses of CO_2 equivalent emissions have been calculated with reference to data of compressor cooling devices used in HVAC systems. Both short and long time horizons have been considered. The article reveals major disproportions while reporting CO_2 equivalent emissions for 100 and 20 year time horizons for chosen compressor refrigeration units used in Europe and the United States. The purpose of this article is to indicate whether the selection of a cooling device operating with a specific refrigerant has similar consequences for the climate. If not, on what those differences depend. Due to the above, in the article the equivalent of kg of CO_2 emission into the atmosphere was determined using the GWP 100 and GWP 20 indexes. No research has been done in the field of GWP index values related to the load of refrigerants in cooling devices. Therefore, in the paper, a broad description of the GWP index itself was provided to fully present the dependent variables and assumptions. Along with the calculation of the CO_2 equivalent and the establishment of the GWP 20/ GWP 100 index, the paper represents a new approach to climate policy regulations in the context of new refrigerants that are implemented in the market.

2. Materials and Methods

To assess the impact of various refrigeration devices on the climatic conditions in terms of the new refrigerants introduced, 50 devices (commonly used in HVAC systems) were selected from 12 leading companies. The list of devices is presented in Table 4. Eventually, devices working with seven different refrigerants were accepted for analysis: R513A, R454B, R290, R1234ze, R32, R134a, R410A. This choice was made because the refrigerants under consideration are currently in use in existing devices, belong to generations 3–6, i.e., those that were created by the climate policy referred to in this paper (Figure 1). The determining factor was also the availability and completeness of the cooling device catalog data. Due to the different method of presenting data in catalogs, as well as technological differences related to the design of devices, and above all heat exchangers, all the considered data are presented in relation to the unit power of the cooling module (kW/n).

The unit power of the cooling module (kW/n) where the reference unit was an exchanger cooled with a single fan was calculated from the formula:

$$\alpha = \frac{Q_c}{n} \tag{1}$$

where Q_c is the cooling power; kW, n is the number of fans.

The unit power of the refrigerant fill weight (kW/kg) was calculated from the formula:

$$\beta = \frac{Q_c}{m} \tag{2}$$

where Q_c is the cooling power; kW, m is the refrigerant charge; kg.

Table 4. List of devices with the scope of the declared power, the number of fans, and a refrigerant load.

Refrigerant	Producer	Model	$Q_{c\,min}$	$Q_{c\,max}$	$m_{r\,min}$	$m_{r\,max}$	No. Fans
R32	Carrier	30RB	42	380	3.7	36.2	1–6
	Swegon	Zeta SKY	46	238	4.1	18.9	2–3
	Daikin	EWAt-B-SS	81	665	10.0	90.0	4–11
	Carrier	30RBP	172	943	17.8	64.8	3–12
	Swegon	Tetris SKY	200	535	19.0	50.0	3–8
R134a	Swegon	Kappa SKY	255	1343	38.0	165.0	5–22
	Swegon	Kappa REV	307	1542	39.0	165.0	5–22
	TRANE	Sintesis	404	1758	77.7	255.8	10–28
	Carrier	30XV	492	1758	93.0	268.0	8–22
R290	Skadec	VCG	63	365	5.0	24.0	6–8
	Hiterna	PRP	85	278	13.0	26.0	2–4
	Skadec	VCGV	292	646	18.0	36.0	2–8
R1234ze	Swegon	Kappa SKY	234	1063	29.0	142.0	5–18
	Airdale	Turbo Chill	240	1000	110.0	525.0	4–24
	Swegon	Kappa Rev	240	1020	39.0	135.0	5–18
	Flakt	FGAC	383	1463	63.0	218.0	6–20
	TRANE	GVAF XP-G	453	1243	145.0	280.0	14–24
	TRANE	RTAF HSE	741	1618	138.0	222.0	16–24
R410A	Carrier	Aqua Snap 30RAP	38	527	3.8	54.2	1–10
	Swegon	Beta Rev	40	233	3.7	21.0	2–4
	TRANE	CGAM	70	457	13.6	69.8	2–10
	Swegon	TETRIS 2	108	913	11.5	80.0	2–12
	Daikin	Trailblazer	109	847	12.7	100.7	4–14
	TRANE	Ascend	492	808	51.6	94.0	8–12
R454B	Flakt	FGAC DG	40	866	13.8	276.8	4–12
	Swegon	Zeta SKY	42	233	13.4	84.2	2–4
R513A	Swegon	Kappa Sky	243	1260	38.0	165.0	5–22
	Flakt	FGAC AE2	479	1697	79.0	288.0	6–20

All devices considered in the analysis below are equipped with the Microchannel Heat Exchanger (MCHX). Due to the lack of detailed data and a much smaller number of devices with lamella exchangers and a small power range, they were not included in the analysis. Figure 3 shows the refrigeration unit capacity for the selected gaseous refrigerants as a function of the unit cooling capacity for the seven selected refrigerants.

In the range of 5–30 kW/n, devices filled with refrigerant 410A and R32 dominate. In turn, from 40 kW/n to more than 85 kW/n, the R1234ze, R134a, R454B, R513A, and R290 refrigerants dominate. The largest charge (load greater than 100 kg) is found in devices with R513A, R1234ze, and R134a, with R1234ze dominating with loads exceeding 500 kg. Charges not exceeding 100 kg refer to the refrigerants R454B, R32, R290, and R410A. It is worth paying attention to the small loads (<50 kg) of refrigerants throughout the range of the kW/n ratio for R290.

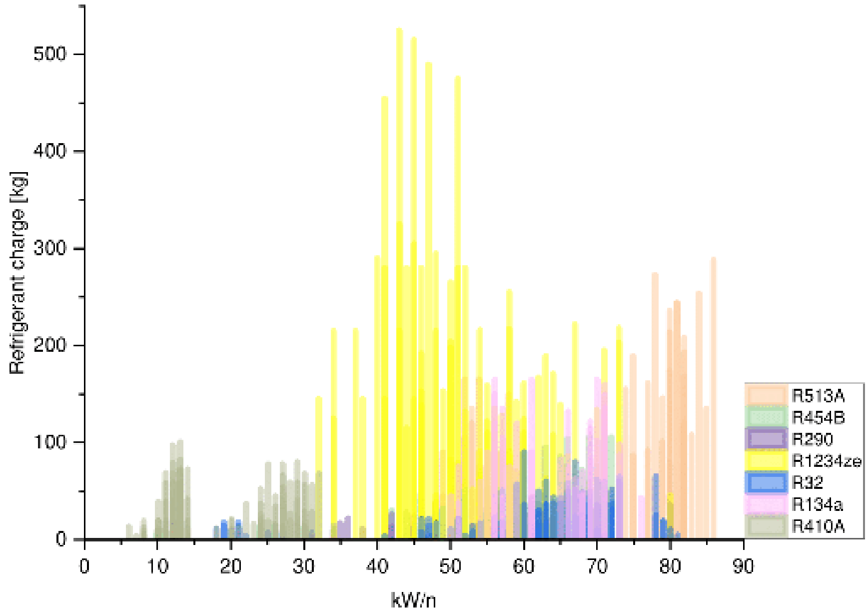


Figure 3. Dependence of the refrigerant mass in the device on kW/n for the selected refrigerants.

For Q/mr ratio, the highest values are for R290 (6.5–18 kW/kg), R410A (5–13 kW/kg) and R134a (5–11 kW/kg). As a result, higher charges for similar power are required for other investigated refrigerants. The lowest ratios are observed for R513A and R32.

To calculate CO_2 equivalent emissions for refrigerants, it is necessary to know the GWP index for each refrigerant and for a specific time horizon. Therefore, in Figure 4, GWP 20 and GWP 100 index values for selected refrigerants and their components are presented.

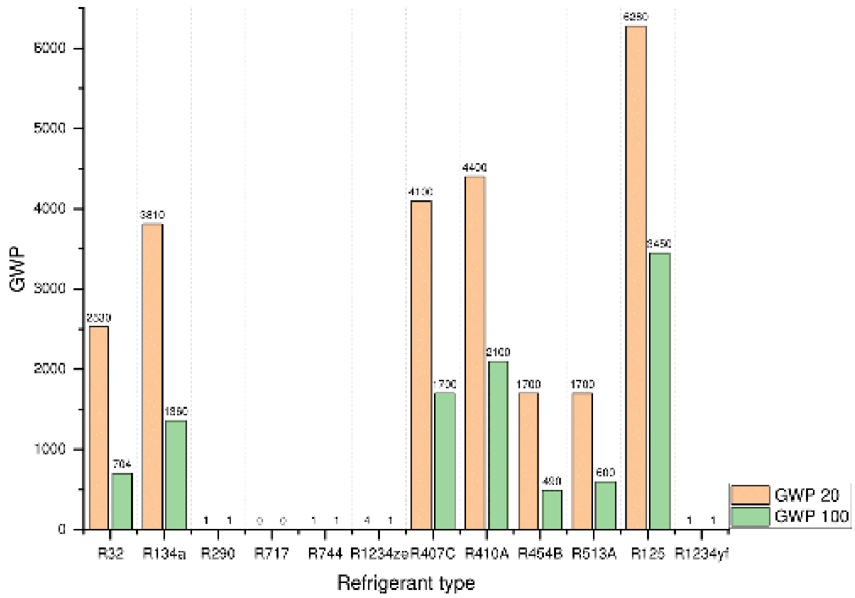


Figure 4. GWP 20 and GWP 100 index values for selected refrigerants and their components [29].

The CO_2 emission equivalent for each homogeneous refrigerant was calculated based on the formula:

$$\text{kg CO}_2\text{e TH}^i = GWP^i \cdot m \quad (3)$$

where: i—time horizon (20 and 100 years); GWP^i—GWP index specified for the 20 and 100-year time horizon, m—refrigerant charge, kg;

As shown in Figure 4, the GWP index is defined for a homogeneous substance. Currently, heterogeneous substances are usually used as substitutes for the so-called old generation. Composition of selected refrigerants is shown in Figure 5. For example, R513A refrigerant is a substitute for installations using R134a refrigerant. The R513A refrigerant still contains R134a (44%) while the dopant is R1234yf (56%). Replacement for R410A is currently R454B. The R410A refrigerant included R32 (50%) and R125 (50%). The R454B refrigerant contains more R32 (69%), while R1234yf (31%) was introduced instead of R125.

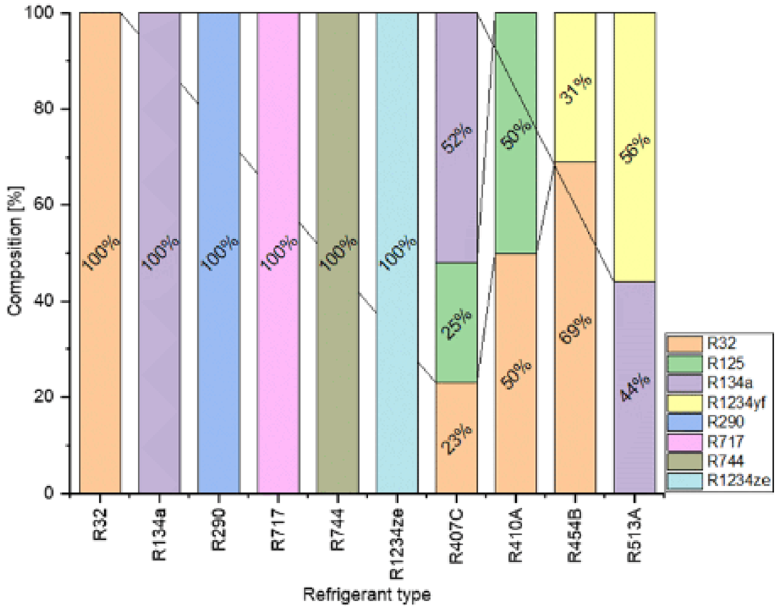


Figure 5. Percentage composition of selected refrigerants [29].

Therefore, the equivalent of CO_2 emission must be determined for each component separately. For nonhomogeneous refrigerants, the CO_2 equivalent emission value was determined based on the percentage composition and the GWP value for the homogeneous substance. The calculations were made based on the following formula:

$$\text{kg } CO_2\text{e TH}^i = \sum_n^{i=1} GWP_j^i \cdot m_j \tag{4}$$

where: GWP_j^i—GWP index defined for the time horizon i and the homogeneous substance j; m_j—loading mass of a homogeneous substance, kg; j—defined homogeneous refrigerant, i—time horizon.

3. Results and Discussion

The article compares the value of equivalent CO_2 emissions for two time horizons of 100 and 20 years. The relative values of GWP 20 with respect to the values of GWP 100 are shown in Table 5 and Figure 6.

Table 5. Relative values of GWP 100 and GWP 20 with respect to the reference value of GWP 100.

Refrigerant	γ^{100} = GWP 100/GWP 100	Γ^{20} = GWP 20/GWP 100
R717	- *	- *
R290	1.00	1.00
R744	1.00	1.00
R1234ze	1.00	4.00
1234yf	1.00	1.00
R454B	1.00	3.47
R513A	1.00	2.83
R32	1.00	3.59
R134a	1.00	2.80
R407C	1.00	2.41
R410A	1.00	2.09
R125	1.00	1.82

* Not presented because GWP 20 and GWP 100 equals 0.

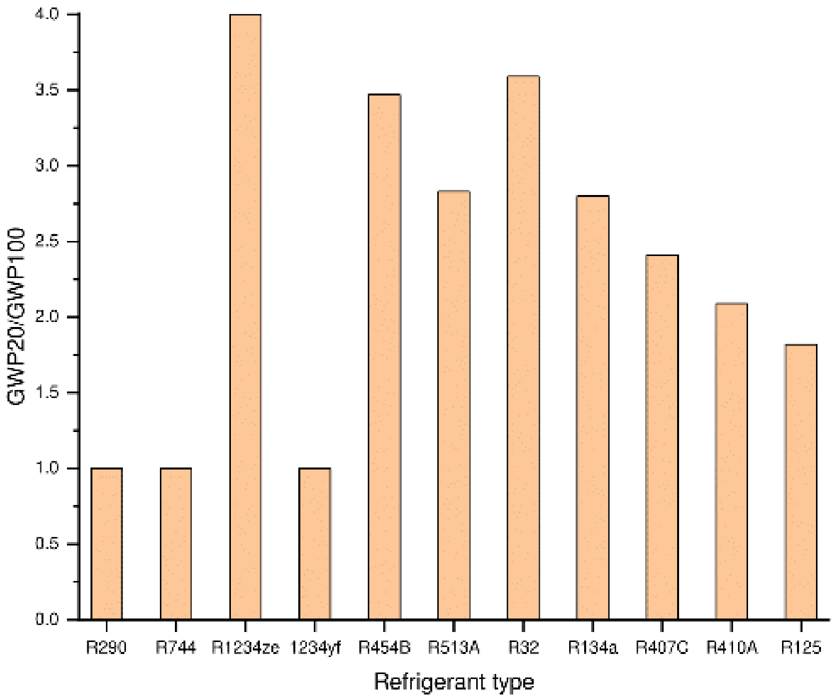


Figure 6. Relative values of GWP 20 with respect to values of GWP 100.

To illustrate the actual environmental impact of refrigerants of various generations, the refrigerant masses presented in Figure 3 were converted into CO_2 equivalent (kg CO_2e) released into the atmosphere for the GWP 100 and GWP 20 indexes. Due to the differences in GWP values (both for the 20 and 100 years period) and the large range of masses of refrigerants used in the devices, it was decided to present the results in graphs for the following ranges specified in Table 6.

Table 6. Ranges used for presenting the values of CO_2 equivalent released to the atmosphere for GWP 100 and GWP 20.

Range	GWP 100 CO_2e (kg)	GWP 20 CO_2e (kg)
I	<1000	<10,000
II	<100,000	<250,000
III	>100,000	>250,000

This division makes it easier to compare refrigerants in terms of their actual impact on climate in a 100- and 20-year time horizon, taking the total mass of the refrigerant contained in the device into account. This is crucial in terms of the GWP index, which is kg of CO_2 equivalent to 1 kg of a given substance. Therefore, when analyzing the choice of a given refrigerant, it is not possible to consider only its GWP, because it does not inform about the actual impact of a given device or system on climate. Only considering GWP taking the mass of the refrigerant into account gives a real picture of the emission of pollutants into the atmosphere. The results of the calculations of the equivalent CO_2 emissions to the atmosphere for the time horizon of TH = 100 and TH = 20, respectively, for the devices analyzed as a function of the unit thermal power of the module are presented in Figure 7.

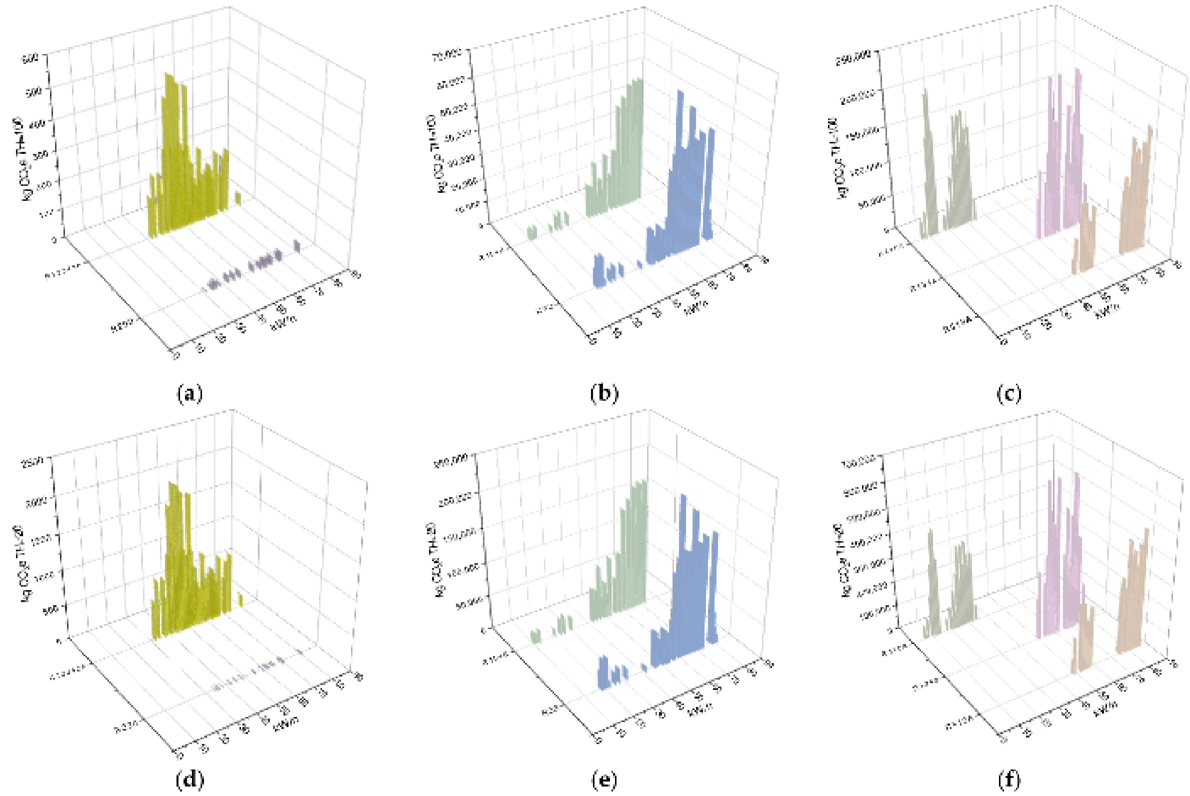


Figure 7. Equivalent of kg CO_2 releases into the atmosphere (for the GWP 100 index); (**a**) GWP 100 index range I, (**b**) GWP 100 index range II, (**c**) GWP 100 index range III, (**d**) GWP 20 index range I, (**e**) GWP 20 index range II, (**f**) GWP 20 index range III.

The lowest equivalent kg CO_2e values were obtained in a 100-year time horizon for R290 and R1234ze. For R290, the emission values are almost uniform with a slight increase towards higher unit powers of the module. In the ranges of 30 ÷ 40 kW/n and 55 ÷ 75 kW/n, these values are similar. For the unit power of the 80 kW/n module, the kg CO_2e values for the R290 and R1234ze refrigerants are similar and are 36 kg and 46 kg CO_2e, respectively. Despite the use of a large mass of R1234ze refrigerant (29 kg ÷ 525 kg), as shown in Figure 3, the kg CO_2e index for this refrigerant is in the range I for GWP 100 and amounts to a maximum of 525 kg CO_2e. However, Figure 7a presents a wide range of kg CO_2e values (from 29 kg CO_2e to more than 525 kg CO_2e). The GWP 100 index for both R290 and R1234ze is 1. Such a large range of values is the result of differences in the design and construction of refrigerating units, as well as thermodynamic and chemical parameters. In the case of R290, a small mass of the medium (5 ÷ 36 kg) proportionally translates into negligible values of kg CO_2e (5 ÷ 36 kg) as shown in Figure 7a. However, it should be remembered that this refrigerant contributes to the formation of summer smog [47].

Higher values of kg CO_2e in a 100-year time horizon were obtained for the R454B and R32 refrigerants (visible in Figure 7b), for which the GWP 100 indexes are 490 kg CO_2e and 704 kg CO_2e, respectively. There are no devices with R513A refrigerant in this range, with a GWP 100 index of 600, which is lower than that of R32. Importantly, the R513A refrigerant is a replacement for R134a. The lowest of the kg CO_2e value for the range II was achieved by devices filled with R454B (3400 kg CO_2e ÷ 51,500 kg CO_2e). Slightly higher values of this index apply to devices filled with R32 refrigerant (2600 kg CO_2e ÷ 63,400 kg CO_2e). The highest values for R454B and R32 were obtained in the range of 55 ÷ 79 kW/n. Beyond and above this range of the unit power of the module, the equivalent of carbon dioxide emission for the atmosphere was significantly lower. This is again influenced by the design and construction of the individual units and the thermodynamic and chemical parameters of the refrigerants.

As shown Figure 7c, the highest kg CO_2e values were obtained in a 100-year time frame for R513A refrigerants and withdrawn R134a and R410A. Values of the GWP 100 index for these refrigerants are, respectively, 600, 1360 and 2100. The lowest values for the range III were achieved by devices filled with R513A (22,800 kg CO_2e 172,500 kg CO_2e). Higher values are noticeable for unit power of the module within the range of 78 ÷ 85 kW/n, while lower values are noted for the ranges of 48 ÷ 55 kW/n and 74 ÷ 78 kW/n. Higher values of this index apply to devices filled with R410A refrigerant (7700 kg CO_2e ÷ 209,200 kg CO_2e). It should be noted that for this refrigerant, units achieved unit power for the module in the range of 5 ÷ 35 kW/n, with the highest equivalent CO_2e obtained for the unit power of the module in the range of 10 ÷ 15 kW/n. The most negative impact on the environment is caused by devices filled with R134a, for which the maximum CO_2e values are 224,400 kg CO_2e, while the minimum values are 51,680 kg CO_2e.

Comparing the values of CO_2 equivalent emissions to the atmosphere related to the cooling devices for which the analysis was carried out, on a 20-year time horizon and a 100-year time horizon, it can be noticed that despite completely different values of GWP 20 compared to GWP 100, the devices were again in the range I group filled with R290 and R1234ze. For R290, kg CO_2e values were exactly the same as the values determined for the time horizon TH = 100. This is due to the equal values of GWP 100 = GWP 20 = 1. Therefore, both short- and long-term effects are the same.

Range II includes R32 and R454B, for which the values of the GWP 20 index are respectively 359% and 347% higher than the GWP 100 index (Table 6). In the range III there are R513A, R134a and R410A again. The increase in equivalent CO_2 emissions into the atmosphere is 283% (R513A), 280% (R134a), and 209% (R410A), respectively (Table 6). Here, a dependence appears where the increase in equivalent CO_2 emissions is smaller in percentage for refrigerants with higher GWP 100 values. The exception is R32, for which this increase is higher (359%) compared to R513A (283%).

The equivalent kg of CO_2 emissions for the least harmful refrigerants presented in Figure 7d clearly show a significant difference in the emission values related to the use of R290 (CO_2e = 10 ÷ 36 kg) and R1234ze (CO_2e = 116 ÷ 2100 kg). It should be noted that for R290 the values are similar across the entire power range of the unit. On the other hand, for

R1234ze, the highest values were obtained for unit powers in the middle range, i.e., from 40 ÷ 60 kW/n.

For refrigerants R454B (CO_2e = 12,200 ÷ 184,800 kg) and R32 (CO_2e = 9400 ÷ 227,700 kg), the highest values of equivalent CO_2 emissions to the atmosphere were obtained for the highest unit power, 60 ÷ 80 kW/n (Figure 7e). However, for the R32 refrigerant in the range of maximum unit power, the equivalent value is significantly lower. This also depends on the device's construction.

In the range III, where refrigerants have the greatest impact on the environment, R410A (CO_2e = 16,230 ÷ 443,600 kg), R134a (CO_2e = 144,800 ÷ 628,600 kg) and R513A (CO_2e = 63,700 ÷ 483,000 kg) were again found (Figure 7f). Among them, the R134a refrigerant has the highest values of CO_2 equivalent emissions to the atmosphere. However, it should be noted that the difference in the maximum values related to individual refrigerants increased significantly compared to the values related to GWP 100. In this case, the effect of the R134a refrigerant is significantly worse compared to R513A and R410A. However, it is worth paying attention to the fact that for R410A (6–34 kW/n) the unit power range is incomparable to the range obtained for R134a (50–76 kW/n) and R513A (48–86 kW/n).

To show how the changes into next-generation refrigerants, Figure 8 presents graphs of kg CO_2e emissions into the atmosphere for both time horizons, i.e., TH = 20 and TH = 100, for selected substitutes for refrigerants. It is essential to understand that some of the new refrigerants are simply mixtures of some old refrigerants. Therefore, Figure 4 together with Figure 5 presents the composition and GWP index values of investigated refrigerants. Those comprise basic information that is required to understand the overall idea of the GWP 20 and GWP 100 comparison. Replacement for R410A a mixture of R32 (50%) and R125 (50%) is R454B, which contains R32 (59%) and 1234yf (41%) (according to Figure 5). The second substitute is R32, which is homogeneous. The placement on the market of a substitute in the form of the R454B refrigerant significantly reduces the equivalent emission of CO_2 into the atmosphere compared to R410A. However, it should be noted that the unit power obtained in devices that work with R410A and R454B is completely different. Comparison of R32 and R454B does not yield such obvious conclusions. In this case, the values of CO_2 equivalent emissions are similar across the entire range of unit capacity. Substitutes for R134a are: R513A made of R134a (44%) and R1234yf (56%) and R1234ze, which is homogeneous, as shown in Figure 5. As can be seen, bringing R1234ze to market yields disproportionately better results compared to R513A refrigerant. CO_2 equivalent emissions to the atmosphere are negligible for R1234ze and significantly high for R513A and R134a, respectively. It should also be noted that the unit power of the module obtained for devices filled with R1234ze is in a much wider range than for R513A and R134a. There is also a substantial difference in the values obtained for the 20- and 100-year time horizons in both refrigerants that are decommissioned from the market.

Figure 9 presents the results of the values of the equivalent CO_2 emissions as a function of the unit power of the refrigerant charge (kW/kg). Only for R290, the values of equivalent CO_2 emissions to the atmosphere, both in the 20 and 100-year time horizon, are at the same level (Figure 9c). For other refrigerants, values calculated for a shorter time horizon are always of a higher value than for a longer time horizon. The higher the Qc/m value, the lower the refrigerant mass used in the system. As shown in Figure 9, higher powers with less filling are obtained for the R290, R410A, and R134A refrigerants. When selecting cooling devices, we should follow the unit cooling power for which, with the required cooling power, the lowest possible emission values are obtained, i.e., for R32 Q_c/m = 3.2 ÷ 3.4 kW/kg, dla R134A Q_c/m = 8.5 ÷ 9.0 kW/kg oraz Q_c/m = 10 ÷ 11.0 kW/kg, dla R410A Q_c/m = 12.0 ÷ 14.0 kW/kg, dla 454B Q_c/m = 4.5 ÷ 7.5 kW/kg, dla R513A Q_c/m = 6.25 ÷ 6.75 kW/kg, dla R1234ze Q_c/m = 7.5 ÷ 9.0 kW/kg.

Along with the environmental impact, chosen properties of R410A, R134a and their constituents are shown in Tables 7 and 8.

Table 7. Transport and physical properties for R410A and its substituents.

Refrigerant	Transport Properties *			Physical Properties		
	Density [kg/m^3]	Viscosity [μPa·s]	Thermal Conductivity [W/m·K]	Critical Temp. [°C]	Evaporation Temp. [°C]	Condensation Temp. [°C]
R410A	1062	119	0.0880	72	−51	43
R454B	985	115	0.1055	77	−51	47
R32	959	114	0.1259	78	−52	42

* Saturated liquid at 25 °C.

Table 8. Transport and physical properties for R134a and its substituents.

Refrigerant	Transport Properties *			Physical Properties		
	Density [kg/m^3]	Viscosity [μPa·s]	Thermal Conductivity [W/m·K]	Critical Temp. [°C]	Evaporation Temp. [°C]	Condensation Temp. [°C]
R134a	1206	200	0.0830	101	−26	80
R513A	1171	166	0.0699	97	−30	78
R1234ze	1163	190	0.0742	110	−18	92

* Saturated liquid at 25 °C.

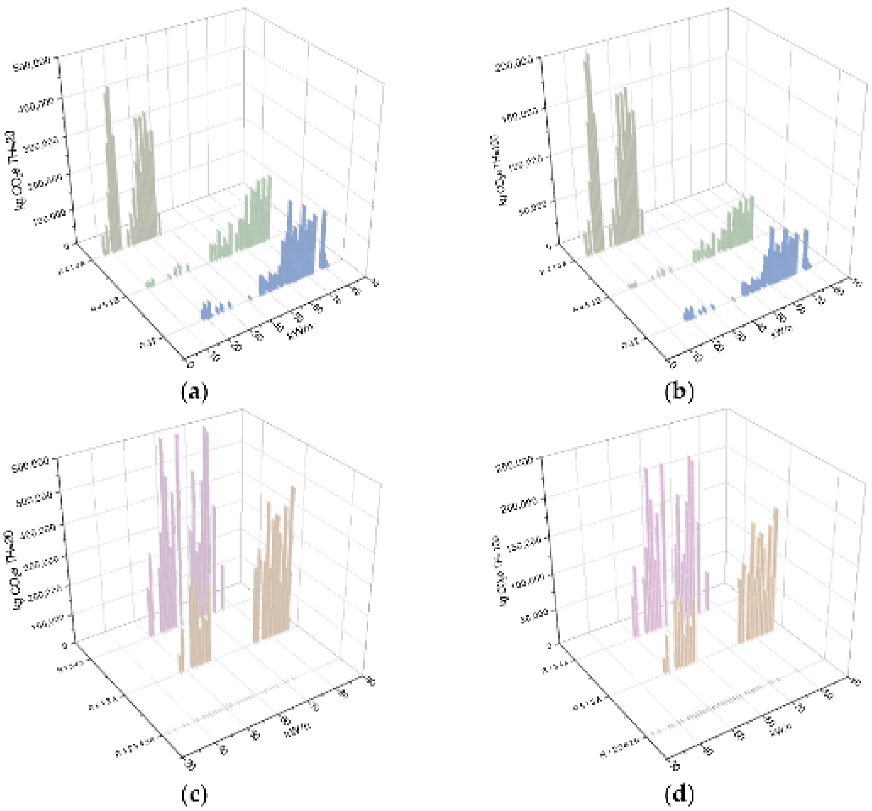


Figure 8. Equivalent of kg CO_2e released to the atmosphere for selected refrigerants and their substitutes for: (**a**) R410A, TH = 20; (**b**) R410A TH = 100, (**c**) R134a TH = 20, (**d**) R134a TH = 100.

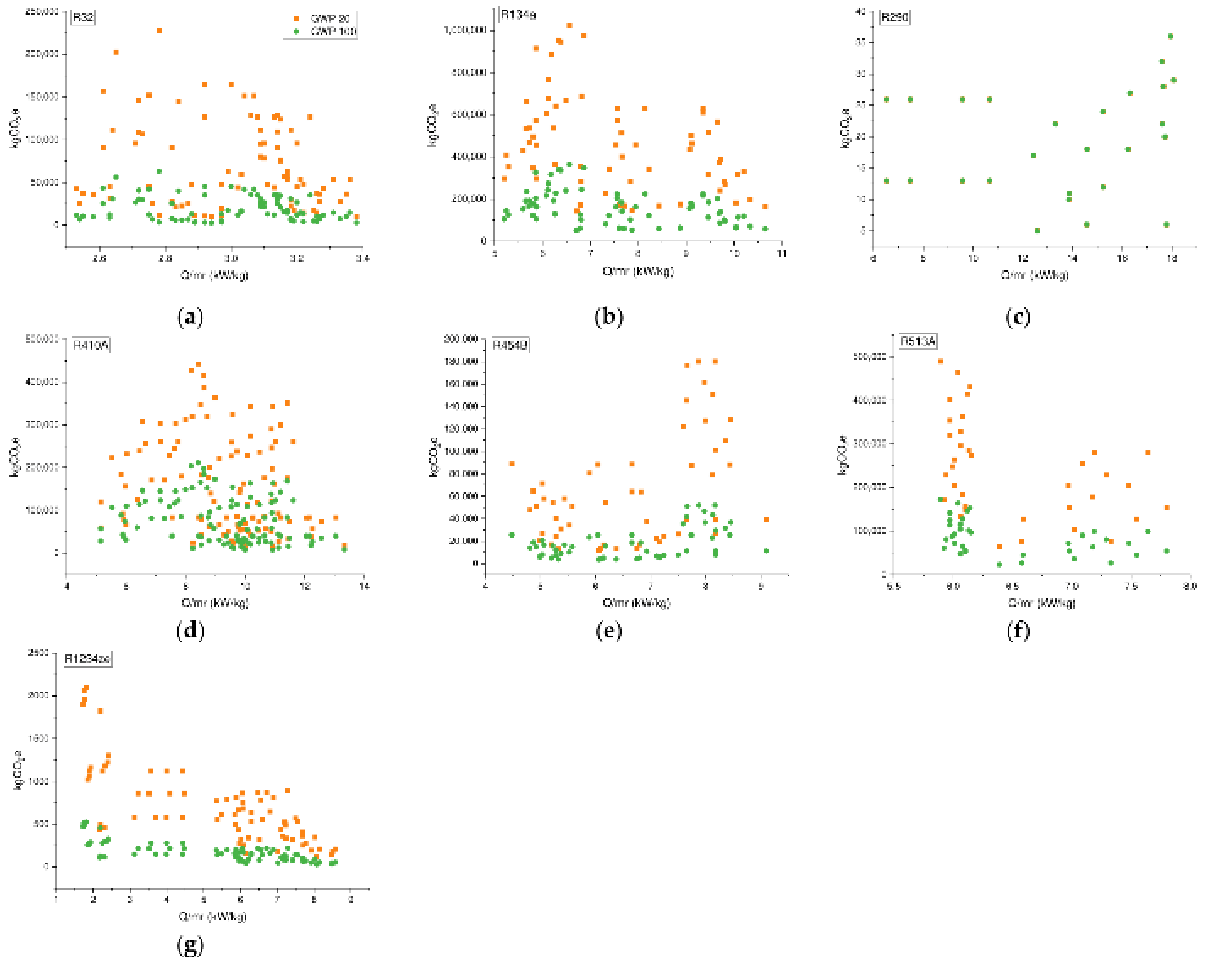


Figure 9. Equivalent CO_2 emissions in released to unit power of the refrigerant charge (kW/kg) for: (**a**) R32, (**b**) R134a, (**c**) R290, (**d**) R410A, (**e**) R454B, (**f**) R513A, (**g**) R1234ze. Green dots—kg CO_2 e TH = 100, Orange dots—kg CO_2 e TH = 20.

In both cases physical properties are similar however, R410A and its substituents have almost identical physical properties. It is strictly connected to the use of some refrigerants as drop-in replacement, so they must share similar physical properties. Nevertheless, one must take into consideration the change in transport properties as well. The comparison of the density and viscosity values in Table 7 does not reveal significant differences between refrigerants. It is worth to note that thermal conductivity values are higher by 20% (R410A to R454B comparison) and by 43% (R410A to R32 comparison). The use of refrigerants with higher thermal conductivity values may result in improved heat transfer characteristics in heat exchangers. R134a substituents have 10–20% lower thermal conductivity and similar densities. However, there is a substantial drop of viscosity value for R513A as a replacement, those may result in reduced viscous losses within compressor system and further on reduce, e.g., pressure drop.

It should be remembered that not only the GWP index but also the toxicity and practical limit of concentration are factors that determine the environmental impact of a given refrigerant. Table 9 lists all refrigerants spoken in this article with their respective GWP 20/GWP 100 ratio, safety class, and practical concentration limit.

Table 9. Comparison between the GWP 20/GWP 100 ratio, safety class, and practical concentration limit for refrigerants commonly used in air-conditioning systems.

	Transport Properties		
Refrigerant	**GWP 20/GWP 100**	**Safety Classes**	**Practical Concentration Limit [kg/m³]**
Homogeneous substances			
R32	3.59	A2L	0.061
R134A	2.8	A1	0.25
R290	1	A3	0.008
R717	- *	B2	0.00035
R744	1	A1	0.07
R1234ze	4	A1	N/A **
Heterogeneous substances			
R407C	2.41	A1	0.31
R410A	2.09	A1	0.44
R454B	3.47	A2L	N/A
R513A	2.83	A1	0.35

* Not presented because GWP 20 and GWP 100 equals 0. ** N/A the data is not yet available.

Data in Table 9 reveal that only homogeneous refrigerants such as R290, R717 and R744 have the same impact on global warming regardless of the time horizon. Each one has however the lowest practical concentration limit; thus, its implementation requires additional effort like mechanical ventilation. In addition, they have low safety classes (beside R744). R1234ze and R32 have the greatest environmental impact in a short time horizon. Furthermore, R32 also requires a mechanical ventilation system due to the low practical concentration level. R1234ze is not toxic and there are no data of the practical concentration limit yet; nevertheless, additional safety systems are also required.

4. Conclusions

In most cases, placing to market new generation refrigerants to replace the older ones allows to reduce their impact on the greenhouse effect observed on Earth. This is true for both the GWP 100 and the GWP 20 indexes. For shorter time horizons, the reduction of the negative impact on the atmosphere is not as strong as for long time horizons. In the shorter time horizons, the differences are much lower, and the environmental impact is starting to be significant also for new generations of refrigerants. It can be safely assumed that for very short time horizons, it may turn out that the use of older but single component refrigerants may be safer with regard to local climate change. It has been proved by comparison of GWP 20 and GWP 100. However, still in the global and long-term perspective, new refrigerants that replace older ones are much less harmful in terms of CO_2e emissions. Therefore, with the gradual shift to low-GWP refrigerants and with a short or very short lifetime, the way of considering the effects generated by emissions of these refrigerants must also be changed. More attention should be paid to the analysis of the harmfulness of these refrigerants in relation to a climate of local scope.

It should be noted that for all three considered ranges of CO_2e emissions to the atmosphere, there are always ranges of minimum and maximum values and they do not directly depend on the unit power value of the module as well as on the power value of individual devices. It means that in all cases the design and construction of the cooling device, including the air flows used to cool the condensers, which are different for individual devices, have an impact on the cooling values. The thermodynamic and chemical values of individual refrigerants are also important.

Furthermore, the values of CO_2e emissions to the atmosphere are closely related to the refrigerant charge. It is necessary to consider the determination and evaluation of cooling devices in terms of the unit capacities obtained the so that, as a result, the greenhouse effect is actually and realistically reduced.

Another factor ensuring the reduction of harmfulness of the refrigerants used is the use of homogeneous gases, or mixtures with regard to their composition. It is important especially in relation to their decomposition into individual chemical compounds, including acids such as, for example, trifluoroacetic acid (TFA), which is a decomposition product of R134a and R1234ze, which are components of the mixture that forms R513A.

The thermodynamic parameters of the introduced refrigerants are also important aspects as they determine the possibility of obtaining adequate cooling with the use of electrical power supplied to compressors and fans.

Catalogue data for refrigerants and cooling devices typically provide values for GWP 100 only. The results of the research carried out suggest that the values for GWP 20 should also be obligatory. It would allow to select devices with more awareness in terms of environment protection.

Future work should focus on both the global and local impact of greenhouse gases expressed in a simple index so that the tool for reporting emissions will be applicable to new types of refrigerants. It is possible to obtain by GWP* index implementation. Currently, no data are available to use and insufficient research and discussion have been done to clearly assess GWP* index.

Author Contributions: Conceptualization, S.S. and Ł.S.; methodology, S.S.; software, Ł.S.; validation, S.S.; formal analysis, S.S. and Ł.S.; investigation, S.S. and Ł.S.; resources, S.S. and Ł.S.; data curation, Ł.S.; writing—original draft preparation, S.S. and Ł.S.; writing—review and editing, S.S. and Ł.S.; visualization, S.S. and Ł.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Smith, S.J.; Wigley, M.L. Global Warming Potentials: 1. Climatic Implications of Emissions Reductions. *Clim. Chang.* **2000**, *44*, 445–457. [CrossRef]
2. Fuglestvedt, J.S.; Berntsen, T.K.; Godal, O.; Sausen, R.; Shine, K.P.; Skodvin, T. Metrics of Climate Change: Assessing Radiative Forcing and Emission Indices. *Clim. Chang.* **2003**, *58*, 267–331. [CrossRef]
3. Shine, K.P. The Global Warming Potential—The Need for an Interdisciplinary Retrial. *Clim. Chang.* **2009**, *96*, 467–472. [CrossRef]
4. Pierrehumbert, R.T. Short-Lived Climate Pollution. *Annu. Rev. Earth Planet. Sci.* **2014**, *42*, 341–379. [CrossRef]
5. Kleinberg, R. *The Global Warming Potential Misrepresents the Physics of Global Warming Thereby Misleading Policy Makers*; Insitute for Sustainable Energy, Boston University: Boston, MA, USA, 2020.
6. Edwards, M.R.; McNerney, J.; Trancik, J.E. Testing Emissions Equivalency Metrics against Climate Policy Goals. *Environ. Sci. Policy* **2016**, *66*, 191–198. [CrossRef]
7. Allen, M.R.; Fuglestvedt, J.S.; Shine, K.P.; Reisinger, A.; Pierrehumbert, R.T.; Forster, P.M. New Use of Global Warming Potentials to Compare Cumulative and Short-Lived Climate Pollutants. *Nat. Clim. Chang.* **2016**, *6*, 773–776. [CrossRef]
8. Shine, K.P.; Fuglestvedt, J.S.; Hailemariam, K.; Stuber, N. Alternatives to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases. *Clim. Chang.* **2005**, *68*, 281–302. [CrossRef]
9. Tanaka, K.; Peters, G.P.; Fuglestvedt, J.S. Policy Update: Multicomponent Climate Policy: Why Do Emission Metrics Matter? *Carbon Manag.* **2014**, *1*, 191–197. [CrossRef]
10. IPCC. *Climate Change: The IPCC Scientific Assessment*; Cambridge University Press: Cambridge, UK, 1990.
11. IPCC; TEAP. *Special Report: Safeguarding the Ozone Layer and the Global Climate System*; Cambridge University Press: Cambridge, UK, 2018.

12. InforMEA The Vienna Convention for the Protection of the Ozone Layer—Overview of the Negotiation Process, Main Obligations and Development of the Vienna Convention. Available online: https://globalpact.informea.org/sites/default/files/documents/The%20Vienna%20Convention%20for%20the%20protection%20of%20the%20Ozone%20Layer.pdf (accessed on 6 May 2022).
13. United Nations Environment Programme. *Handbook for the International Treaties for the Protection of the Ozone Layer: The Vienna Convention (1985); The Montreal Protocol (1987)*, 6th ed.; UNEP: Nairobi, Kenya, 2003.
14. United Nations. *Montreal Protocol on Substances That Deplete the Ozone Layer (with Annex)*; United Nations: Geneva, Switzerland, 1987.
15. United Nations. *Kyoto Protocol to the United Nations Framework Convention on Climate Change*; United Nations: Geneva, Switzerland, 1998.
16. United Nations. *United Nations Framework Convention on Climate Change*; United Nations: Geneva, Switzerland, 1992.
17. James, M. Calm Refrigeration Transitions . . . Again. In *Moving Towards Sustainability, Proceedings of the ASHRAE/NIST Conference, Gaithersburg, MD, USA, 29–30 October 2012*; ASHRAE: Atlanta, GA, USA, 2012.
18. UNTC. Available online: https://treaties.un.org/pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-2&chapter=27&clang=_en#1 (accessed on 13 May 2022).
19. Decision I/9: ODP for Halon 2402 | Ozone Secretariat. Available online: https://ozone.unep.org/treaties/montreal-protocol/meetings/first-meeting-parties/decisions/decision-i9-odp-halon-2402 (accessed on 12 May 2022).
20. UNFCCC. What Is the United Nations Framework Convention on Climate Change. Available online: https://unfccc.int/process-and-meetings/the-convention/what-is-the-united-nations-framework-convention-on-climate-change (accessed on 6 May 2022).
21. Forster, P.; Ramaswamy, V.; Artaxo, P.; Berntsen, T.; Betts, R.; Fahey, D.W.; Haywood, J.; Lean, J.; Lowe, D.C.; Myhre, G.; et al. Changes in Atmospheric Constituents and in Radiative Forcing. In *Climate Change 2007: The Physical Science Basis. Contributuin of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, NY, USA, 2007.
22. IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, NY, USA, 2013.
23. Lynch, J.; Cain, M.; Pierrehumbert, R.; Allen, M. Demonstrating GWP*: A Means of Reporting Warming-Equivalent Emissions That Captures the Contrasting Impacts of Short- and Long-Lived Climate Pollutants. *Environ. Res. Lett.* **2020**, *15*, 044023. [CrossRef]
24. Zhang, H.; Wu, J.; Lu, P. A Study of the Radiative Forcing and Global Warming Potentials of Hydrofluorocarbons. *J. Quant. Spectrosc. Radiat. Transf.* **2011**, *112*, 220–229. [CrossRef]
25. Allen, M.R.; Shine, K.P.; Fuglestvedt, J.S.; Millar, R.J.; Cain, M.; Frame, D.J.; Macey, A.H. A Solution to the Misrepresentations of CO2-Equivalent Emissions of Short-Lived Climate Pollutants under Ambitious Mitigation. *npj Clim. Atmos. Sci.* **2018**, *1*, 16. [CrossRef]
26. Cain, M.; Lynch, J.; Allen, M.R.; Fuglestvedt, J.S.; Frame, D.J.; Macey, A.H. Improved Calculation of Warming-Equivalent Emissions for Short-Lived Climate Pollutants. *Npj Clim. Atmos. Sci.* **2019**, *2*, 29. [CrossRef] [PubMed]
27. Costa, C.; Wironen, M.; Racette, K.; Wollenberg, E. *Global Warming Potential* (GWP*): Understanding the Implications for Mitigating Methane Emissions in Agriculture*; CCAFS: Wageningen, The Netherlands, 2021.
28. Fischer, S.K.; Hughes, P.J.; Fairchild, P.D.; Kusik, C.L.; Dieckmann, J.T.; McMahon, E.M.; Hobday, N. *Energy and Global Warming Impacts of CFC Alternative Technologies. Executive Summary*; U.S. Department of Energy: Washington, DC, USA, 1991.
29. United Nations Environment Programme. *Montreal Protocol on the Substances That Deplete the Ozone Layer: 2018 Report of the Refrigeration, Air Conditioning and Heat Pumps Technical Options Comittee*; United Nations: Geneva, Swietzerland, 2018.
30. Makhnatch, P.; Khodabandeh, R. The Role of Environmental Metrics (GWP, TEWI, LCCP) in the Selection Of Low GWP Refrigerant. *Energy Procedia* **2014**, *61*, 2460–2463. [CrossRef]
31. Troch, S.; Lee, H.; Hwang, Y.; Radermacher, R. Harmonization of Life Cycle Climate Performance (LCCP) Methodology. In Proceedings of the International Refrigeration and Air Conditionign Conference, West Lafayette, IN, USA, 11–14 July 2016.
32. Wang, Z.Y.; Wang, H.Q.; Liu, C.R. LCCP Evaluation on Environmental Impact of Air-Conditioning Cold and Heat Source. *Appl. Mech. Mater.* **2013**, *291–294*, 1789–1794. [CrossRef]
33. Andersen, S.O.; Wolf, J. *Improved Life-Cycle Climate Performance (LCCP) Metrics: Room AC Carbon Footprint. Vienna OEWG Side Event*; UNEP: Nairobi, Kenya, 2018.
34. WMO. *Scientific Assesment of Ozone Depletion: 2014, Global Ozone Research Monitoring Project—Repoert No. 55*; WMO: Geneva, Switzerland, 2014.
35. WMO; UNEP. *World Meteorological Organization Global Ozone Research and Monitoring Project-Report No. 58 Scientific Assesment of Ozone Depletion: 2018*; WMO: Geneva, Switzerland, 2018.
36. UNEP; ASHRAE. *FACTSHEET 1: Update on New Refrigerants Designations and Safety Classifications*; UNEP: Nairobi, Kenya, 2020.
37. *ISO 817:2014*; Refrigerants—Designation and Safety Classification. International Organization for Standardization: Geneva, Switzerland, 2014.
38. Czynniki Chłodnicze::Schiessl Polska. Available online: https://www.schiessl.pl/pl/czynniki-chlodnicze (accessed on 16 May 2022).
39. Mota-Babiloni, A.; Makhnatch, P.; Khodabandeh, R. Recent Investigations in HFCs Substitution with Lower GWP Synthetic Alternatives: Focus on Energetic Performance and Environmental Impact. *Int. J. Refrig.* **2017**, *82*, 288–301. [CrossRef]

40. Vallero, D.A. Air Pollution Biogeochemistry. In *Air Pollution Calculations*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 175–206. [CrossRef]
41. Danny Harvey, L.D. A Guide to Global Warming Potentials (GWPs). *Energy Policy* **1993**, *21*, 24–34. [CrossRef]
42. IPCC. *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCCIS92 Emission Scenarios*; Reports of Working Groups I and III of the Intergovernmental Panel on Climate Change, Forming Part of the IPCC Special Report to the First Session of the Conference of the Parties to the UN Framework Convention on Climate Change; Cambridge University Press: Cambridge, UK, 1995.
43. Mate, J.; Kanter, D. *The Benefits of Basing Policies on the 20 Year GWP of HFCs*; Greenpeace: Amsterdam, The Netherlands, 2020.
44. Walravens, F. *Autor Opinii: Environmental Investigation Agency*; European Commission: Brussels, Belgium, 2020.
45. The European Parliment and the Council of the European Union. Regulation (EU) no 517/2014 of the European Parliment and of the Council of 16 April 2014 on Fluorinated Greenhouse Gases and Repealing Regulation (EC) No 842/2006. *Off. J. Eur. Union* **2014**, *150*, 195–230.
46. Minx, J.C.; Lamb, W.F.; Andrew, R.M.; Canadell, J.G.; Crippa, M.; Döbbeling, N.; Forster, P.M.; Guizzardi, D.; Olivier, J.; Peters, G.P.; et al. A Comprehensive and Synthetic Dataset for Global, Regional, and National Greenhouse Gas Emissions by Sector 1970-2018 with an Extension to 2019. *Earth Syst. Sci. Data* **2021**, *13*, 5213–5252. [CrossRef]
47. BITZER. *Refrigerant Report | Enhanced Reader*; BITZER: Sindelfingen, Germany, 2020.

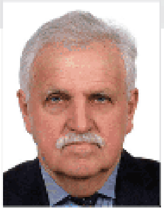
DOI: 10.15199/9.2023.12.5

mgr inż. ŁUKASZ STEFANIAK

ORCID ID: 0000-0002-0291-1575
Katedra Klimatyzacji, Ogrzewnictwa,
Gazownictwa i Ochrony Powietrza
Politechnika Wrocławska
Osoba do kontaktu
lukasz.stefaniak@pwr.edu.pl

dr inż. KRZYSZTOF RAJSKI

ORCID ID: 0000-0002-3673-428X
Katedra Klimatyzacji, Ogrzewnictwa,
Gazownictwa i Ochrony Powietrza
Politechnika Wrocławska



prof. dr hab. inż. JAN DANIELEWICZ

ORCID ID: 0000-0002-4418-8485
Katedra Klimatyzacji, Ogrzewnictwa,
Gazownictwa i Ochrony Powietrza
Politechnika Wrocławska

Przegląd zastosowania nanopłynów oraz materiałów porowatych w pośrednim chłodzeniu wyparnym

A Review of Nanofluids and Porous Materials Application for Indirect Evaporative Cooling

Słowa kluczowe: *wymiana ciepła i masy, nanocząstki, naturalne czynniki chłodnicze, pośrednie chłodzenie wyparne*

Streszczenie
Pośrednie chłodzenie wyparne staje się coraz bardziej popularne ze względu na wykorzystanie przyjaznych dla środowiska czynników chłodniczych: powietrza (R-729) i wody (R-718). Istotą procesu jest wymiana ciepła i masy, która zachodzi w wymienniku. Opracowania zagraniczne szeroko opisują nowoczesne technologie wspomagające ten proces, podczas gdy polskojęzyczna literatura nie porusza zagadnienia niemalże w ogóle. W artykule skupiono się na dwóch głównych innowacjach wynikających z przeglądu literatury (od 2010 roku): wprowadzeniu nanopłynów opartych na wodzie oraz zastosowaniu materiałów porowatych na powierzchni kanału mokrego. Przeanalizowano kluczowe parametry stosowane do opisu urządzeń do chłodzenia wyparnego takie jak sprawności: termometru mokrego, punktu rosy oraz egzergetyczną, wydajność chłodniczą, EER oraz COP. Przedstawiono wyniki badań nanopłynów jedno-, dwu- i trzyskładnikowych. Analiza wykazała poprawę parametrów charakteryzujących pośrednie urządzenia wyparne wynoszące od kilku do kilkudziesięciu procent przy zastosowaniu nanopłynów w zależności od temperatury powietrza na wlocie. Dokonano przeglądu stosowanych materiałów porowatych stanowiących powierzchnie kanału mokrego. Wydzielono cztery główne typy stosowanych materiałów: porowate ceramiczne oraz włókna naturalne, polimerowe i tekstylne. Zestawiono wady oraz zalety stosowania tych materiałów w wymiennikach pośrednich w celu ułatwienia wyboru rodzaju materiału. Określono, że spośród dwóch omawianych modyfikacji w pierwszej kolejności należy skupić się na aplikacji materiałów porowatych, jako że są one związane bezpośrednio z konstrukcją wymiennika. Natomiast nanopłyny można zastosować w urządzeniach istniejących. W podsumowaniu stwierdzono, że rozwój technologii pośredniego chłodzenia wyparnego może stanowić istotne oraz ekologiczne uzupełnienie obecnie stosowanych sprężarkowych systemów chłodzenia.

Keywords: *heat and mass transfer, nanoparticles, natural refrigerants, indirect evaporative cooling*

Abstract
Indirect evaporative cooling is becoming increasingly popular due to the use of environmentally friendly refrigerants: air (R-729) and water (R-718). The main idea of the process is the heat and mass transfer that takes place in the exchanger. Foreign studies extensively describe modern technologies supporting this process, while the Polish-language literature does not cover the issue almost at all. The article focuses on two main innovations resulting from the literature review (as of 2010): the introduction of water-based nanofluids and the use of porous materials on the surface of the wet channel. Main parameters used to describe evaporative cooling devices include wet thermometer, dew point, and exergetic efficiencies, cooling capacity, EER, and COP. Results for single-, two-, and three-component nanofluids are presented. The analysis showed performance improvements for indirect evaporative units of several to tens of percent with nanofluids, depending on the inlet air temperature. The applied porous materials used on the surface of the wet channel were reviewed. Four main types of materials used have been distinguished: porous ceramic and natural fibers, polymer fibers, and fabric fibers. The advantages and disadvantages of using these materials in indirect heat exchangers were summarized to facilitate the choice of material type. It was determined that of the two modifications discussed, the application of porous materials should be focused on first, since they are directly related to the construction of the heat exchanger. In contrast, nanofluids can be applied to existing devices. Eventually, it was pointed out that the development of indirect evaporative cooling technology can be an important and ecological complement to the currently used compressor systems.

1. Wstęp

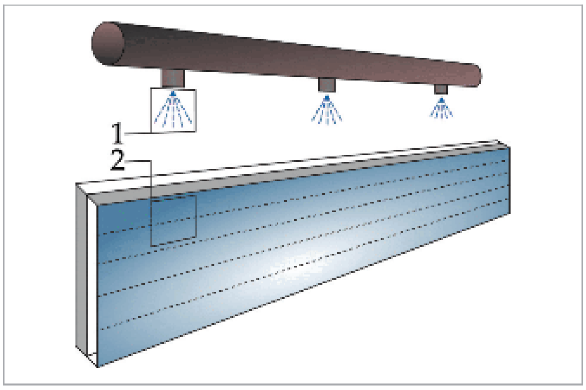
Chłodzenie wyparne w literaturze obcojęzycznej ponownie zyskuje na popularności. Związane jest to z poszukiwaniem technologii, które są przyjazne środowisku oraz ograniczą zapotrzebowanie na energię dostarczaną do systemów HVAC. Systemy, które mają zapewnić komfort i wymagane warunki wewnątrz budynków i pomieszczeń technicznych (chłodzenie i klimatyzacja) są wysoce energochłonne dlatego też poszukuje się możliwości wdrożenia do takich systemów chłodzenia wyparnego [39].

Wyróżnić można dwa główne typy chłodzenia wyparnego – bezpośrednie oraz pośrednie. W pierwszym powietrze ochładzane ma bezpośredni kontakt z wodą zraszającą. W drugim powietrze ochładzane oddzielone jest ściankami wymiennika od kanałów mokrych (rys. 1). Powietrze dostarczane do wymiennika (3) oddaje ciepło do kanału mokrego, gdzie zachodzi jego odbiór (odparowanie wody). W ten sposób powietrze dostarczane do pomieszczenia (4) jest ochładzane. W związku z tym, że w systemie pośrednim nie dochodzi do zwiększenia zawartości wilgoci w powietrzu ochładzanym jest ono częściej stosowane na potrzeby chłodzenia pomieszczeń [51].

Dlatego autorzy artykułu skupili się na technologii pośredniego chłodzenia wyparnego w ujęciu zastosowania innowacji, które nie są opisywane w literaturze krajowej, a mogą pozytywnie wpłynąć na rozwój stosowania pośredniego chłodzenia wyparnego w Polsce, gdzie klimat staje się coraz bardziej suchy. Na rysunku 2 przedstawiono przykładowy wymiennik stosowany w pośrednim chłodzeniu wyparnym.

Punkt 1 dotyczy zmiany czynnika zraszającego z wody na nanopłyny oparte na wodzie. Idea ta wynika z dążenia do zintensyfikowania procesu wymiany ciepła pomiędzy kanałem suchym i mokrym. Zastosowanie tego typu innowacji zostało przeanalizowane w czterech opracowaniach [21], [22], [45], [46]. Uwzględnione parametry to sprawności: punkty rosy, termometru mokrego oraz egzergetyczna, a także COP, EER oraz wydajność chłodnicza. W każdym przypadku wykazano poprawę badanego parametru w zakresie od kilku do kilkudziesięciu procent w porównaniu do wyników z zastosowaniem wody bez dodatku nanocząstek.

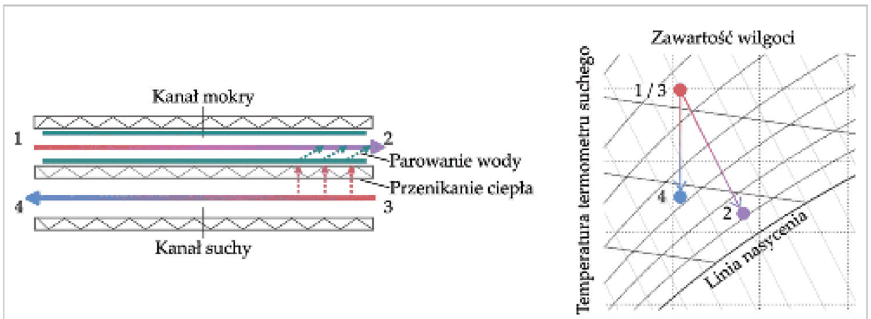
Punkt 2 skupia się na modyfikacji powierzchni kanału mokrego. Ideą jest zapewnienie równomiernego rozkładu wody po powierzchni zraszanej. Dodatkowo zmagazynowanie wody na materiale porowatym skutkuje brakiem konieczności ciągłej pracy pompy wody zraszającej. Zastosowanie



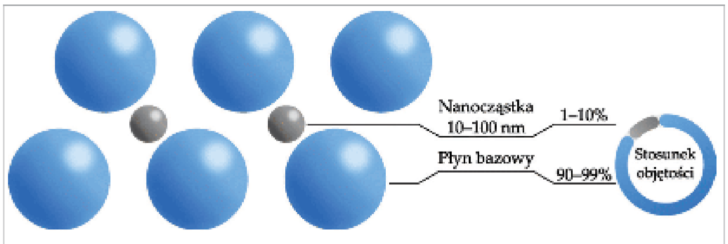
Rys. 2. Schemat pośredniego wymiennika do chłodzenia wyparnego – przykład
Fig. 2. Diagram of indirect evaporative cooling heat exchanger – an example

ma tu najczęściej bawełna, jednak w literaturze znaleźć można badania nad pozyskiwaniem włókien z liści ananasa, szczmielu białego lub gąbczaka walcowatego [43]. Zapewnienie pokrycia wodą całej powierzchni po stronie kanałów mokrych jest istotne, ponieważ w artykułach numerycznych, które są najbardziej popularne w temacie chłodzenia wyparnego, prawie zawsze występuje założenie o równomiernym pokryciu powierzchni kanału filmem wodnym. Jedynie opracowanie Zhu i in. [54] nie ma takiego założenia, a w dodatku wyniki potwierdzają, że ma to znaczący wpływ na wyniki analiz numerycznych. Rezultatem, zastosowania warstwy porowatej na powierzchni kanału mokrego w porównaniu do warstwy nieporowatej jest wzrost wydajności chłodniczej o około 20% [47].

Wspomaganie procesu wymiany ciepła w wymiennikach ciepła przez zastosowanie mieszanin płynów i ciał stałych nie jest innowacją. Badania nad zawieszaniem w płynie cząstek o rozmiarze od mikrometra do milimetra zostały podjęte już 50 lat temu [2-4]. Ze względu na duże rozmiary zawieszanych ciał stałych nie zostały podjęte próby dalszego wdrażania tej technologii. Dopiero w latach 90. do badań wprowadzone zostały nanocząstki (o średnicy mniejszej niż 100 nm) [13], [14], [18], [25], [31]. Schemat struktury nanopłynu został pokazany na rys. 3. Rozwój badań wyraźnie dzieli się na dwie dziedziny. Pierwszą jest rodzaj płynu bazowego. Stosowane płyny to woda, olej i glikol etylenowy [33], [38]. Drugą dziedziną jest materiał wykorzystanych nanocząstek. Mogą być one wykonane ze złota lub srebra [37], tytanu [31], miedzi [29], cynku [53], aluminium lub krzemu [31], MWCNT (*Multiwall Carbon Nanotubes*) i innych metalicznych, niemetalicznych i polimerowych materiałów [9], [12]. Wraz z rozwojem idei stosowania nanopłynów zintensyfikowano badania nad samymi nanocząsteczkami. Oprócz wykorzystania jednolitych substancji w publikacjach (od 2011 roku) pojawiły się także wzmianki o nanocząsteczkach hybrydowych [32], [40], [41] oraz trójskładnikowych [1], [19], [50].



Rys. 1. Uproszczony schemat pośredniego wymiennika wyparnego wraz z interpretacją na wykresie i-x
Fig. 1. Indirect evaporative cooler simplified scheme with psychometric representation



Rys. 3. Struktura nanopłynu
Fig. 3. Nanofluid structure

2. Cel

Przegląd skupia się na prezentacji innowacji wprowadzanych do technologii chłodzenia wyparnego od roku 2010. Dokonano rozróżnienia na zastosowanie nanopłynów, które mają na celu poprawę wymiany ciepła przez zastosowanie w wodzie zraszającej nanocząsteczek substancji poprawiających przewodzenie ciepła. Drugim poruszonym obszarem jest modyfikowanie powierzchni zraszanej przez aplikację materiałów porowatych. Zmiany te mają za zadanie zapewnić równomierne rozprowadzenie wody na ścianach wymiennika po stronie mokrej, a także zapewnić najcieńszą możliwą warstwę wody, która nie będzie stanowiła dodatkowego oporu cieplnego.

W artykule przedstawiono zarówno przegląd zastosowanych nanopłynów oraz materiałów do modyfikacji powierzchni zraszanej, jak też wyniki badań prowadzonych dla wybranych zmian. Technologia chłodzenia wyparnego wpisuje się w obecne tendencje dotyczące ochrony środowiska, oszczędności energii oraz zasobów. Dlatego rozwój technologii, które zwiększają możliwości wykorzystania takich urządzeń jest istotny w obecnych realiach energetycznych oraz polityki klimatycznej.

3. Metody

W artykule omówiono wybrane modyfikacje wprowadzane do technologii pośredniego chłodzenia wyparnego. Analiza obejmuje okres od roku 2010 do chwili obecnej. Na podstawie przeglądu literatury analizie poddano najbardziej popularne (modyfikacja powierzchni po stronie kanału mokrego) oraz najbardziej innowacyjne (zastosowanie nanopłynów do zraszania wymiennika) rozwiązanie. W polskojęzycznej literaturze informacje na ten temat nie występują niemalże w ogóle – dlatego zdecydowano się przedstawić przegląd innowacji z tego zakresu.

W związku z tym, że nie wszystkie badane parametry są opisane w literaturze polskojęzycznej, poniżej przedstawiono wzory do ich obliczeń dla analizy nanopłynów. Jednym z najbardziej popularnych wskaźników jest sprawność termometru mokrego (Wet Bulb Effectiveness (ε_{wb})). Jest ona definiowana jako iloraz różnicy temperatury powietrza na wlocie ($T_{ca,i}$) i wylocie ($T_{ca,o}$) z wymiennika do różnicy temperatury powietrza na wlocie ($T_{ca,i}$) oraz jego temperatury termometru mokrego ($T_{wb,i}$):

$$\varepsilon_{wb} = \frac{T_{ca,i} - T_{ca,o}}{T_{ca,i} - T_{wb,i}} \tag{1}$$

Wartości mogą przekraczać 100% ponieważ powietrze może być schłodzone poniżej temperatury termometru mokrego przy minimalnym zwiększeniu zawartości wilgoci.

Kolejnym parametrem jest sprawność punktu rosy (*Dew Point Effectiveness* (ε_{dew})). Jedyną różnicą w odniesieniu do obliczenia ε_{wb} jest zmiana w mianowniku. Zamiast temperatury termometru mokrego użyta jest temperatura punktu rosy; ε_{dew} wykorzystywana jest do oceny procesów, w których powietrze może zostać schłodzone poniżej temperatury termometru mokrego powietrza na wlocie:

$$\varepsilon_{dew} = \frac{T_{ca,i} - T_{ca,o}}{T_{ca,i} - T_{dew,i}} \tag{2}$$

Ostatnim ze wskaźników jest efektywność egzergetyczna (*Exergy Efficiency* (ε_{ex})). Jest obliczana jako iloraz różnicy egzergii w powietrzu na wylocie ($Ex_{ca,o}$) i wlocie ($Ex_{ca,i}$) do różnicy egzergii powietrza na wlocie ($Ex_{wa,i}$) i wylocie ($Ex_{wa,o}$) po stronie mokrej powiększonej o egzergię filmu wodnego (Ex_{wf}) [28]:

$$\varepsilon_{ex} = \frac{Ex_{ca,o} - Ex_{ca,i}}{Ex_{wa,i} - Ex_{wa,o} + Ex_{wf}} \tag{3}$$

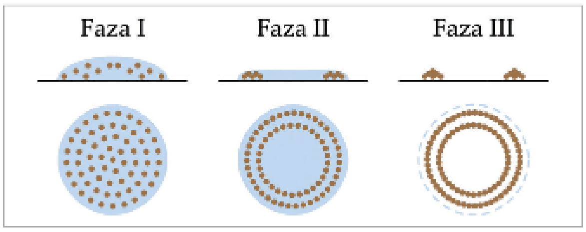
Opracowania dotyczące zastosowania nanopłynów w chłodzeniu wyparnym bazują na wodzie. Dlatego też w analizach wyniki zostały przedstawione w postaci współczynnika poprawy wydajności (*Performance Enhancement Ratio* (PER)). Jest on definiowany jako iloraz różnicy wartości danego parametru (V_p) i wartości dla wody (V_w) do wartości dla wody (V_w):

$$PER = \frac{V_p - V_w}{V_w} \cdot 100\% \tag{4}$$

4. Wyniki

4.1. Nanopłyny w chłodzeniu wyparnym

Aby w pełni zrozumieć ideę zastosowania nanopłynu przy procesach, które opierają się na parowaniu, przedstawiono fazy parowania oraz wysychania kropli nanopłynu (rys. 4). W całym procesie wyróżniono 3 istotne fazy [15]. Faza I, w której dominuje parowanie płynu bazowego (wody). Cały proces przebiega w stałych warunkach termicznych, które parametrami zbliżone są do samej wody. Zawieszone nanocząsteczki na tym etapie nie wpływają znacząco na proces wymiany ciepła i masy. Faza II to etap wysychania kropli. Dominuje w niej efekt zastosowania nanocząstek, a objętość wody jest już zmniejszona. Na skutek wysokiej przewodności cieplnej nanocząstek, obserwuje się chwilowy, gwałtowny wzrost temperatury oraz strumienia przekazywanego ciepła. Właśnie ten etap jest kluczowy dla procesu parowania. W porównaniu do kropli wody, czas od spadnięcia na powierzchnię do powrotu do stanu sprzed zraszania jest znacznie krótszy. W fazie III powstaje już tylko osad



Rys. 4. Schemat parowania oraz wysychania nanopłynu [15]
Fig. 4. Nanofluid evaporation and dryout scheme [15]

nanocząstek na badanej powierzchni. Należy zwrócić uwagę, że na skutek wykorzystania nanocząstek, średnica kropli w trakcie parowania oraz wysychania jest jednakowa. Nie dochodzi zatem do zmniejszenia powierzchni kontaktu wody i powietrza, na której zachodzi proces parowania.

Jedynie nanopłyny oparte na wodzie wykorzystywane są w chłodzeniu wyparnym dlatego też dalsza część ogranicza się tylko do tego rodzaju nanopłynów. W analizowanym okresie badane w publikacjach nanocząstki to: tlenek glinu (Al_2O_3), nanodiament (ND), węglik krzemu (SiC), tlenek miedzi (CuO), ditlenek krzemu (SiO_2), miedź (Cu), tlenek tytanu (TiO_2) i tlenek magnezu (MgO). W tabeli 1 przedstawiono rodzaj badanych nanocząstek zawieszonych w wodzie wraz ze stosunkiem objętości oraz zwiększenie przewodności cieplnej (λ). W zależności od rodzaju oraz stosunku objętości nanocząstek zmierzone zwiększenie przewodności cieplnej (λ) wynosi od kilku do nawet kilkudziesięciu procent.

TABELA 1. Zwiększenie przewodności cieplnej (λ) nanopłynu w stosunku do wody

TABLE 1. Increase in thermal conductivity (λ) of nanofluid relative to water

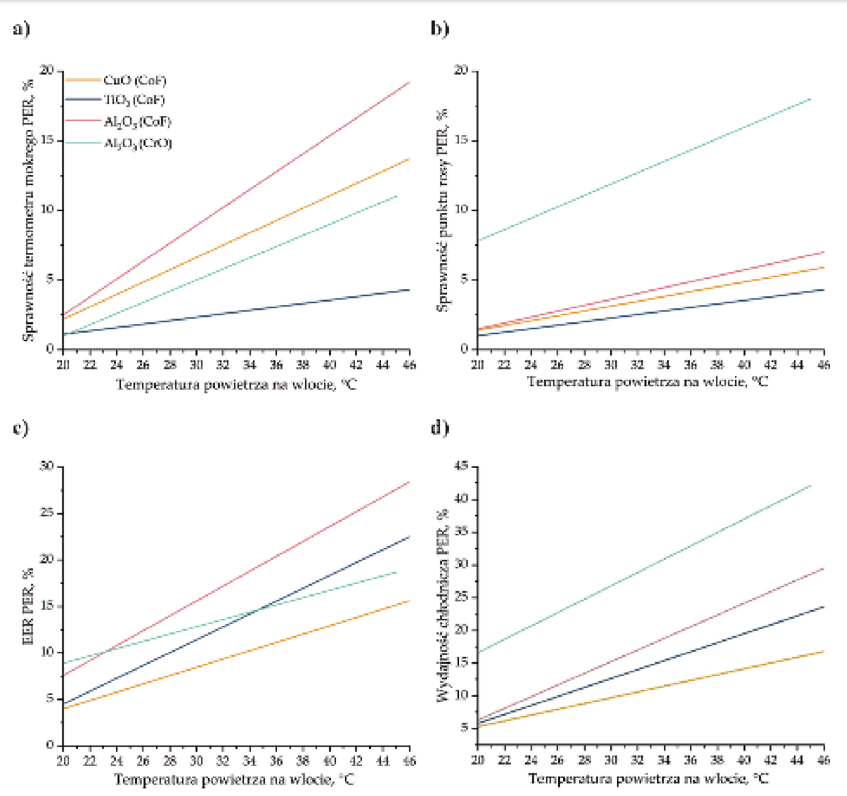
Rok	Źródło	Nano-cząstki	Stosunek objętości, %	Przyrost λ, %
2010	Chandrasekar et al. [10]	Al_2O_3	0,33-3,0	1,6-9,7
2010	Yeganeh et al.[52]	ND	3,0	7,2
2011	Lee et al. [26]	SiC	3,0	7,2
2012	Khedkar et al.[23]	CuO	1,0-7,5	5,8-32,3
2016	Amin et al.[6]	SiO_2–Cu	1,0	11,0
2016	Kumar et al.[24]	CuO/TiO_2	0,02-0,06	3,0-25,0/1,0-15,0
2018	Leong et al. [27]	Cu/TiO_2	0,8	9,8
2021	Nfawa et al.[35]	CuO–MgO	1,3	16,0

Samo zwiększenie przewodności cieplnej nie stanowi o przydatności do zastosowania nanopłynów w chłodzeniu wyparnym. Dlatego też pod uwagę wzięto badania z udziałem nanopłynów przeprowadzone na wymiennikach wyparnych, krzyżowym (CrF) [45] oraz przeciwprądowym (CoF) [46]. W analizie wymiennika krzyżowego wykorzystano jednoskładnikowe nanopłyny z domieszką Al_2O_3, TiO_2, CuO. W wymienniku przeciwprądowym zastosowano jedynie nanopłyn z zawiesiną Al_2O_3.

Analizie poddano kolejno parametry: sprawność termometru mokrego, sprawność punktu rosy, EER oraz wydajność chłodniczą. Wyniki PER także wahają się w zakresie kilku do kilkudziesięciu procent. Jednak w przypadku każdego z parametrów widoczny jest wzrost PER wraz ze wzrostem temperatury powietrza na wlocie do wymiennika. Wyniki są zaprezentowane w funkcji temperatury powietrza na wlocie do wymiennika na rys. 5.

Oprócz nanopłynów jednoskładnikowych, badaniom poddano także nanopłyny hybrydowe trójskładnikowe [22] oraz hybrydowe [2]. Oba eksperymenty przeprowadzone zostały z wykorzystaniem tego samego rodzaju wymiennika CoF. Jednakowe były także warunki testów: temperatura termometru suchego na wlocie 35°C, wilgotność względna powietrza 32%, przepływ objętościowy na wlocie 0,28 m³/s. W przypadku zastosowania każdego z nanopłynów widoczna jest poprawa uzyskanych parametrów w porównaniu do wody. Poprawa ta nie przekracza jednak kilku procent, co przy nakładzie prac związanych z przygotowaniem nanopłynów [16], może nie przynosić wymiernych efektów. Największe różnice między zastosowaniem hybryd trójskładnikowych i hybryd zauważyć można w sprawności egzergetycznej (rys. 6 c) i c')). Natomiast porównywalny PER osiągany jest w obu rodzajach nanopłynów dla sprawności punktu rosy oraz COP (rys. 6 a), a'), b), b')).

Jak wykazano samo zastosowanie nanocząsteczek jest istotne w procesie poprawy wymiany ciepła przez zwiększenie przewodności cieplnej. Z punktu widzenia tego opracowania istotny jest także fakt, że proces odparowania nanopłynu jest zintensyfikowany w porównaniu do wody. W związku z tym istnieje

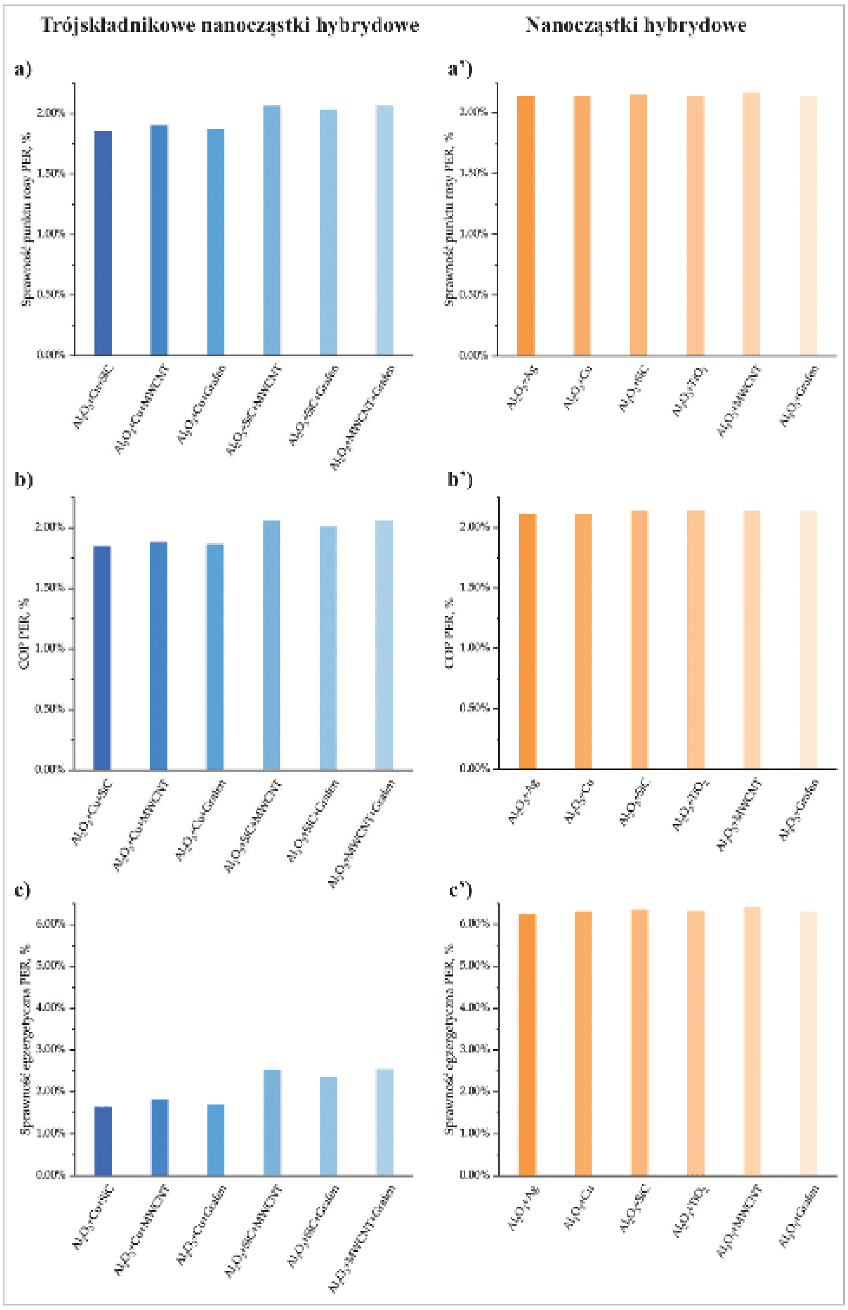


Rys. 5. Wskaźnik PER przy wykorzystaniu różnych nanocząstek w nanopłynach opartych na wodzie wwymienniku CoF i CrF w funkcji temperatury na wlocie: a) sprawność termometru mokrego, b) sprawność punktu rosy, c) EER; d) wydajność chłodnicza [45], [46]

Fig. 5. PER due to use of different nanoparticles in water based nanofluids for CoF and CrF exchanger (as a function of inlet air temperature): a) wet bulb effectiveness, b) dew point effectiveness, c) EER, d) colling capacity [45], [46]

możliwość zastosowania nanopłynów w procesie pośredniego chłodzenia wyparnego. W przywołanych opracowaniach wykazano poprawę wybranych parametrów wymienników używanych w procesie chłodzenia wyparnego.

Należy zwrócić uwagę na brak eksperymentalnych badań zastosowania nanopłynów w chłodzeniu wyparnym. Wyniki numeryczne, bez potwierdzenia na urządzeniach modelowych lub rzeczywistych mogą znacznie odbiegać od wyników doświadczalnych.



Rys. 6. Wskaźnik PER przy wykorzystaniu nanocząstek hybrydowych oraz trójskładnikowych w nanopłynach opartych na wodzie w wymienniku CoF w funkcji temperatury na wlocie: a) i a') sprawność punktu rosy; b) i b') COP; c) i c') sprawność egzergetyczna [21], [22]

Fig. 6. PER due to use of hybrid and ternary nanoparticles in water based nanofluids for CoF exchanger (as a function of inlet air temperature): a) and a') dew point effectiveness; b) and b') COP; c) and c') exergy effectiveness [21], [22]

4.2. Modyfikacja powierzchni

Istotnym celem modyfikowania powierzchni ścianek wymiennika po stronie mokrej jest zapewnienie równomiernej i możliwie cienkiej warstwy filmu wodnego na całej powierzchni zraszanej. W pracującym urządzeniu może dojść do sytuacji, gdy tylko część ściany po stronie mokrej jest pokryta filmem wodnym, co ogranicza powierzchnię, z której woda odparowuje. Potencjał procesu chłodzenia wyparnego jest w ten sposób limitowany. Samej wody na ściankach nie może być także zbyt dużo. Woda, ze względu na duże ciepło właściwe, staje się dodatkowym izolatorem na drodze wymiany ciepła między kanałem suchym i mokrym. Schemat problemów z filmem wodnym po stronie mokrego kanału pokazano na rys. 7. Należy także bezwzględnie wziąć pod uwagę rodzaj materiału, który wykorzystany jest do wykonania samego wymiennika. Nie każdy z materiałów stosowanych do pokrywania ścian kanału mokrego jest wodoodporny. A to właśnie wodoodporność i zapewnienie sztywności konstrukcji jest wymagane od materiału, z którego wymiennik jest zbudowany. Obecnie stosowane są ściany z tworzyw sztucznych, które są atrakcyjne pod względem finansowym, a zarazem zapewniają sztywność konstrukcji. Często spotyka się również aluminium, które ma bardzo dobre właściwości przewodzenia ciepła (między kanałem suchym i mokrym). Obecnie w konstrukcji wymiennika dąży się do jak najcieńszych ścian o dużej przewodności cieplnej i wysokiej zwilżalności po stronie kanału mokrego. Ma to główne wpływ na wymiary urządzeń do pośredniego chłodzenia wyparnego. Rozpowszechnienie stosowania tej technologii wymaga budowy kompaktowych urządzeń.

Charakterystyczną cechą pośrednich wymienników wyparnych jest zagęszczenie kanałów. Nie pozostaje zatem zbyt wiele przestrzeni na pokrycie ścian wymiennika dodatkową warstwą materiału. Poza niewielką grubością pokrycia wymagane jest także to, aby materiał był hydrofilowy i pozwalał na łatwe odparowanie wody z jego powierzchni. W literaturze wyróżnia się cztery główne materiały do pokrywania powierzchni kanałów mokrych: ceramiczny porowaty oraz trzy rodzaje włókien: naturalne, polimerowe i tekstylne. Zestawiono wady, zalety oraz źródła literaturowe dla każdego materiału (tabela 2). Wskazano także, czy dany materiał jest przydatny do stosowania (+) oraz czy ma on ograniczenia przy zastosowaniu w chłodzeniu wyparnym (±).

Zastosowanie materiałów porowatych wynika z dążenia do ograniczenia czasu pracy pomp wody zraszającej. W sytuacji, kiedy na ścianach kanału mokrego woda będzie zmagazynowana, to nie ma konieczności ciągłego jej dostarczania przez pompy. W efekcie ogranicza się zapotrzebowanie na energię elektryczną, a tym samym bilans energii dostarczonej do układu staje się korzystniejszy.

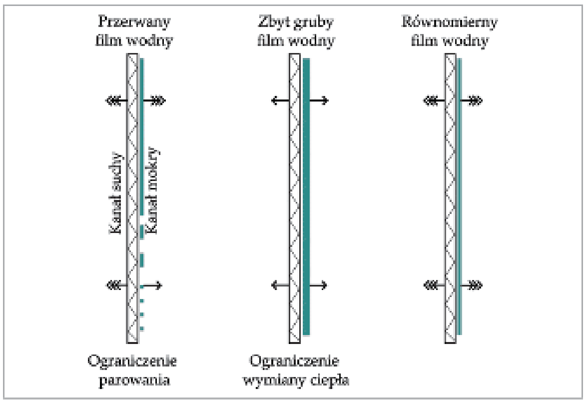
Porowate materiały ceramiczne cenione są za możliwość magazynowania znaczących ilości wody w swoich porach. Ich zagęszczenie pozwala także wydłużyć czas kontaktu przepływającego powietrza z filmem wodnym. Jednak wraz ze wzrostem porowatości, pogorsza się wytrzymałość materiału i staje się on kruchy i podatny na uszkodzenia. Zastosowanie takich materiałów w układach pośredniego chłodzenia wyparnego nie wymaga jednak osiągania maksymalnych właściwości magazynowania wody w materiale ceramicznym. W związku z tym istnieje możliwość bezpiecznego stosowania tego rodzaju materiału [44].

Włókna naturalne z kolei są łatwe oraz niedrogie w pozyskaniu i przygotowaniu do użytku. Natomiast w większość tych materiałów kontakt z wodą powoduje rozwarstwienie ich włókien. Dodatkowo warstwa włókien w krótkim okresie pokrywa się pleśnią. Występują gatunki roślin, które mają większą odporność na pleśń, lecz nie eliminuje to problemu całkowicie [5]. W celu szerszego zastosowania takich materiałów należałoby rozważyć używanie kompozytów z włókien naturalnych oraz polimerów, jednak należy wziąć pod uwagę możliwości oraz wymagania procesu produkcji takich kompozytów [30].

Włókna polimerowe służą często do pokrycia ścian kanałów aluminiowych lub wykonanych z tworzyw sztucznych. Włókna te są odporne na korozję oraz osadzanie się kamieni a wodnego, a jednocześnie cechują się możliwością magazynowania wody. Jednak bardziej popularne staje się tworzenie membran kompozytowych opartych na tworzywach sztucznych (polistyren, polipropylen, polietylen czy PET) [30]. Zaletami tej technologii jest produkcja materiału, który umożliwi skonstruowanie lekkiego, mniejszego i trwałego wymiennika. Dodatkowo w procesie produkcji materiału w łatwy sposób można uzyskać falisty lub żebrowany kształt w celu zwiększenia powierzchni wymiany ciepła [30].

Włókna tekstylne, pomimo najlepszych właściwości pod względem chłodzenia wyparnego (absorpcyjność oraz odparowanie wody), mają najgorsze właściwości wytrzymałościowe. Konieczne jest stosowanie tego typu materiałów na sztywnych oraz wodoodpornych ścianach wymiennika. W tym przypadku mogą być także stosowane membrany kompozytowe oparte na włóknach tekstylnych, które częściowo eliminują problemy spowodowane niekorzystnymi właściwościami fizycznymi [30].

W przeciwieństwie do nanopłynów, struktury porowate są szeroko opisywane w literaturze. Przykłady



Rys. 7. Pokrycie powierzchni wymiennika po stronie mokrej filmem wodnym
Fig. 7. Water film coverage on the wet channel surface

masowo produkowanych wymienników ze porowatymi strukturami powierzchni wymiany ciepła przedstawiono na rys. 8. W przypadku firmy SEELEY w wymienniku Coolerado HMX stosowany jest polimer. Natomiast w produkcie Wind Domination firmy AOLAN jest to kompozyt celulozowo-papierowy.

5. Wnioski

Przedstawione wyniki wskazują na korzystne cechy nanopłynów opartych na wodzie stosowanych w wyparnych wymiennikach ciepła. Wyniki badań potwierdzają znaczną poprawę przewodności cieplnej nanopłynów, przy czym wynosi ona od 1,6% do 25,0%. Jednocześnie wskazano na skuteczność zastosowania nanopłynów w procesach chłodzenia wyparnego, gdzie w zależności od temperatury powietrza na wlocie do wymiennika poprawa wybranych parametrów sięgała kilkudziesięciu procent.

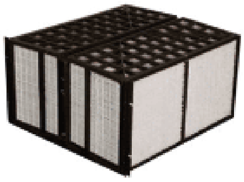
Nie należy zapominać o wzrastającym stężeniu wszystkich substancji rozpuszczonych w wodzie zraszającej, który jest skutkiem jej odparowania. Dotyczy to także wspomnianych nanopłynów, które są roztworem nanocząstek i wody. Przy doborze rodzaju materiału nanocząstek należy brać pod uwagę wymagania procesów przygotowania danego nanopłynu, które mogą być nie tylko kosztowne, ale także energo- i czasochłonne.

Wybór materiału na konstrukcję wymiennika oraz do pokrycia powierzchni kanałów mokrych powinien być wynikiem analizy właściwości fizycznych danego materiału. Zadaniem konstrukcji jest zapewnienie trwałości oraz zapewnienia

TABELA 2. Wady i zalety oraz przydatność wybranych materiałów porowatych stosowanych w chłodzeniu wyparnym [30]
TABLE 2. Porous materials used in evaporative cooling disadvantages and advantages and applicability [30]

Materiał	Wady	Zalety	Źródła	Przydatność
Ceramiczny porowaty	kruchość	porowatość, magazynowania wody	Hammel i in. (2014)[20] Chen i in. (2021)[11]	+
Włókna naturalne	rozwarstwianie, rozwój pleśni	koszt, brak konieczności dodatkowych obróbek	Lv i in. (2021) [30] Sofia i in. (2022) [43]	±
Włókna polimerowe	koszt, łączenie z materiałami wodoodpornymi	antykorozyjność, odporność na osadzanie się kamienia	Ashari I in. (2010) [8] Velasco Gomez I in. (2012) [48]	+
Włókna tekstylne	miękkość	plastyczność, antykorozyjność	Niyomvas I in. (2013) [36] Duan I in. (2016)[17] Xu I in. (2016) [49]	±

a)



b)

Rys. 8. Przykład zastosowania: a) materiału polimerowego w wymienniku Coolerado HMX firmy SEELEY [42], b) kompozytu celulozowo-papierowego w wymienniku Wind Domination firmy AOLAN [7]
Fig. 8. Example of application: a) polymer material in Coolerado HMX by SEELEY [42], b) wood pulp paper fiber composite in Wind Domination by AOLAN [7]

szczelności między częścią suchą i mokrą. Natomiast materiały porowate, które są obecnie przedmiotem badań, mają zapewnić równomierne powstawanie możliwie cienkiego filmu wodnego na całej powierzchni kanału mokrego oraz zmagazynować wodę. Efektem jest zwiększenie wydajności nawet o 20% oraz skrócenie czasu pracy pomp wody zraszającej.

W ostatnich latach temat chłodzenia wyparnego coraz częściej pojawia się w literaturze, a ponieważ chłodzenie to nie ma negatywnego wpływu na środowisko, to proces ten staje się popularny i coraz częściej stosowany. Głównym ograniczeniem stosowania chłodzenia wyparnego jest panujący klimat i bezpośredni kontakt powietrza z wodą (zagrożenie bakteriologiczne). Obecny rozwój technologii pośredniego chłodzenia wyparnego oraz innowacje omówione w artykule pozwalają wnioskować, że ta technologia chłodzenia powietrza na potrzeby klimatyzacji będzie stawała się popularna również poza obszarami klimatu suchego.

6. Podsumowanie

Opisane w artykule innowacje wprowadzane do technologii pośredniego chłodzenia wyparnego świadczą o możliwości wykorzystania tego typu urządzeń nie tylko do celów przemysłowych, ale także na cele chłodzenia obiektów użytkowych i mieszkalnych. W związku z dużą zależnością wydajności urządzenia od parametrów powietrza zewnętrznego, należy rozpatrywać technologię chłodzenia wyparnego w aspekcie urządzeń współpracujących ze standardowymi, sprężarkowymi układami chłodniczymi.

Korzystną cechą chłodzenia wyparnego jest brak negatywnego wpływu na środowisko. W tym wypadku czynnikami chłodniczymi są: powietrze (R-729) oraz woda (R-718), których używanie nie powoduje bezpośredniej emisji CO_2. Dodatkowym atutem technologii jest prostota konstrukcji urządzeń i niewielkie zużycie energii elektrycznej do napędu pomp i wentylatorów.

Warto zatem rozważyć wprowadzenie nanopłynów czy powierzchni porowatych do pośrednich wymienników wyparnych. W pierwszej kolejności należy zatem rozważać modyfikację powierzchni zraszanej, która jest bezpośrednio związana z procesem produkcji wymiennika. Dopiero w dalszym etapie aplikacja nanopłynów jest uzasadniona, ponieważ może to zostać wykonane bez konieczności ingerencji w konstrukcję samego urządzenia.

Dodatkowo za zastosowaniem powierzchni porowatych przemawia fakt, że są one ogólnie stosowane w produkowanych obecnie urządzeniach do pośredniego chłodzenia wyparnego. nanopłynów jest jedynie opisane w literaturze, a wyniki nie są poparte wynikami badań urządzeń rzeczywistych.

LITERATURA

[1] Adun, Humphrey, Doga Kavaz, and Mustafa Dagbasi. 2021. "Review of Ternary Hybrid Nanofluid: Synthesis, Stability, Thermophysical Properties, Heat Transfer Applications, and Environmental Effects." *Journal of Cleaner Production* 328 (December): 129525. https://doi.org/10.1016/j.jclepro.2021.129525.

[2] Ahuja, Avtar S. 1982. "Thermal Design of a Heat Exchanger Employing Laminar Flow of Particle Suspensions." *International Journal of Heat and Mass Transfer* 25 (5): 725–28. https://doi.org/10.1016/0017-9310(82)90179-X.

[3] Ahuja, Avtar Singh. 1975a. "Augmentation of Heat Transport in Laminar Flow of Polystyrene Suspensions. I. Experiments and Results." *Journal of Applied Physics* 46 (8): 3408–16. https://doi.org/10.1063/1.322107.

[4] ———. 1975b. "Augmentation of Heat Transport in Laminar Flow of Polystyrene Suspensions. II. Analysis of the Data." *Journal of Applied Physics* 46 (8): 3417–25. https://doi.org/10.1063/1.322062.

[5] Al-Sulaiman, Faleh. 2002. "Evaluation of the Performance of Local Fibers in Evaporative Cooling." *Energy Conversion and Management* 43 (16): 2267–73. https://doi.org/10.1016/S0196-8904(01)00121-2.

[6] Amiri, Mohammad, Salman Movahedirad, and Faranak Manteghi. 2016. "Thermal Conductivity of Water and Ethylene Glycol Nanofluids Containing New Modified Surface SiO2-Cu Nanoparticles: Experimental and Modeling." *Applied Thermal Engineering* 108 (September): 48–53. https://doi.org/10.1016/j.applthermaleng.2016.07.091.

[7] AOLAN INDUSTRY CO., LTD. n.d. "Evaporative Air Cooler Wind Domination." Dostęp Sierpień 15, 2023. https://www.aolan-china.com/product-detail.html?id=10

[8] Ashari, A., T.M. Bucher, H. Vahedi Tafreshi, M.A. Tahir, and M.S.A. Rahman. 2010. "Modeling Fluid Spread in Thin Fibrous Sheets: Effects of Fiber Orientation." *International Journal of Heat and Mass Transfer* 53 (9–10): 1750–58. https://doi.org/10.1016/j.ijheatmasstransfer.2010.01.015.

[9] Biercuk, M. J., M. C. Llaguno, M. Radosavljevic, J. K. Hyun, A. T. Johnson, and J. E. Fischer. 2002. "Carbon Nanotube Composites for Thermal Management." *Applied Physics Letters* 80 (15): 2767–69. https://doi.org/10.1063/1.1469696.

[10] Chandrasekar, M., S. Suresh, and A. Chandra Bose. 2010. "Experimental Investigations and Theoretical Determination of Thermal Conductivity and Viscosity of Al2O3/Water Nanofluid." *Experimental Thermal and Fluid Science* 34 (2): 210–16. https://doi.org/10.1016/j.expthermflusci.2009.10.022.

[11] Chen, Yu, Nannan Wang, Oluwafunmilola Ola, Yongde Xia, and Yanqiu Zhu. 2021. "Porous Ceramics: Light in Weight but Heavy in Energy and Environment Technologies." *Materials Science and Engineering: R: Reports* 143 (January): 100589. https://doi.org/10.1016/j.mser.2020.100589.

[12] Choi, S. U. S., Z. G. Zhang, W. Yu, F. E. Lockwood, and E. A. Grulke. 2001. "Anomalous Thermal Conductivity Enhancement in Nanotube Suspensions." *Applied Physics Letters* 79 (14): 2252–54. https://doi.org/10.1063/1.1408272.

[13] Choi, Stephen U. S., and Jeffrey A. Eastman. 1995. "Enhancing Thermal Conductivity of Fluids with Nanoparticles." In *1995 International Mechanical Engineering Congress and Exhibition, San Francisco, CA (United States), 12-17 Nov 1995*.

[14] Choi, Stephen U. S., and Shinpyo Lee. 1996. "Application of Metallic Nanoparticle Suspensions in Advanced Cooling Systems." In *1996 International Mechanical Engineering Congress and Exhibition, Atlanta, GA (United States), 17-22 Nov 1996*.

[15] Chon, Chan Hee, Sokwon Paik, Joseph B. Tipton, and Kenneth D. Kihm. 2007. "Effect of Nanoparticle Sizes and Number Densities on the Evaporation and Dryout Characteristics for Strongly Pinned Nanofluid Droplets." *Langmuir* 23 (6): 2953–60. https://doi.org/10.1021/la061661y.

[16] Das, Sarit Kumar, Stephen U. S. Choi, and Hrishikesh E. Patel. 2006. "Heat Transfer in Nanofluids—A Review." *Heat Transfer Engineering* 27 (10): 3–19. https://doi.org/10.1080/01457630600904593.

[17] Duan, Zhiyin, Changhong Zhan, Xudong Zhao, and Xuelin Dong. 2016. "Experimental Study of a Counter-Flow Regenerative Evaporative Cooler." *Building and Environment* 104 (August): 47–58. https://doi.org/10.1016/J.BUILDENV.2016.04.029.

[18] Eastman, J. A., U. S. Choi, S. Li, L. J. Thompson, and S. Lee. 1996. "Enhanced Thermal Conductivity through the Development of Nanofluids." *MRS Proceedings* 457 (February): 3. https://doi.org/10.1557/PROC-457-3.

[19] Elnaqeeb, Thanaa, Isaac Lare Animasaun, and Nehad Ali Shah. 2021. "Ternary-Hybrid Nanofluids: Significance of Suction and Dual-Stretching on Three-Dimensional Flow of Water Conveying Nanoparticles with Various Shapes and Densities." *Zeitschrift Für Naturforschung A* 76 (3): 231–43. https://doi.org/10.1515/zna-2020-0317.

[20] Hammel, E.C., O.L.-R. Ighodaro, and O.I. Okoli. 2014. "Processing and Properties of Advanced Porous Ceramics: An Application Based Review." *Ceramics International* 40 (10): 15351–70. https://doi.org/10.1016/j.ceramint.2014.06.095.

[21] Kashyap, Sarvesh, Jahar Sarkar, and Amitesh Kumar. 2021a. "Effect of Surface Modifications and Using Hybrid Nanofluids on Energy--Exergy Performance of Regenerative Evaporative Cooler." *Building and Environment* 189 (February): 107507. https://doi.org/10.1016/j.buildenv.2020.107507.

[22] ———. 2021b. "Performance Enhancement of Regenerative Evaporative Cooler by Surface Alterations and Using Ternary Hybrid Nanofluids." *Energy* 225 (June): 120199. https://doi.org/10.1016/j.energy.2021.120199.

[23] Khedkar, Rohit S., Shriram S. Sonawane, and Kailas L. Wasewar. 2012. "Influence of CuO Nanoparticles in Enhancing the Thermal Conductivity of Water and Monoethylene Glycol Based Nanofluids." *International Communications in Heat and Mass Transfer* 39 (5): 665–69. https://doi.org/10.1016/j.icheatmasstransfer.2012.03.012.

[24] Kumar, Nishant, and Shriram S. Sonawane. 2016. "Experimental Study of Thermal Conductivity and Convective Heat Transfer Enhancement Using CuO and TiO 2 Nanoparticles." *International Communications in Heat and Mass Transfer* 76 (August): 98–107. https://doi.org/10.1016/j.icheatmasstransfer.2016.04.028.

[25] Lee, S., S. U.-S. Choi, S. Li, and J. A. Eastman. 1999. "Measuring Thermal Conductivity of Fluids Containing Oxide Nanoparticles." *Journal of Heat Transfer* 121 (2): 280–89. https://doi.org/10.1115/1.2825978.

[26] Lee, Seung Won, Sung Dae Park, Sarah Kang, In Cheol Bang, and Ji Hyun Kim. 2011. "Investigation of Viscosity and Thermal Conductivity of SiC Nanofluids for Heat Transfer Applications." *International Journal of Heat and Mass Transfer* 54 (1–3): 433–38. https://doi.org/10.1016/j.ijheatmasstransfer.2010.09.026.

[27] Leong, Kin Yuen, Idayu Razali, K.Z. Ku Ahmad, Hwai Chyuan Ong, M.J. Ghazali, and Mohd Rosdzimin Abdul Rahman. 2018. "Thermal Conductivity of an Ethylene Glycol/Water-Based Nanofluid with Copper-Titanium Dioxide Nanoparticles: An Experimental Approach." *International Communications in Heat and Mass Transfer* 90 (January): 23–28. https://doi.org/10.1016/j.icheatmasstransfer.2017.10.005.

[28] Lin, Jie, Duc Thuan Bui, Ruzhu Wang, and Kian Jon Chua. 2018. "On the Exergy Analysis of the Counter-Flow Dew Point Evaporative Cooler." *Energy* 165 (December): 958–71. https://doi.org/10.1016/j.energy.2018.10.042.

[29] Liu, M.-S., M. C.-C. Lin, I.-T. Huang, and C.-C. Wang. 2006. "Enhancement of Thermal Conductivity with CuO for Nanofluids." *Chemical Engineering & Technology* 29 (1): 72–77. https://doi.org/10.1002/ceat.200500184.

[30] Lv, Jing, Haodong Xu, Mengya Zhu, Yuwei Dai, Hongzhi Liu, and Zhao Li. 2021. "The Performance and Model of Porous Materials in the Indirect Evaporative Cooling System: A Review." *Journal of Building Engineering* 41 (September): 102741. https://doi.org/10.1016/j.jobe.2021.102741.

[31] Masuda, Hidetoshi, Akira Ebata, Kazunari Teramae, and Nobuo Hishinuma. 1993. "Alteration of Thermal Conductivity and Viscosity of Liquid by Dispersing Ultra-Fine Particles. Dispersion of Al2O3, SiO2 and TiO2 Ultra-Fine Particles." *Netsu Bussei* 7 (4): 227–33. https://doi.org/10.2963/jjtp.7.227.

[32] Minea, Alina Adriana. 2016. "A Review on the Thermophysical Properties of Water-Based Nanofluids and Their Hybrids." *The Annals of "Dunarea de Jos" University of Galati. Fascicle IX, Metallurgy and Materials Science* 39 (1): 35–47.

[33] Mintsa, Honorine Angue, Gilles Roy, Cong Tam Nguyen, and Dominique Doucet. 2009. "New Temperature Dependent Thermal Conductivity Data for Water-Based Nanofluids." *International Journal of Thermal Sciences* 48 (2): 363–71. https://doi.org/10.1016/j.ijthermalsci.2008.03.009.

[34] Murshed, S.M.S., K.C. Leong, and C. Yang. 2005. "Enhanced Thermal Conductivity of TiO_2—Water Based Nanofluids." *International Journal of Thermal Sciences* 44 (4): 367–73. https://doi.org/10.1016/j.ijthermalsci.2004.12.005.

[35] Nfawa, Sadeq R., Abd Rahim Abu Talib, Adi Azriff Basri, and Siti Ujila Masuri. 2021. "Novel Use of MgO Nanoparticle Additive for Enhancing the Thermal Conductivity of CuO/Water Nanofluid." *Case Studies in Thermal Engineering* 27 (October): 101279. https://doi.org/10.1016/j.csite.2021.101279.

[36] Niyomvas, Banyat, and Bunjerd Potakarat. 2013. "Performance Study of Cooling Pads." *Advanced Materials Research* 664 (February): 931–35. https://doi.org/10.4028/www.scientific.net/AMR.664.931.

[37] Patel, Hrishikesh E., Sarit K. Das, T. Sundararajan, A. Sreekumaran Nair, Beena George, and T. Pradeep. 2003. "Thermal Conductivities of Naked and Monolayer Protected Metal Nanoparticle Based Nanofluids: Manifestation of Anomalous Enhancement and Chemical Effects." *Applied Physics Letters* 83 (14): 2931–33. https://doi.org/10.1063/1.1602578.

[38] Pinto, Rodrigo Vidonscky, and Flávio Augusto Sanzovo Fiorelli. 2016. "Review of the Mechanisms Responsible for Heat Transfer Enhancement Using Nanofluids." *Applied Thermal Engineering* 108 (September): 720–39. https://doi.org/10.1016/j.applthermaleng.2016.07.147.

[39] Rajski, Krzysztof, Ali Sohani, Sina Jafari, Jan Danielewicz, and Marderos Ara Sayegh. 2022. "Energy Performance of a Novel Hybrid Air Conditioning System Built on Gravity-Assisted Heat Pipe-Based Indirect Evaporative Cooler." *Energies* 15 (7): 2613. https://doi.org/10.3390/en15072613.

[40] Ranga Babu, J.A., K. Kiran Kumar, and S. Srinivasa Rao. 2017. "State-of-Art Review on Hybrid Nanofluids." *Renewable and Sustainable Energy Reviews* 77 (September): 551–65. https://doi.org/10.1016/j.rser.2017.04.040.

[41] Sarkar, Jahar, Pradyumna Ghosh, and Arjumand Adil. 2015. "A Review on Hybrid Nanofluids: Recent Research, Development and Applications." *Renewable and Sustainable Energy Reviews* 43 (March): 164–77. https://doi.org/10.1016/j.rser.2014.11.023.

[42] SEELEY INTERNATIONAL. n.d. "Coolerado HMX Indirect Evaporative Cooler." Dostęp Sierpień 15, 2023. https://www.seeleyinternational.com/us/product/coolerado-hmx-commercial-north-america/.

[43] Sofia, Evi, Nandy Putra, and Engkos A. Kosasih. 2022. "Development of Indirect Evaporative Cooler Based on a Finned Heat Pipe with a Natural-Fiber Cooling Pad." *Heliyon* 8 (12): e12508. https://doi.org/10.1016/j.heliyon.2022.e12508.

[44] Sun, Tiezhu, Xiang Huang, Yueying Qu, Fenghao Wang, and Yi Chen. 2020. "Theoretical and Experimental Study on Heat and Mass Transfer of a Porous Ceramic Tube Type Indirect Evaporative Cooler." *Applied Thermal Engineering* 173 (June): 115211. https://doi.org/10.1016/j.applthermaleng.2020.115211.

[45] Tariq, Rasikh, Changhong Zhan, Nadeem Ahmed Sheikh, and Xudong Zhao. 2018. "Thermal Performance Enhancement of a Cross-Flow-Type Maisotsenko Heat and Mass Exchanger Using Various Nanofluids." *Energies* 11 (10): 2656. https://doi.org/10.3390/en11102656.

[46] Tariq, Rasikh, Changhong Zhan, Xudong Zhao, and Nadeem Ahmed Sheikh. 2018. "Numerical Study of a Regenerative Counter Flow Evaporative Cooler Using Alumina Nanoparticles in Wet Channel." *Energy and Buildings* 169 (June): 430–43. https://doi.org/10.1016/j.enbuild.2018.03.086.

[47] UNNO, Noriyuki, Kazuhisa YUKI, Ryo INOUE, Yasuo KOGO, Jun TANIGUCHI, and Shin-ichi SATAKE. 2020. "Enhanced Evaporation of Porous Materials with Micropores and High Porosity." *Journal of Thermal Science and Technology* 15 (1): JTST0007–JTST0007. https://doi.org/10.1299/jtst.2020jtst0007.

[48] Velasco Gómez, Eloy, Ana Tejero González, and Francisco Javier Rey Martínez. 2012. "Experimental Characterisation of an Indirect Evaporative Cooling Prototype in Two Operating Modes." *Applied Energy* 97 (September): 340–46. https://doi.org/10.1016/J.APENERGY.2011.12.065.

[49] Xu, Peng, Xiaoli Ma, Xudong Zhao, and Kevin S. Fancey. 2016. "Experimental Investigation on Performance of Fabrics for Indirect Evaporative Cooling Applications." *Building and Environment* 110 (December): 104–14. https://doi.org/10.1016/j.buildenv.2016.10.003.

[50] Xuan, Zihao, Yuling Zhai, Mingyan Ma, Yanhua Li, and Hua Wang. 2021. "Thermo-Economic Performance and Sensitivity Analysis of Ternary Hybrid Nanofluids." *Journal of Molecular Liquids* 323 (February): 114889. https://doi.org/10.1016/j.molliq.2020.114889.

[51] Yang, Hongxing, Wenchao Shi, Yi Chen, and Yunran Min. 2021. "Research Development of Indirect Evaporative Cooling Technology: An Updated Review." *Renewable and Sustainable Energy Reviews* 145 (July): 111082. https://doi.org/10.1016/j.rser.2021.111082.

[52] Yeganeh, M., N. Shahtahmasebi, A. Kompany, E.K. Goharshadi, A. Youssefi, and L. Šiller. 2010. "Volume Fraction and Temperature Variations of the Effective Thermal Conductivity of Nanodiamond Fluids in Deionized Water." *International Journal of Heat and Mass Transfer* 53 (15–16): 3186–92. https://doi.org/10.1016/j.ijheatmasstransfer.2010.03.008.

[53] Yu, Wei, Huaqing Xie, Lifei Chen, and Yang Li. 2009. "Investigation of Thermal Conductivity and Viscosity of Ethylene Glycol Based ZnO Nanofluid." *Thermochimica Acta* 491 (1–2): 92–96. https://doi.org/10.1016/j.tca.2009.03.007.

[54] Zhu, Guangya, Weijian Chen, Dalin Zhang, and Tao Wen. 2023. "Performance Evaluation of Counter Flow Dew-Point Evaporative Cooler with a Three-Dimensional Numerical Model." *Applied Thermal Engineering* 219 (January): 119483. https://doi.org/10.1016/j.applthermaleng.2022.119483.

energies

Review

Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review

Łukasz Stefaniak *, Agnieszka Grabka, Juliusz Walaszczyk, Krzysztof Rajski, Jan Danielewicz *, Wiktoria Jaskóła, Maja Wochniak and Weronika Żyta

Faculty of Environmental Engineering, Wrocław University of Science and Technology, 50377 Wrocław, Poland
* Correspondence: lukasz.stefaniak@pwr.edu.pl (Ł.S.); jan.danielewicz@pwr.edu.pl (J.D.)

Abstract: Dewpoint indirect evaporative cooling (DIEC) offers an energy-efficient, eco-friendly alternative to conventional air conditioning by using water and air to lower temperatures. With the rising demand for sustainable cooling solutions—especially in regions facing water scarcity and high energy costs—optimizing these systems for real-world conditions is more important than ever. One major challenge is ensuring that DIEC systems perform well when water is supplied intermittently rather than continuously. In this review, we examine how intermittent water supply affects the cooling performance and overall efficiency of DIEC systems. We discuss recent studies that highlight the importance of key factors such as the properties of heat exchanger materials, design modifications, and control strategies. Our analysis reveals that while innovative materials like hydrophilic membranes and adaptive design features can improve performance, their widespread use is often limited by cost and scalability. We also point out critical research gaps, particularly in applying intermittent water spraying to non-porous heat exchangers. Overall, our findings underscore the need for integrated water management strategies in DIEC design. We advocate a cross-disciplinary approach—bridging fluid dynamics, material science, and environmental engineering—to develop more resilient and sustainable cooling technologies.

Keywords: natural refrigerants; air conditioning; sustainable cooling; energy efficiency

check for updates

Academic Editor: S. A. Sherif

Received: 25 February 2025
Revised: 22 April 2025
Accepted: 28 April 2025
Published: 30 April 2025

Citation: Stefaniak, Ł.; Grabka, A.; Walaszczyk, J.; Rajski, K.; Danielewicz, J.; Jaskóła, W.; Wochniak, M.; Żyta, W. Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review. *Energies* **2025**, *18*, 2296. https://doi.org/10.3390/en18092296

1. Introduction

Energy consumption for air conditioning (AC) has increased dramatically over recent decades due to improvements in living standards [1,2], urbanization [3,4], and climate change [5]. The reliance on AC systems to maintain thermal comfort has led to significant resource depletion and increased carbon emissions [6]. Globally, buildings account for approximately 30–40% of total energy consumption and a comparable share of CO_2 emissions [7]. Among the various contributors, Heating, Ventilation, and Air Conditioning (HVAC) systems consume nearly half of a building's total energy use [8].

With the global population spending more time indoors, the demand for efficient and sustainable cooling solutions is increasing significantly. This is especially true in rapidly developing regions such as China, where cooling-related electricity demand in non-residential buildings is projected to rise from 166 TWh in 2015 to 564 TWh in 2050 [9]. The Middle East and North Africa (MENA) region faces increasing cooling demands, with space cooling energy use growing by 396% from 1990 to 2016 [10]. Also, in the U.S., research indicates that rising temperatures and humidity levels are projected to increase cooling needs by up to 8–15% with 1.5–2.0 °C of global warming [11].

However, the challenge of space cooling is multifaceted. It is not only the increasing temperatures and humidity [12] that pose a problem but also the rising costs of energy. If immediate action is not taken, global energy consumption for cooling is projected to more than double by 2050, putting immense pressure on power grids and increasing greenhouse gas emissions [13].

To address these challenges, cooling solutions can be categorized into passive and active methods, as illustrated in Figure 1. Passive cooling techniques focus on reducing indoor temperatures without the use of mechanical systems. These methods are often integrated into the initial design of buildings and urban landscapes to create naturally cooler environments. These methods, when implemented correctly, can significantly minimize the reliance on active cooling [14–16]. As they do not consume energy during the building lifetime, they should be implemented as the first option. However, sometimes, this is impossible due to existing architecture or other spatial or policy restrictions. Then, active cooling solutions (the right side of the figure) can be implemented. They involve mechanical and technological systems that actively regulate indoor temperatures by removing heat from buildings. These systems typically require electricity or other energy inputs, making them more resource-intensive than passive solutions. However, they provide precise thermal control and are widely used in various climates and building types. Among those, conventional vapor compression refrigeration systems dominate the AC market, due to their long history of development, reliable performance, and widespread availability. These systems, however, depend heavily on electricity and environmentally harmful refrigerants [17]. Alternative technologies, such as absorption and adsorption cooling systems, have been explored but often face challenges such as high costs, complexity, and low efficiency when compared to conventional vapor compressor systems [18].

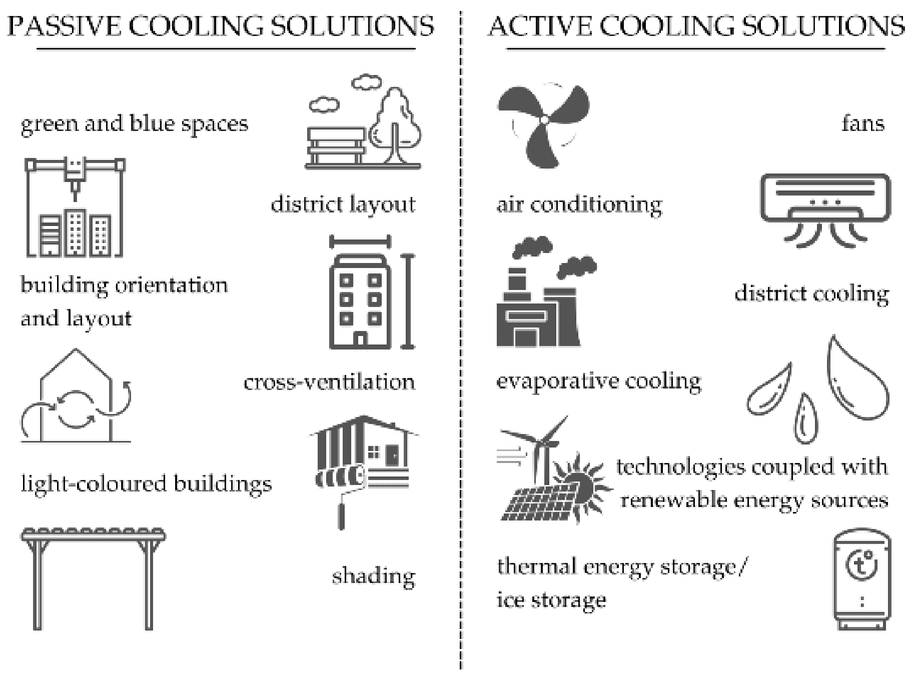


Figure 1. Passive and active cooling solutions examples.

2. Evaporative Cooling Technology

In this context, evaporative cooling (EC) technologies appear as energy-efficient, refrigerant-free alternatives to other mechanical cooling systems. By using the effect of just water evaporation, EC requires up to 80% less electricity than conventional HVAC systems [19].

2.1. Overview

As a principle, EC relies on the latent heat of vaporization. As water evaporates, it absorbs heat from the surrounding air, lowering the temperature. In practice, warm air is passed over a wetted or water-saturated surface, where sensible heat is used in the liquid-to-vapor phase change. This cooling effect is more pronounced under lower humidity conditions.

Consequently, EC systems are more sustainable than traditional vapor compression refrigeration, as they consume less energy, lower greenhouse gas emissions, and avoid high global warming potential refrigerants. Their simple design also reduces both initial capital and maintenance costs, making them suitable for sustainable development, especially in arid regions with access to water.

Integration with renewable energy sources further enhances the environmental benefits. For instance, coupling evaporative coolers with solar-powered fans can create self-sustaining cooling systems [20,21].

Evaporative cooling technologies have demonstrated significant potential for improving energy efficiency in cooling systems compared to traditional vapor compression systems. Studies have shown that evaporative cooling can enhance the energy efficiency ratio (EER) of chillers by up to 63% when using cooling towers and improve the EER of air handling units by 67% with indirect evaporative cooling (IEC) [22]. EC hybrid and multi-stage designs have shown the best performance, reaching coefficient of performance (COP) values as high as 35 [23]. Evaporative-cooled condensers can increase the COP by around 50% and decrease power consumption by up to 20% compared to air-cooled condensers [24]. IEC systems have demonstrated very high COPs in hot, dry, and humid climates, requiring energy only for fans and a small amount of water [25]. Experimental studies have shown that evaporative cooling can increase the COP by up to 44% and decrease power consumption by 20% in split air-conditioning systems [26].

Overall, EC technology is promising. However, it faces challenges in humid environments or where water access is restricted. Still, recent research and development aim to overcome these limitations, potentially increasing IEC's market share in the coming decades and reducing energy consumption and carbon footprint in the building sector [27].

2.2. Fundamentals

Evaporative cooling has been used by people for a long time now [28–30], as the technology is simple and affordable [31]. The progression from direct evaporative cooling (DEC) to indirect evaporative cooling (IEC) is illustrated in Figure 2, highlighting advancements in cooling performance and control over humidity. While DEC reduces air temperature through direct contact between air and water, it results in an increased humidity ratio of the treated air. IEC improves upon this by preventing a humidity increase in the treated air but is constrained by the wet-bulb temperature as the cooling limit. DIEC overcomes these limitations by achieving air temperatures below the wet-bulb temperature, approaching the dewpoint. One of the latest development paths integrates an intermittent water spray system into DIEC to enhance energy and water efficiency, further advancing the sustainability of the technology. The evolution of EC technology with a short description is presented in Figure 2.

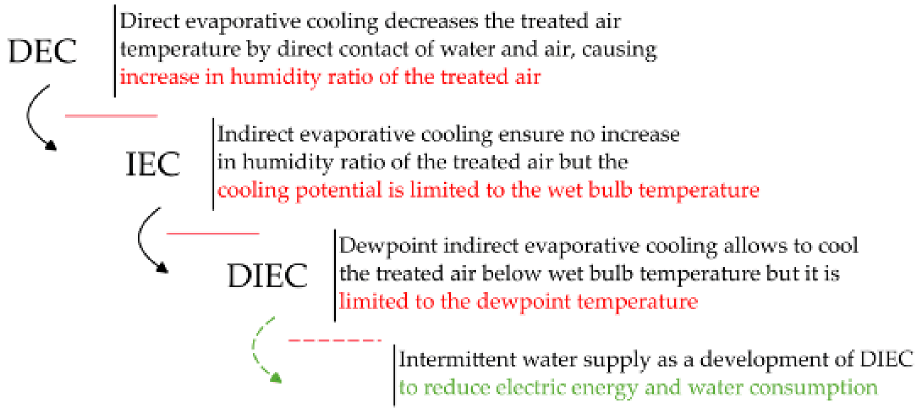


Figure 2. Evolution of evaporative cooling technologies toward DIEC.

In order to clearly state the differences and the limitations that occur in EC, a schematic representation of the device and channel arrangement with a psychometric representation is presented in Figure 3. As a supplement, Table 1 presents a comparison of the system in a condensed way, consisting of crucial aspects in three evaporative cooling technology types.

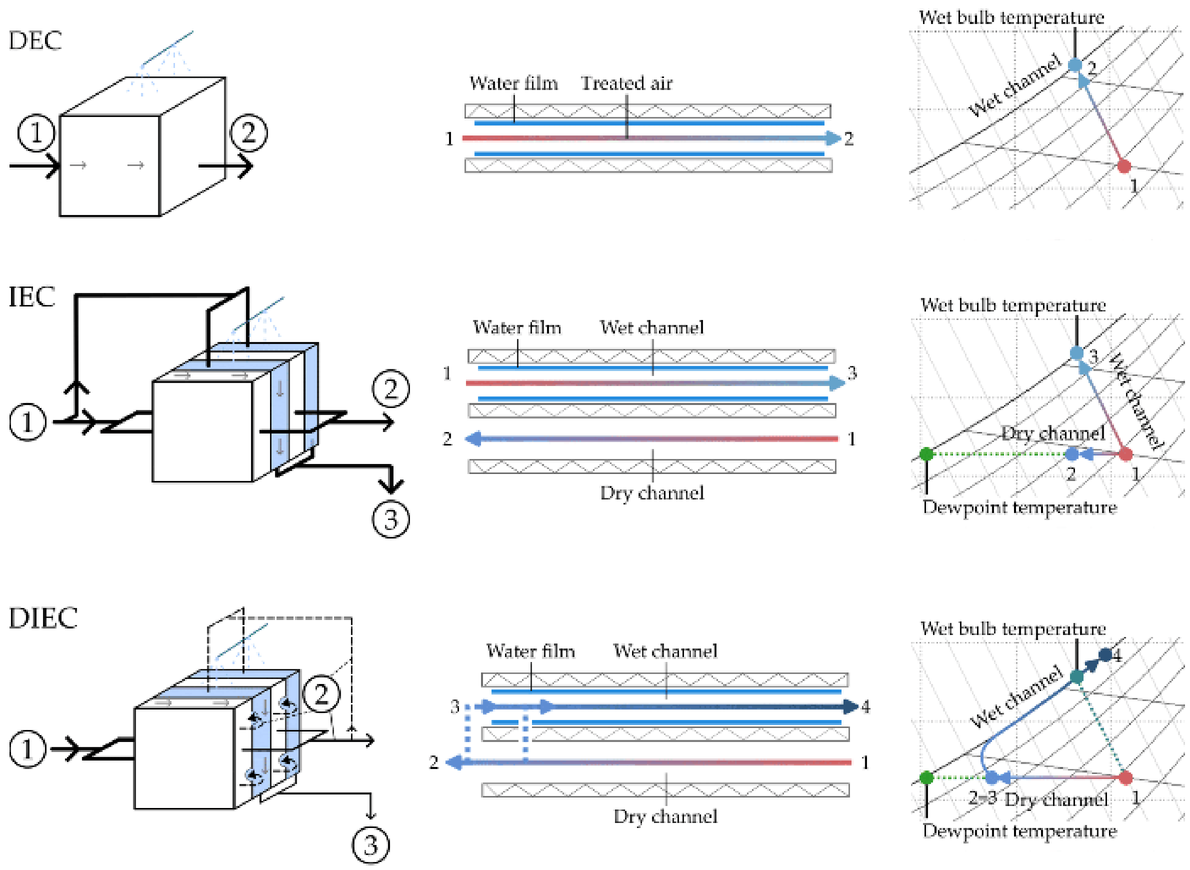


Figure 3. Operational principles and thermodynamic interpretation of DEC, IEC, and DIEC.

Table 1. Performance and efficiency comparison of DEC, IEC, and DIEC.

Parameter	DEC	IEC	DIEC
Process	Untreated air passes over a water film, leading to direct evaporation and cooling.	Air passes through separate dry and wet channels; heat is transferred from the dry channel to the wet channel.	Builds on IEC with part of cooled air returned into wet channels.
Result	Air is cooled but gains humidity, following a constant wet-bulb temperature line.	Air is cooled without increasing humidity.	Achieves cooling below the wet-bulb temperature.
Thermodynamic Limitations	Performance is limited by increased humidity, making it less effective in humid climates.	Separates air streams for humidity control but still limited by wet-bulb temperature.	Partly returned cooled air canlead to approaching the dewpoint temperature limit.
Efficiency and Applicability	Energy-efficient but dependent on ambient humidity; less effective in humid regions [32,33].	More efficient than DEC and suitable for dry climates [34,35].	Highest efficiency; suitable for both dry and humid climates [36].
Typical Components	Fan, wetted surface, and water supply system.	Fan, heat exchanger, and water distribution system.	Fan(s), heat exchanger, and water distribution system.
Advantages	High energy savings, low greenhouse gas emissions, and simple design.	Maintains humidity control; more effective than DEC in dry climates.	Achieves the lowest temperatures; is highly energy-efficient and adaptable to various climates.
Limitations	Increase in treated air humidity ratio.	Cooling limited to wet-bulb temperature.	More complex design.

3. Research Gap and Scope

Recent review articles on the topic of EC have been presented by the authors in Table 2. Only recent reviews have been chosen from last three years. Recent advances in evaporative cooling technologies have been investigated across multiple research domains. Each paper is described with a short summary. Together, these works demonstrate the growing scientific interest in evaporative cooling in many different directions and applications. Hardly any of the recent reviews tackle the water management system or heat exchanger surface modification in a comprehensive way.

Table 2. Recent research reviews on evaporative cooling.

Year	Source	Summary
2025	[37]	Critical review of the thermodynamics and kinetic theories behind liquid–vapor transitions in evaporative cooling, comparing models like Kirchhoff-type and Hertz–Knudsen formulas to improve efficiency and design.
2024	[38]	Comprehensive overview of the current techniques used for evaporative cooling systems for photovoltaic (PV) modules, highlighting their potential to improve the overall performance of PV systems, especially in hot and dry climates.
2024	[19]	Review of advances made in evaporative cooling technologies and their potential as a promising alternative to conventional mechanical cooling systems for providing indoor thermal comfort.

Table 2. *Cont.*

Year	Source	Summary
2024	[36]	Comprehensive review of dewpoint evaporative cooling (DPEC) technology, including its principles, performance improvements, mathematical modeling, and integrated applications in both hot and dry as well as hot and humid regions.
2023	[39]	Conceptual review of evaporative cooling technologies, including their working principles, types, and advantages over conventional HVAC systems in terms of energy efficiency and environmental friendliness.
2023	[40]	Comprehensive review of the current literature on direct evaporative cooling (DEC) systems, focusing on the different approaches adopted to model and predict the performance of these systems.
2022	[41]	Review of the different types of evaporative cooling technologies and their applications in providing energy-efficient and environmentally friendly cooling.
2022	[42]	Comprehensive overview of dewpoint evaporative cooling (DPEC) techniques, including their current applications, limitations, and future research directions to support carbon-neutral development.

3.1. Research Gap

The authors identify the research gap in this section. As presented in Figure 2, the development of EC technology is moving toward IEC and even further to DIEC. As it is the most developed configuration, ideas on further development were presented by the researchers. One of the main methods was to reduce water pump energy consumption, adopting the idea of using porous materials that can store water within the heat exchanger. The results are visible in Table 3, which presents basic data on studies that evaluated intermittent water spraying (coefficient of performance (COP), wet-bulb effectiveness (ε_{wb}), and dewpoint effectiveness (ε_{dp}) are also presented). Only one work investigated intermittent water spraying in a non-porous heat exchanger. As a supplementary but crucial part, the spray time and pause time are presented in Figure 4.

As a principle, intermittent water spraying should be analyzed on regular, non-porous heat exchangers to evaluate the operation of such devices [43].

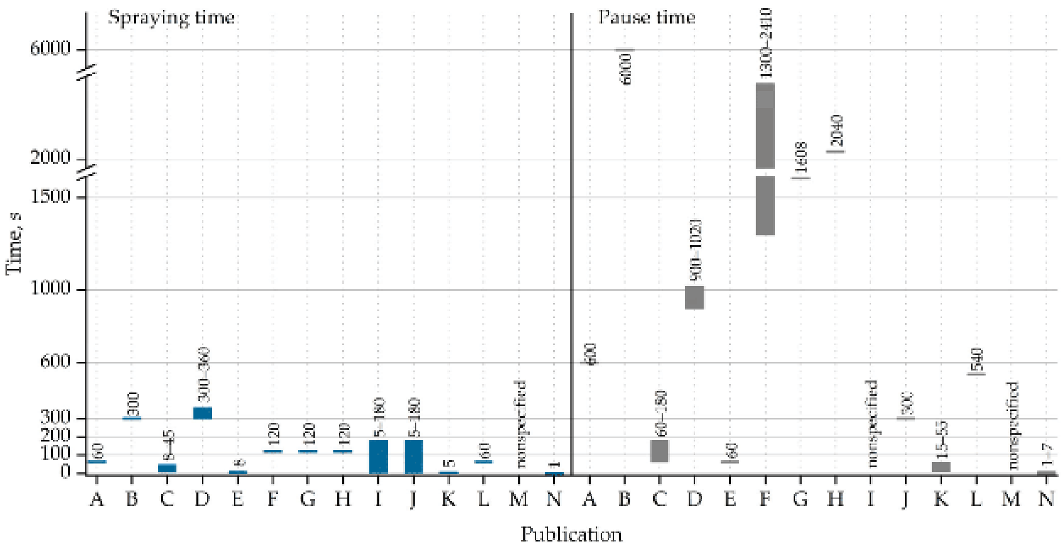


Figure 4. Water system operation intervals for publications: A [44], B [45], C [46], D [47], E [48], F [49], G [50], H [51], I [52], J [53], K [54], L [55], M [56], and N [57].

Table 3. Studies on intermittent water spraying.

Year	Source	Type *	Porous Heat Exchanger Surface	Surface Type	Inlet Air Conditions °C/%	COP	ε_{wb}	ε_{dp}
2017	Xu et al. [44]	E	Yes	Fabric	37.8/21.7	52.5	1.14	0.75
2017	Wang et al. [45]	E	Yes	Ceramics	36.5/21	34.9	0.40–0.42	-
2020	Sun et al. [46]	E	Yes	Ceramics	34–40/53	-	0.76–1.08	-
2021	Elahi et al. [47]	E	Yes	Wood fibers	28–41/30	45.4	0.80	-
2021	Chen et al. [48]	E	Yes	Plant fiber–polymer composite	30.4–38/21–48	-	1.24	0.98
2022	Shi et al. [49]	T/E	Yes	Stainless steel + sintered porous nickel	23, 32/70, 30	146.3	-	0.63
2022	Shi et al. [50]	E	Yes	Stainless steel + sintered porous nickel	26–32/41	17.3	0.68	-
2023	Shi et al. [51]	E	Yes	Stainless steel + sintered porous nickel	24–36/40	22.5	0.63	-
2023	Chen et al. [52]	E	Yes	Fiber fabric	35/40	-	-	-
2023	Chen et al. [53]	E	Yes	TiO_2/SiO_2 nano-coated polypropylene	22/60–64	9.0	-	-
2023	Jin et al. [54]	T/E	No	Fin-plate aluminum	35/45	-	-	-
2024	Chen et al. [55]	E	Yes	TiO_2/SiO_2 nano-coated polypropylene	35/45	-	0.81	-
2024	Khan et al. [56]	E	Yes	SuperKool cellulose cooling pad	31–34/55–75	35.2	0.85	0.80
2024	Shim et al. [57]	E	Yes	Aluminum-layered double hydroxides	30/60	-	-	-

* E—experimental; T—theoretical.

3.2. Scope

Considering the identified research gap, the authors decided to focus on very narrow and yet not described topics. In terms of intermittent water spraying in IEC/DIEC-type devices, the scope must tackle only the heat exchanger material and water supply system. These are the only factors that may affect the possibility of intermittent water spraying applications in non-porous IEC/DIEC devices.

4. Heat Exchanger Surface Modification

An important goal of modifying the surface of wet-side exchanger walls is to ensure an even and thin layer of water film on the entire sprayed surface. In an operating device, a situation may occur when only part of the wall on the wet side is covered with a water film, which limits the surface area from which water evaporates [27,58]. The potential of the evaporative cooling process is thus limited. There cannot be too much water on the walls either. Due to its high specific heat, water becomes an additional insulator in the heat exchange path between the dry and wet channels [59].

A key challenge in the design of these heat exchangers arises when water supply is intermittent. Under such conditions, the ability of the heat exchanger material to absorb and store water becomes important. The selection of materials for constructing these heat exchangers is therefore driven by a range of properties (the most important factors are presented as a graph in Figure 5):

- Wettability—A measure of how easily a liquid spreads over a surface. High wettability ensures even water distribution, which is essential during short water spray cycles.
- Water Storage Capacity—The ability of a material to hold water—often a function of its porosity and capillary structure—which becomes crucial when water is supplied intermittently.
- Application Versatility—Materials may be used as standalone structures or as surface coatings on substrates. Their mechanical strength and adhesion characteristics determine their suitability in either role.

- Bacterial Risk—Extended water retention can lead to biofilm formation and microbial growth. Hence, antibacterial properties or the ability to undergo surface treatments is a significant factor.
- Thermal Performance—The efficiency of heat transfer, which is largely governed by the material's thermal conductivity and surface area, directly impacts cooling performance.

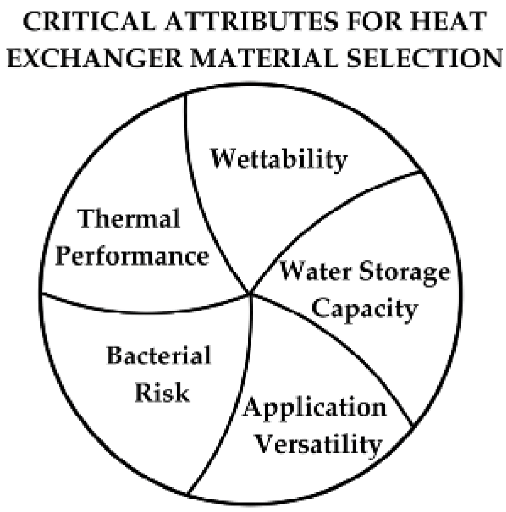


Figure 5. Crucial factors in material selection.

4.1. Wettability

Wettability is an important factor of materials in evaporative cooling systems, with higher wettability generally leading to improved performance [60]. Studies have shown that hydrophilic surfaces, characterized by low contact angles, promote better water spreading and heat transfer [61,62]. Recently, polymeric foam materials have been investigated for evaporative cooling applications [63,64].

The study by Caruana et al. [60] found that surfaces with higher wettability, characterized by lower contact angles, enhance cooling efficiency by promoting uniform water distribution. Among the tested surfaces, the hydrophilic lacquer (HPHI) had the lowest static contact angle (average 69°), followed by the standard epoxy coating (STD) at 75°, and the uncoated aluminum (AL) at 89°.

Further experiments by Caruana et al. [62] showed that the hydrophilic lacquer (HPHI) surface demonstrated the lowest contact angle (median: 50°), confirming its great wettability, while aluminum (AL) and standard epoxy-coated (STD) surfaces had contact angles of 75° and 81°, respectively. The presence of limescale altered wettability, with HPHI and AL showing improved wetting behavior, while STD experienced reduced wettability.

Choi et al. [61] provide more universal and general results. Wettability significantly influences the heat transfer performance of evaporative cooling devices by affecting the contact angle and fluid distribution on surfaces. A lower contact angle, indicating higher wettability, enhances heat transfer by promoting uniform liquid spreading and reducing thermal resistance. Studies show that hydrophilic surfaces improve evaporation rates due to larger heat transfer areas and thinner liquid films, leading to higher cooling efficiency.

The study by Castillo-Gonzalez et al. [64] showed that foam materials produced at a low flow rate exhibit enhanced wettability, which is beneficial for evaporative cooling. Under optimized conditions, the foam demonstrated a static contact angle of about $72° + 3°$, alongside a 250% increase in water absorption and a capillary rise of 120 mm. In contrast, foams processed at higher flow rates had a higher contact angle (approximately

80° ± 4°), lower water uptake, and reduced capillary rise of 90 mm, indicating diminished cooling performance.

When water is supplied intermittently, the time to fully saturate the whole area of the wet channels is relatively short. Therefore, the better the wettability, the greater the chance to fully wet the channel surfaces within a shorter spray time.

4.2. Water Storage Capacity

Porous materials can become a reservoir for water within their microstructure. This stored water can continue to evaporate during the intervals between sprays, thereby maintaining cooling performance [65]. Therefore, it is a crucial factor in terms of a non-constant water supply to the system.

The high water storage capacity of a heat exchanger material examined by Shi et al. [49] shows that a porous indirect evaporative cooler can maintain cooling for a maximum non-spraying duration of 2410 s, reducing water pump operation time by 95.2% compared to continuous spraying. This ability is strictly connected with the water retention capacity of porous media, which allows for intermittent spraying strategies, significantly lowering energy consumption.

A similar approach was presented by Duan et al. [66], where the results show that cellulose/PET fiber achieved the highest permeability-to-effective-pore-radius ratio, increasing its ability to retain and distribute water for prolonged cooling. Moreover, Coolmax and cellulose/PET fibers demonstrated significant water evaporation rates, with cellulose/PET achieving an average evaporation rate of 4.34×10^{-4} kg/($m^2 \cdot s$), contributing to improved cooling efficiency.

A study at a smaller scale is provided by Tang et al. [67]. The study highlights a bilayer structure (BLS) composed of a bottom hydrogel layer and an upper microporous aerogel layer, which significantly enhances water retention. With a 2 mm thick SiO_2 aerogel, the evaporative cooling time span is extended by 11 times compared to a single hydrogel layer, ensuring prolonged cooling even in arid conditions.

Materials with lower porosity may require the addition of surface coatings that improve water absorption. Polymer composites, for instance, can be engineered with embedded hydrophilic particles to enhance their overall water storage ability [68].

Water storage capacity is a crucial factor for intermittent water spraying implementation. The longer a material can store water for evaporation, the shorter the time required for water to be supplied; so, the pump operation time and energy consumption is lower.

4.3. Standalone Materials and Coatings

The design of evaporative cooling systems may call for materials that serve as either the primary structural element or as a functional coating applied to an underlying substrate [69]. Standalone materials such as monolithic porous ceramics are advantageous due to their water retention ability and durability. However, they may be heavier or more brittle compared to metals or composites [70,71]. Wicking metal plates, particularly aluminum, have been identified as suitable for indirect evaporative cooling due to their shape formation ability and durability [72]. Fibrous materials like cellulose/PET fiber and Coolmax fabric have shown promising wicking and evaporation performance, outperforming wood pulp paper [66].

Beside popular materials, new natural materials are investigated. Geopolymers, made from industrial and agricultural waste, have been proposed as green alternatives for evaporative cooling [73]. Those experimental studies on novel organic materials for direct evaporative cooling in hot–dry climates have revealed eucalyptus fibers and ceramic pipes as the most effective, with cooling effectiveness ranging from 72 to 33% and from 68 to

26%, respectively, at air velocities between 0.1 and 1.2 m/s. Yellow stone also showed competitive performance, while dry bulrush basket and Cyprus marble exhibited relatively poor results [74].

In contrast, coatings—for example, hydrophilic layers on aluminum fins—offer flexibility by combining the high thermal conductivity of metals with the favorable surface properties of advanced coatings [75]. The key challenges in coating applications are ensuring robust adhesion under cyclic wetting/drying conditions and maintaining long-term stability without degradation of wettability or water storage capability.

Hydrophilic coatings, such as TiO_2 and graphene, have been shown to improve the efficiency and coefficient of performance of indirect evaporative coolers. The study by You et al. [76] compared hydrophilic coatings applied to an IEC system. Their esults showed that the TiO_2-coated IEC improved enthalpy efficiency by 5.33%, wet-bulb efficiency by 9.91%, and the COP by 3.22 compared to uncoated surfaces. The graphene-coated IEC increased the performance even more, with enthalpy efficiency increasing by 14.75%, wet-bulb efficiency by 12.07%, and the COP by 7.69 compared to the uncoated IEC.

Another study provides results of more advanced coating applications. Fathi et al. [77] investigated the effects of a dual-scale hierarchically porous aluminum coating (AL-HPC), created by brazing aluminum powders of different particle sizes onto a flat aluminum plate. Their experimental results showed that coated surfaces exhibit superior wickability compared to plain aluminum, with larger particle sizes (114 μm) achieving a 60% higher wicking height than smaller ones (27 μm). The coating also significantly increases the dryout heat flux, with the 114 μm particle size achieving 8.1 kW/m^2—3.4 times higher than that of the smallest particle size tested. Additionally, coating thickness plays a critical role, with the thickest coating (1200 μm) achieving a dryout heat flux of 10.6 kW/m^2 and a maximum heat transfer coefficient of 251 W/m^{2}K, 13 times higher than that of a plain surface.

For intermittent water spraying, there is no significant difference regardless of whether the material is standalone or coated (in terms of heat exchanger construction). The important part is that it can store water for a certain amount of time. Thus, it opens the possibility for further development and investigation into materials for intermittent water spraying.

4.4. Microbial Risk

The topic of microbial risk in EC is not discussed widely and is mainly connected with Legionella [78,79] and rarely with, for example, fungi [80,81]. Thus, this section is mainly based on previous work by the authors that elaborated on all kinds of microbial risk in EC [82].

The selection of heat exchanger materials in evaporative cooling systems is crucial due to the risk of biofilm formation, which can significantly impact both efficiency and hygiene. Biofilms, composed of bacteria, fungi, and other microorganisms, can develop on heat exchanger surfaces when water is constantly present. These biofilms pose potential health risks, especially in systems where air and water interact, leading to indoor air contamination [83–85]. Despite the fact that porous and hydrophilic surfaces are beneficial for water retention and distribution, they can at the same time cause microbial colonization if proper maintenance is neglected.

The hydrophobic and superhydrophilic coatings discussed earlier can become potential solutions for controlling water behavior on heat exchanger surfaces. Superhydrophilic coatings allow water to spread evenly, forming a thin film that enhances evaporation and prevents localized stagnation, thereby reducing microbial growth [85]. On the other hand, hydrophobic surfaces repel water, limiting moisture retention and making it difficult for biofilms to establish.

However, any material needs to be discussed in terms of microbial risk. The selection of materials for heat exchangers must balance factors such as water resistance, structural rigidity, and microbial safety. Many EC systems utilize plastics due to their cost-effectiveness and durability, though they must be carefully engineered to support effective water evaporation. Still, bacterial adhesion remains a concern, particularly for textile-based surfaces where the interaction between hydrophilic and hydrophobic fibers is still debated. Research suggests that both superhydrophilic and superhydrophobic surfaces reduce bacterial attachment, whereas moderately hydrophobic materials exhibit the highest microbial adhesion.

In terms of intermittent water spraying, it can be concluded that a lack of standing water and thick water films should improve safety. Still, proper maintenance is needed.

4.5. Discussion and Summary

Overall, the literature indicates that an integrated approach—where material selection is closely aligned with operational strategies (such as water spray timing and flow rates)—can lead to significant improvements in evaporative cooling performance. Future work should continue to refine these materials, focusing on advanced surface treatments and composite formulations that can meet the dual demands of high thermal performance and effective water management under intermittent supply conditions.

For ease of use, the above details are summarized and presented in Table 4.

Table 4. Summary of material types.

Material Type	Wettability	Water Storage Capacity	Standalone/Coating	Bacterial Risk
Porous Ceramics	High wettability (contact angles typically < 20°)	High porosity (pore volume often in the 40–70% range)	Often used as standalone elements	Moderate risk; may require antibacterial treatments
Metal Foams/Perforated Metals	Moderate to high (may need surface modification for optimal wettability)	Moderate water storage due to engineered pore structure	Can serve as both standalone and substrate for coatings	Lower risk due to smoother surfaces; still requires monitoring
Polymer Composites	Variable; often improved via incorporation of hydrophilic fillers	Typically lower than ceramics; can be enhanced with additives	Commonly used as coatings or integrated in composite panels	Risk depends on formulation; additives can reduce biofilm formation
Hybrid/Coated Systems	Designed for high wettability; surface treatments lower contact angles significantly	Dependent on the coating's porosity and structure; tailored for water retention	Primarily used as coatings on thermally conductive substrates	Formulated to minimize bacterial adhesion through biocidal additives

5. Water Supply System

In this paragraph, the authors focus on advancements in water spraying systems for indirect evaporative coolers (IECs), emphasizing design parameters that optimize cooling performance while balancing energy and water consumption. The goal of this section is to provide a comprehensive understanding of how water spraying systems can be optimized to enhance cooling performance while minimizing energy and water consumption. The basic water spraying system division and critical factors are presented in Figure 6.

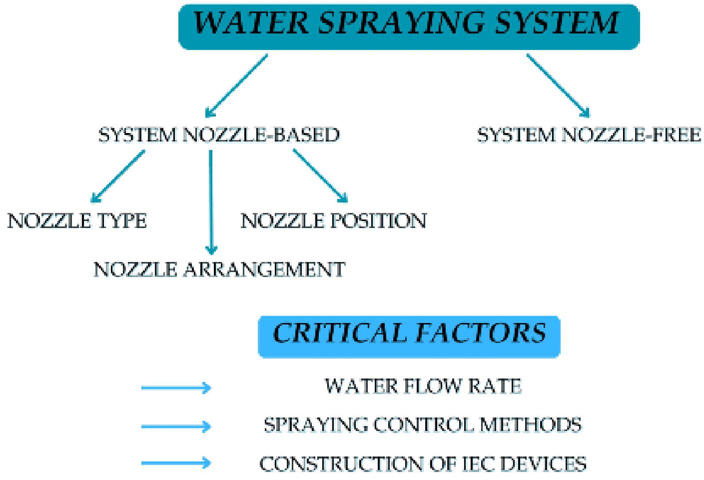


Figure 6. Division of the water spraying systems and their crucial factors.

5.1. *Nozzle-Based Systems*

Nozzle-based water spraying systems are widely used in IECs to enhance cooling efficiency. These systems rely on nozzles to atomize water into fine droplets, which are then distributed over the heat exchanger surface. The primary function of nozzles is to create a uniform water film on the heat exchanger surface, ensuring efficient heat and mass transfer.

Research has focused on optimizing nozzle types, arrangements, and spray strategies to improve water distribution and overall performance. Spiral nozzles have shown superior coverage and uniformity [46], while optimal nozzle arrangements can increase system COP by up to 16% [86]. CFD simulations have revealed that top-side nozzle configurations paired with air–water counter-flow can significantly improve water film coverage and temperature drop [87]. Additionally, hydrophilic and fiber coatings can further enhance water film coverage and the COP [87]. However, modeling IEC systems remains challenging due to the complexity of boundary conditions and operating parameters, such as nozzle orientations and water flow rates [88]. Despite these challenges, nozzle-based systems continue to be the most common water spraying method in IECs due to their effectiveness and potential for optimization.

As nozzles are an important factor affecting the overall performance of the device, they are described in depth in the following sections.

5.1.1. Nozzle Type

A study by Sun et al. [46] experimentally evaluated five common spray nozzles: spiral, conical, square, sector, and target impact types. The target impact nozzle provides the highest coverage (89.2%) and best uniformity but delivers too little water volume, making it unsuitable for IEC applications, though effective for spray chambers requiring fine droplets. The spiral nozzle offers the second-best coverage (78.4%) and uniformity (1.35), with a balanced water distribution, making it the most suitable choice for IEC applications. Conical and sector nozzles have the lowest coverage and uniformity, while the square nozzle performs moderately with a 68.4% coverage ratio. Yang et al. [89] provided a study on a gas–liquid two-phase swirling atomizing nozzle that uses bubble cutting technology to produce micron-sized, evenly distributed droplets with a stable spray at 0.2–0.6 MPa and a liquid flow rate of 2–8 kg/h. It features a simple, easy-to-clean threaded design, interchangeable nozzle styles, and low energy consumption (7.59 W/kg), making it highly efficient for spray cooling applications. Generalized nozzle-type characteristics are presented in Table 5.

Table 5. Nozzle-type characteristics.

Nozzle Type	Coverage Ratio	Uniformity	Water Consumption	Remarks
Gas–Liquid Two-Phase Swirling Atomizing	-	-	Low	High atomization quality even with small water flow
Target Impact	High	High	High	Best performance, high water use
Spiral	Medium	Medium	Medium	Optimal balance
Square	Medium	Medium	Medium	Moderate performance
Conical	Low	Low	Low	Less efficient
Sector	Low	Low	Low	Least efficient

5.1.2. Nozzle Position

Nozzle placement can be categorized based on the mounting capability as upper, middle, or lower configurations. The upper configuration, suitable for most IEC setups, generates counter-flow water streams against secondary airflow (when air is blown upward). The middle configuration, though challenging to install, provides effective water distribution across large exchanger blocks. The lower configuration, ideal for space-constrained installations, produces concurrent water streams aligned with secondary airflow [28]. Most studies spray water into wet channels using top-mounted nozzles [43,90]. Experiments with top-mounted nozzles and downward airflow demonstrated higher wet-bulb effectiveness in counter-flow configurations [91]. Other researchers confirm that secondary airflow and water spray should generally oppose each other [92]. A general division of nozzle position is presented in Figure 7.

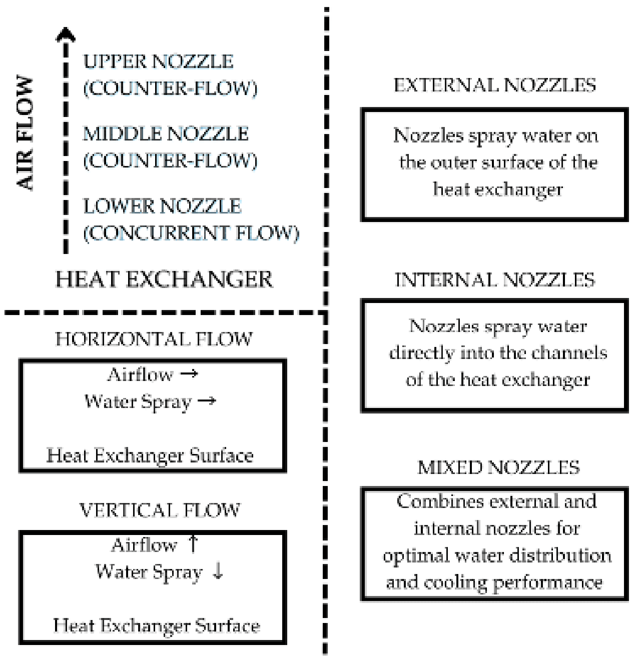


Figure 7. Spray nozzle position (arrows show the direction of the water and air flow).

A study by Al-Zubaydi and Hong [93] evaluated the impact of three different water spraying modes—external, internal, and mixed—on the performance of an IEC system.

The mixed spraying mode was better than the other two, achieving a maximum wet-bulb efficiency of 76%, compared to 72.9% for the internal mode and 70% for the external mode. The cooling capacity was also highest in the mixed mode, reaching 1.8 kW at an inlet temperature of 37.2 °C, while the internal and external modes achieved 1.59 kW and 1.4 kW, respectively. The coefficient of performance (COP) followed a similar trend, with the mixed mode reaching a peak COP of 17.9, which is higher than the internal (15.5) and external (14.25) modes. Additionally, at lower primary air velocities, the temperature drop was more significant, improving cooling effectiveness. Increasing secondary air velocity enhanced the system's overall performance, leading to an 11% increase in COP in the mixed mode. The study concluded that optimizing water spraying configurations, particularly using a mixed mode, can significantly enhance IEC performance.

The study by Yang et al. [89] analyzed the effect of a spray evaporative cooling system on the performance of an air-cooled chiller, comparing horizontal and vertical spray modes. The results showed that applying the spray system increased the coefficient of performance (COP) by 3.78–8.33%, with the highest improvement observed at a water flow rate of 20 kg/h. Vertical spraying was more effective than horizontal spraying, with a COP increase of 0.28–1.94 due to better evaporation and greater air cooling efficiency. At an ambient temperature of 40 °C, the COP increase ranged from 6% to 9%, while at 25 °C, the increase was only around 2%, indicating that the system is more beneficial in hotter climates. Total electricity consumption was reduced by 2.37–13.53%, demonstrating significant energy savings. The optimized spray system, using gas–liquid two-phase swirl nozzles, achieved high atomization quality with minimal power consumption of 7.59 W/kg. The study suggests that adjusting spray water flow rates based on cooling capacity can further enhance performance and prevent water waste.

Ma et al. [87] analyzed the effect of different nozzle configurations on the performance of an indirect evaporative cooler (IEC) using CFD modeling. The best performance was observed with the top-side nozzle arrangement and counter-flow air–water configuration, achieving a 59.2% increase in water film coverage and a 27.4% temperature drop compared to the bottom configuration at a water supply rate of 65 L/s. The study also found that further increasing the water flow rate beyond 65 L/s did not provide any gains, primarily increasing pump power consumption.

Nozzle placement plays a crucial role in the performance of evaporative cooling systems, with top-mounted and counter-flow configurations generally providing the best efficiency. Studies indicate that mixed spraying modes and vertical spray patterns enhance cooling effectiveness, energy savings, and overall system performance. Optimizing nozzle arrangements improves water distribution and heat transfer.

5.1.3. Nozzle Arrangement

Ma et al. [86] examined an IEC with a 400 × 400 mm spray area and 330 mm nozzle height. For single-nozzle setups, a 45° spray cone angle and 30° inclination angle were optimal. The best performance was achieved with a centerline nozzle arrangement spaced 160 mm apart, which improved spray uniformity to a coefficient of 0.74 and increased the coverage ratio to 0.72. Compared to the original single-line nozzle setup, this optimized arrangement enhanced surface wettability, raising the wettability factor from 0.48 to 0.89. As a result, the optimized IEC design achieved a 16% increase in the coefficient of performance (COP) and improved cooling efficiency. The temperature drop of the primary air was greater in the optimized setup, reaching 26.1 °C compared to 27.4 °C in the original design. Additionally, energy efficiency improved due to better water distribution, leading to reduced overall power consumption.

Another study by De Antonellis [91] found that a four-nozzle configuration slightly outperformed an eight-nozzle setup, as it reduced water droplet collisions with exchanger walls. The conclusion drawn from the experiments indicate that it is the water flow that has the strongest impact and not the type and number of nozzles.

Still, there are a limited number of experiments that evaluate nozzle arrangement in evaporative cooling. Those which are presented differ in results. Thus, it is difficult to state what impact nozzle arrangement has on performance.

5.2. Nozzle-Free Systems

Systems without nozzles rely on passive mechanisms such as capillary action or gravity to distribute water over the heat exchanger surface. These systems are gaining popularity due to their simplicity and lower energy requirements. In nozzle-free systems, water is distributed through porous materials or gravity-fed channels, eliminating the need for pumps and nozzles. Nozzle-free systems are highly efficient in water use, making them suitable for arid regions; also, no pumps or nozzles are required, reducing energy use. These systems are simpler to design and maintain.

5.2.1. Wicking Systems

Wicking systems use porous membranes to transport water via capillary pressure. For example, Zhou et al. [94] examined the effect of using a porous membrane for water transport via capillary pressure in a dewpoint evaporative cooling device. The membrane's automatic wicking capability ensured uniform water distribution, eliminating the need for pumps and reducing energy consumption. The system achieved a maximum temperature drop of 14.8 °C, with cooling capacities ranging from 13 to 150 W/m^2 under optimal conditions. Higher air velocities (0.5–2.5 m/s) led to a 3.1 °C rise in product air temperature, reducing wet-bulb and dewpoint efficiencies by 25.1% and 17.5%, respectively. Therefore, it can be stated that a system without nozzles reacts similarly at higher air velocities as a system with nozzles. The study found that the best performance occurred in high-temperature, low-humidity environments, with an optimal air-to-water volume ratio of 0.5. Long-term tests confirmed the system's stability, with product air temperature fluctuations limited to 0.6 °C. This design reduces water consumption by 50% compared to nozzle-based systems, making it ideal for water-scarce regions. These findings suggest that automatic wicking membranes can enhance cooling efficiency while minimizing energy use.

The study by Duan et al. [66] provides data on different materials used in wicking and evaporation performance testing. Among the tested materials, cellulose/PET fiber exhibited the highest permeability and capillary rise, ensuring efficient water distribution. Coolmax fabric demonstrated similar high evaporation rates, outperforming wood pulp paper in water transport efficiency. The study found that wicking performance is primarily influenced by the permeability-to-effective pore radius ratio, with cellulose/PET fiber showing the best results. Experimental validation confirmed that water evaporation rates increase with surface temperature and airflow velocity, improving cooling efficiency. The optimized wicking system maintained stable water distribution, reducing evaporation resistance and enhancing mass transfer.

Guo et al. [95] investigated the impact of wicking systems on water transport and evaporation performance in thin porous media using Dutch Twill Weave (DTW) screens. Experimental results showed that the evaporative wicking process significantly influences heat and mass transfer, with the temperature drop caused by evaporation improving cooling efficiency. The study found that evaporative cooling reduces liquid viscosity and alters evaporation rates, affecting wicking height and thermal performance. Ignoring the evaporative cooling effect led to an overestimation of wicking height by up to 12%

and an underestimation of evaporation rate by 14%. The results emphasize the need to consider local thermal non-equilibrium effects when designing efficient wicking-based cooling systems.

Another investigation by Abada et al. [96] evaluated the impact of wicking systems on water transport and evaporative cooling performance in different fabric materials. Fabrics with high capillary rise, such as fiber-based textiles, demonstrated superior moisture-wicking ability, improving water distribution and evaporation efficiency. Compared to Kraft paper, the best performing fabrics showed 160% to 355% higher absorbency, leading to enhanced cooling effects. The vertical wicking height of certain fabrics reached up to 27.8 cm within 120 min, ensuring continuous moisture supply to the evaporative surface. Faster moisture diffusion rates prevented dry spots, while optimized evaporation properties enhanced cooling capacity. The study concluded that fiber fabrics with high capillary action and diffusion properties are ideal for evaporative cooling systems.

5.2.2. Gravity-Fed Systems

Gravity-fed systems are based on water stored in an upper reservoir and dripped into distributors which evenly spread the water across the heat exchanger surface. The study by Duan et al. [97] examined the performance of a counter-flow regenerative evaporative cooler using a gravity-based water transport system. The results showed that wet-bulb effectiveness ranged from 0.55 to 1.06, while the energy efficiency ratio (EER) varied between 2.8 and 15.5. Water evaporation rate was found to accelerate with higher inlet air velocity, improving overall cooling efficiency. Feed water temperature had a negligible impact, with effectiveness decreasing by only 5% when the temperature increased from 18.9 °C to 23.1 °C. As a water pump in this system is used just to transport water to the upper reservoir, energy consumption is significantly lowered.

5.3. *Water Flow Rate*

During water system design, the water flow rate is the first parameter to consider, as IEC performance depends primarily on flow rate and only marginally on nozzle number and size [91]. A higher water flow increases the wetted heat exchanger area. This leads to a larger amount of evaporated water and to a higher cooling capacity [98]. Similar results were presented by Sun et al. [46], where the coverage ratio improved with increased water flow, regardless of the types of nozzles.

The relation between coverage ratio and water flow is more important at lower flow rates [46]. IEC performance is particularly sensitive to water flow rate variations at low flow rates [98]. For example, heat exchangers coated with a novel hydrophilic lacquer demonstrated higher wet-bulb effectiveness compared to those with standard epoxy coatings, especially at low flow rates [99].

These results suggest that increasing water flow improves cooling performance up to a point. Beyond, further increases do not significantly enhance cooling capacity and may lead to unnecessary energy consumption by the water pump (if present in the system).

In terms of non-constant water spraying, the water flow must also be adjusted to the inlet air parameters, device construction, and the desired result.

5.4. *Spraying Control Methods*

Water can be supplied to the system in a continuous, intermittent, or adaptive way. Continuous spraying is the most popular as it does not require any control system. The water is supplied during operation with the set flow rate. In the case of intermittent water spraying, the topic is presented in Figure 4. The operation of the water system is cyclic and there is a set time for spraying and pausing. In the other case, the next spraying cycle can be triggered by a predefined temperature threshold (e.g., +0.5 °C) [49,51]. This can become an adaptive method for spraying the heat exchanger using real-time feedback from the device. A general division is described in Table 6.

Table 6. Division of spraying control methods.

Method	Description	Advantages	Limitations
Continuous	Uninterrupted water spray.	Stable cooling output.	High water/pump energy use.
Intermittent	Cyclic operation (spraying time and pause time).	Reduces water use.	Complex control systems required.
Adaptive	Control based on real-time humidity/temperature feedback.	Optimizes water–energy trade-offs.	Requires advanced sensors/software.

In summary, non-constant water spraying should be further investigated as a promising way to reduce energy and water consumption and to increase the overall performance of evaporative cooling devices.

5.5. Other Considerations

Techniques like rolling dot matrix twills, groove lines, or supplementary water distribution grids enhance water retention [28]. In order to supply water of required quality, water softeners are proposed to prevent scale buildup in long-term spray systems [89]. Water sources used for spraying can be connected to tap water [89] but also to some alternatives like condensed water from existing air handling units, which can result in additional water savings [100]. Khalid et al. [101] tested ice-cooled feed water and found that wet-bulb and dewpoint effectiveness decreased by less than 5% as water temperature rose from 20 °C to 24 °C. Consequently, it can be stated that feed water temperature minimally impacts wet-bulb or dewpoint effectiveness [97]. While evaporative cooling relies on significant amounts of water [102], regional water scarcity and local legislation may limit its adoption [28], especially in terms of the impact of climate change on water supply systems [103,104]. However, there is a promising way to gather rainwater [105,106] that can be used in EC systems [107,108].

Table 7 compares factors like water use, energy use, carbon footprint, and water scarcity impact between IEC systems and traditional HVAC [28,100,102].

Table 7. Comparison of IEC systems and traditional HVAC.

Factor	IEC Systems	Traditional HVAC
Water Use	Medium to High	Low
Energy Use	Low	High
Carbon Footprint	Low	High
Water Scarcity Impact	High in Arid Regions	Low

6. Future Directions

- Optimization of intermittent spraying in non-porous heat exchangers. Although research has started exploring intermittent water spraying, most investigations have focused on porous heat exchangers (Figure 4). Future work should (a) evaluate the dynamic behavior of intermittent spraying on non-porous surfaces, (b) optimize spray–pause cycles under various ambient and operational conditions, and (c) compare performance metrics—such as COP and wet-bulb effectiveness—with those in porous configurations. This will help validate if minor modifications in the water supply strategy can yield significant energy savings without replacement of the heat exchanger.

- Integration with advanced material and coating technologies. The earlier sections highlighted the importance of surface wettability and water storage capacity in maintaining an effective water film (as discussed in Section 4). Further research is needed to (a) develop and test novel materials or coatings that combine high wettability with prolonged water retention, (b) ensure long-term stability under intermittent spray conditions, and (c) mitigate microbial risks through surface treatments. These studies should provide evidence and data to create heat exchangers that can sustain efficient cooling during the spray-off intervals.
- Adaptive control strategies based on real-time feedback. As discussed in Section 5.4, adaptive water spraying modes offer promising avenues for optimizing energy and water consumption. Future research should (a) refine sensor-based control systems that dynamically adjust spraying cycles in response to real-time temperature and humidity changes, (b) simulate the relation between adaptive strategies and different heat exchanger geometries, and (c) validate these models in full-scale systems. This approach will integrate the operational strategies with material performance, ensuring that the cooling system responds to varying environmental conditions.
- Utilization of alternative water sources and sustainable energy integration. In light of the discussions in Section 5.5 about the environmental impacts and challenges related to water scarcity, future research should (a) assess the feasibility and performance implications of using alternative water sources such as rainwater or reclaimed water, and (b) explore the integration of renewable energy—such as solar power—to sustainably run water pumps and control systems. This research direction will align the technological advancements with broader sustainability goals.

In summary, researchers have made good progress in making evaporative cooling systems more efficient and environmentally friendly, but there is still a lot of potential for further improvement. By focusing on smarter water spraying, better materials, and renewable energy, the next generation of cooling systems can save even more energy and water. This will not only help meet the growing need for effective cooling solutions but will also support wider efforts to reduce energy use and protect our water resources.

7. Conclusions

This review examines indirect evaporative cooling systems, especially when they use intermittent water spraying instead of a constant flow. The findings show that using water in short timed intervals can save both energy and water while keeping the cooling effective. This method helps reduce the amount of time the water pump needs to run, which cuts down on power use. For instance, studies have shown that intermittent spraying can reduce water pump operation time by up to 95.2% compared to continuous spraying while maintaining cooling efficiency.

The heat exchanger material has a great impact on overall performance. Materials that easily spread water and hold onto it help form a thin, even layer of water on the surface. This thin film is key to making the cooling process work well. Studies indicate that hydrophilic coatings, such as TiO_2 and graphene, improve wet-bulb efficiency by 9.91% and 12.07%, respectively, while enhancing the coefficient of performance (COP) by up to 7.69%. If these materials can keep water for longer period of time, the cooling effect lasts even during the off periods when the spray stops. For example, porous heat exchanger materials allow for extended non-spraying durations of up to 2410 s, further optimizing cooling performance.

Another important point is the need to balance good cooling with keeping the system clean. While a very wet surface can improve cooling, it can also encourage the growth of bacteria if the system is not properly maintained. Coatings that help stop bacteria from sticking to the surface could be a solution.

The way water is sprayed also has a big impact. Whether the system uses traditional nozzles, gravity-fed water, or materials that pull water along by themselves, each method affects how evenly the water is spread and how well the system cools. Well-designed spray patterns can help drop the air temperature faster and make the system work more efficiently, while some alternative methods may use even less energy. Studies have shown that using optimized nozzle configurations can increase system COP by up to 16%.

The most important finding considers water use. Implementing intermittent water spraying can lower water consumption. This is a promising affordable cooling technology that will not use excess water in regions with water scarcity.

Overall, this review shows that although current evaporative cooling systems are already more eco-friendly alternatives to traditional air conditioning, there is still great potential for improvement. By combining smart, timed water spraying with improved heat exchanger materials, these systems can become even more efficient and cost-effective.

Author Contributions: Conceptualization, Ł.S., A.G., J.W., K.R., and J.D.; investigation, Ł.S., A.G., and J.W.; writing—original draft preparation, Ł.S., A.G., J.W., K.R., W.J., M.W., and W.Ż.; writing—review and editing, Ł.S., A.G., J.W., K.R., and J.D.; visualization, Ł.S. and A.G.; supervision, K.R. and J.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AC	Air Conditioning
AL	Aluminum
BLS	Bilayer Structure
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DEC	Direct Evaporative Cooling
DIEC	Dewpoint Indirect Evaporative Cooling
DTW	Dutch Twill Weave
EC	Evaporative Cooling
EER	Energy Efficiency Ratio
HPC	Hierarchically Porous Coating
HPHI	Hydrophilic Lacquer
HVAC	Heating, Ventilation, and Air Conditioning
IEC	Indirect Evaporative Cooling
MENA	Middle East and North Africa
PET	Polyethylene Terephthalate
STD	Standard Epoxy Coating

References

1. Lundgren, K.; Kjellstrom, T. Sustainability Challenges from Climate Change and Air Conditioning Use in Urban Areas. *Sustainability* **2013**, *5*, 3116–3128. [CrossRef]
2. Roaf, S.; Nicol, F.; Humphreys, M.; Tuohy, P.; Boerstra, A. Twentieth Century Standards for Thermal Comfort: Promoting High Energy Buildings. *Arch. Sci. Rev.* **2010**, *53*, 65–77. [CrossRef]

3. De Cian, E.; Falchetta, G.; Pavanello, F.; Sue Wing, I.; Romitti, Y. The Impact of Air-Conditioning on Residential Electricity Demand across World Countries. *SSRN Electron. J.* **2023**, *131*. [CrossRef]
4. Park, W.Y.; Shah, N.; Ding, C.; Qu, Y. *Challenges and Recommended Policies for Simultaneous Global Implementation of Low-GWP Refrigerants and High Efficiency in Room Air Conditioners*; Barkeley Lab: Berkeley, CA, USA, 2019. [CrossRef]
5. Davis, L.W.; Gertler, P.J. Contribution of Air Conditioning Adoption to Future Energy Use under Global Warming. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 5962–5967. [CrossRef] [PubMed]
6. Al-Yasiri, Q.; Géczi, G. Global Warming Potential: Causes and Consequences. *Acad. Lett.* **2021**, *3202*, 1–10. [CrossRef]
7. Taipale, K. From Light Green to Sustainable Buildings. In *State of the World 2012: Moving Toward Sustainable Prosperity*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 129–136. [CrossRef]
8. Simpeh, E.K.; Pillay, J.P.G.; Ndihokubwayo, R.; Nalumu, D.J. Improving Energy Efficiency of HVAC Systems in Buildings: A Review of Best Practices. *Int. J. Build. Pathol. Adapt.* **2022**, *40*, 165–182. [CrossRef]
9. Wang, X.; Purohit, P. Transitioning to Low-GWP Alternatives with Enhanced Energy Efficiency in Cooling Non-Residential Buildings of China. *Mitig. Adapt. Strateg. Glob. Change* **2022**, *27*, 1–28. [CrossRef]
10. Kalbasi, R.; Tahmasebi, A.; Ghaderi, M.; Yari, M.; Izadi, F. Toward Sustainable Energy-Based Buildings with Focusing on Electricity Demand Reduction—Case Studies in Middle East Region Climate. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102294. [CrossRef]
11. Obringer, R.; Nateghi, R.; Maia-Silva, D.; Mukherjee, S.; Vineeth, C.R.; McRoberts, D.B.; Kumar, R. Implications of Increasing Household Air Conditioning Use Across the United States Under a Warming Climate. *Earths Future* **2022**, *10*, e2021EF002434. [CrossRef]
12. Maia-Silva, D.; Kumar, R.; Nateghi, R. The Critical Role of Humidity in Modeling Summer Electricity Demand across the United States. *Nat. Commun.* **2020**, *11*, 1686. [CrossRef]
13. IEA. *Space Cooling Net Zero Emissions Guide*; IEA: Paris, France, 2023.
14. ESMAP. *Primer for Space Cooling*; World Bank: Washington, DC, USA, 2020.
15. Chetan, V.; Nagaraj, K.; Kulkarni, P.S.; Modi, S.K.; Kempaiah, U.N. Review of Passive Cooling Methods for Buildings. *J. Phys. Conf. Ser.* **2020**, *1473*, 012054. [CrossRef]
16. Elnagar, E.; Pezzutto, S.; Duplessis, B.; Fontenaille, T.; Lemort, V. A Comprehensive Scouting of Space Cooling Technologies in Europe: Key Characteristics and Development Trends. *Renew. Sustain. Energy Rev.* **2023**, *186*, 113636. [CrossRef]
17. Szczęśniak, S.; Stefaniak, Ł. Global Warming Potential of New Gaseous Refrigerants Used in Chillers in HVAC Systems. *Energies* **2022**, *15*, 5999. [CrossRef]
18. Pezzutto, S.; Quaglini, G.; Riviere, P.; Kranzl, L.; Novelli, A.; Zambito, A.; Wilczynski, E. Screening of Cooling Technologies in Europe: Alternatives to Vapour Compression and Possible Market Developments. *Sustainability* **2022**, *14*, 2971. [CrossRef]
19. Ishugah, T.F.; Kiplagat, J.; Madete, J.; Musango, J. Current Status, Challenges, and Opportunities of Evaporative Cooling for Building Indoor Thermal Comfort Using Water as a Refrigerant: A Review. *Int. J. Energy Res.* **2024**, *2024*, 1026136. [CrossRef]
20. Xue, T.; Wan, Y.; Huang, Z.; Chen, P.; Lin, J.; Chen, W.; Liu, H. A Comprehensive Review of the Applications of Hybrid Evaporative Cooling and Solar Energy Source Systems. *Sustainability* **2023**, *15*, 16907. [CrossRef]
21. Rasheed, S.; Ali, M.; Ali, H.; Sheikh, N. Experimental Analysis of the Dew Point Indirect Evaporative Cooler Operating with Solar Panels. *Eng. Proc.* **2022**, *12*, 90. [CrossRef]
22. Afonicevs, V.; Strauts, U.; Bogdanovs, N.; Lesinskis, A. Evaporative Cooling Technology Efficiency Compared to Traditional Cooling System-Case Study. *Eng. Rural Dev.* **2020**. [CrossRef]
23. Haile, M.G.; Garay-Martinez, R.; Macarulla, A.M. Review of Evaporative Cooling Systems for Buildings in Hot and Dry Climates. *Buildings* **2024**, *14*, 3504. [CrossRef]
24. Sharma, K.; Gupta, R.L.; Katarey, S. Performance Improvement of Air Conditioning System Using Applications of Evaporative Cooling: A Review Paper. *Int. J. Therm. Eng.* **2019**, *2*, 1–5. [CrossRef]
25. John Dartnall, W.; Revel, A.; Giotis, V. Air-Conditioning Employing Indirect Evaporative Cooling Can Be Shown to Derive Its Energy From the Solar Source. *ASME Int. Mech. Eng. Congr. Expo. Proc.* **2010**, *6*, 575–580. [CrossRef]
26. Ndukaife, T.A.; Nnanna, A.G.A. Enhancement of Performance and Energy Efficiency of Air Conditioning System Using Evaporatively Cooled Condensers. *Heat Transf. Eng.* **2019**, *40*, 375–387. [CrossRef]
27. Mohammed, R.H.; El-Morsi, M.; Abdelaziz, O. Indirect Evaporative Cooling for Buildings: A Comprehensive Patents Review. *J. Build. Eng.* **2022**, *50*, 104158. [CrossRef]
28. Duan, Z.; Zhan, C.; Zhang, X.; Mustafa, M.; Zhao, X.; Alimohammadisagvand, B.; Hasan, A. Indirect Evaporative Cooling: Past, Present and Future Potentials. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6823–6850. [CrossRef]
29. Lin, J.; Chua, K.J. Advanced Dew-Point Evaporative Cooling Systems. In *Green Energy and Technology*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 107–116. [CrossRef]

30. Olaniyan, O.T.; Wike, N.Y.; Adetunji, C.O.; Adetunji, J.B.; Akinbo, O.; Adetuyi, B.O.; Inobeme, A.; Ajenifujah-Solebo, S.O.; Chinedu, P.U.; Ogundolie, F.A.; et al. Historic Use of Evaporative Cooler Structures by Continent. *Eng. Princ. Model. Econ. Evaporative Cool.* **2023**, 15–24. [CrossRef]
31. Abdullah, S.; Zubir, M.N.B.M.; Muhamad, M.R.B.; Newaz, K.M.S.; Öztop, H.F.; Alam, M.S.; Shaikh, K. Technological Development of Evaporative Cooling Systems and Its Integration with Air Dehumidification Processes: A Review. *Energy Build* **2023**, *283*, 112805. [CrossRef]
32. Velasco-Gómez, E.; Tejero-González, A.; Jorge-Rico, J.; Rey-Martínez, F.J. Experimental Investigation of the Potential of a New Fabric-Based Evaporative Cooling Pad. *Sustainability* **2020**, *12*, 7070. [CrossRef]
33. Hassan, Z.; Misaran, M.S.; Siambun, N.J. Performance of The Direct Evaporative Cooler (DEC) Operating in A Hot and Humid Region of Sabah Malaysia. *J. Adv. Res. Fluid Mech. Therm. Sci.* **2022**, *93*, 17–27. [CrossRef]
34. Jain, J.K.; Hindoliya, D.A. Energy Saving Potential of Indirect Evaporative Cooler under Indian Climates. *Int. J. Low-Carbon Technol.* **2016**, *11*, 193–198. [CrossRef]
35. Chen, M.; Liu, X.; Hu, E. Indirect Evaporative Cooling—An Energy Efficient Way for Air Conditioning. *Adv. Mat. Res.* **2013**, *608–609*, 1198–1203. [CrossRef]
36. Xiao, X.; Liu, J. A State-of-Art Review of Dew Point Evaporative Cooling Technology and Integrated Applications. *Renew. Sustain. Energy Rev.* **2024**, *191*, 114142. [CrossRef]
37. Tian, Z.; Liu, Y.; Chen, Y.; Song, C.; Wang, D. Description of liquid–vapor transition behaviors in evaporative cooling technologies: A critical review. *Energy Build.* **2025**, *336*, 115646. [CrossRef]
38. Cengiz, M.; Kayri, İ.; Aydın, H. A Collated Overview on the Evaporative Cooling Applications for Photovoltaic Modules. *Renew. Sustain. Energy Rev.* **2024**, *197*, 114393. [CrossRef]
39. Kalsia, M.; Sharma, A.; Kaushik, R.; Kaushik, R.D. Evaporative Cooling Technologies: Conceptual Review Study. *Evergreen* **2023**, *10*, 421–429. [CrossRef]
40. Wilkins, M.; Fumo, N. A Review of Models on Direct Evaporative Cooling. *Am. J. Undergrad. Res.* **2023**, *20*, 45–55. [CrossRef]
41. Hashim, R.; Hammdi, S.; Eidan, A. Evaporative Cooling: A Review of Its Types and Modeling. *Basrah J. Eng. Sci.* **2022**, *22*, 36–47. [CrossRef]
42. Zhu, G.; Wen, T.; Wang, Q.; Xu, X. A Review of Dew-Point Evaporative Cooling: Recent Advances and Future Development. *Appl. Energy* **2022**, *312*, 118785. [CrossRef]
43. Stefaniak, Ł.; Walaszczyk, J.; Karpuk, M.; Rajski, K.; Danielewicz, J. The Possibility of Intermittent Water Spray Implementation in a Non-Porous Indirect Evaporative Cooler. *Energies* **2025**, *18*, 882. [CrossRef]
44. Xu, P.; Ma, X.; Zhao, X.; Fancey, K. Experimental Investigation of a Super Performance Dew Point Air Cooler. *Appl. Energy* **2017**, *203*, 761–777. [CrossRef]
45. Wang, F.; Sun, T.; Huang, X.; Chen, Y.; Yang, H. Experimental Research on a Novel Porous Ceramic Tube Type Indirect Evaporative Cooler. *Appl. Therm. Eng.* **2017**, *125*, 1191–1199. [CrossRef]
46. Sun, T.; Huang, X.; Chen, Y.; Zhang, H. Experimental Investigation of Water Spraying in an Indirect Evaporative Cooler from Nozzle Type and Spray Strategy Perspectives. *Energy Build* **2020**, *214*, 109871. [CrossRef]
47. Elahi, S.H.; Farhani, S.D. Increasing Evaporative Cooler Efficiency by Controlling Water Pump Run and off Times. *Int. Commun. Heat Mass Transf.* **2021**, *127*, 105525. [CrossRef]
48. Chen, Y.; Huang, X.; Sun, T.; Chu, J. Experimental Study of Plant Fiber-Polymer Composite for Indirect Evaporative Cooler Application. *Appl. Therm. Eng.* **2021**, *199*, 117543. [CrossRef]
49. Shi, W.; Min, Y.; Ma, X.; Chen, Y.; Yang, H. Dynamic Performance Evaluation of Porous Indirect Evaporative Cooling System with Intermittent Spraying Strategies. *Appl. Energy* **2022**, *311*, 118598. [CrossRef]
50. Shi, W.; Min, Y.; Ma, X.; Chen, Y.; Yang, H. Performance Evaluation of a Novel Plate-Type Porous Indirect Evaporative Cooling System: An Experimental Study. *J. Build. Eng.* **2022**, *48*, 103898. [CrossRef]
51. Shi, W.; Yang, H.; Ma, X.; Liu, X. A Novel Indirect Evaporative Cooler with Porous Media under Dual Spraying Modes: A Comparative Analysis from Energy, Exergy, and Environmental Perspectives. *J. Build. Eng.* **2023**, *76*, 106874. [CrossRef]
52. Chen, Y.; Yan, H.; Min, Y. Visualized Study of Wetting Enhancement and Thermal Performance of Fiber-Coated Indirect Evaporative Cooler. *Appl. Therm. Eng.* **2023**, *221*, 119904. [CrossRef]
53. Chen, Y.; Yan, H.; Pan, Y. Wetting and Evaporative Performance Analysis of Wet Channels in Indirect Evaporative Cooler with Hydrophilic Nano-Coating. *Appl. Therm. Eng.* **2023**, *229*, 120622. [CrossRef]
54. Jin, Q.; Yu, Y.; Zhang, J. Numerical and Experimental Study on Intermittent Spray Cooling for Plate-Fin Heat Exchanger. *Appl. Therm. Eng.* **2023**, *234*, 121328. [CrossRef]
55. Chen, Y.; Liu, L.; Yan, H.; Tao, Q.; Fan, Y. Study of a Nano-Coated Hydrophilic Polymer for Indirect Evaporative Cooler from Wetting, Thermal and Corrosion Resistance Performance. *Appl. Therm. Eng.* **2024**, *257*, 124180. [CrossRef]

56. Khan, I.; Khalid, W.; Ali, H.M.; Sajid, M.; Ali, Z.; Ali, M. An Experimental Investigation on the Novel Hybrid Indirect Direct Evaporative Cooling System. *Int. Commun. Heat Mass Transf.* **2024**, *155*, 107503. [CrossRef]
57. Shim, J.; Ki, S.; Seo, D.; Moon, B.; Bang, S.; Nam, Y. Intermittent Spray Cooling on Rationally-Designed Hierarchical Surfaces for Enhanced Evaporative Heat Transfer Performance. *Int. Commun. Heat Mass Transf.* **2024**, *153*, 107354. [CrossRef]
58. Ma, X.; Shi, W.; Yang, H. Spray Parameter Analysis and Performance Optimization of Indirect Evaporative Cooler Considering Surface Wettability. *J. Build. Eng.* **2024**, *82*, 108175. [CrossRef]
59. Gorbachev, M.; Terekhov, V. Simulating Heat and Mass Transfer Processes during Water Film Evaporation in a Horizontal Channel. *J. Phys. Conf. Ser.* **2020**, *1675*, 012112. [CrossRef]
60. Caruana, R.; De Antonellis, S.; Marocco, L.; Liberati, P.; Guilizzoni, M. Experimental Characterization of the Wettability of Coated and Uncoated Plates for Indirect Evaporative Cooling Systems. *Fluids* **2023**, *8*, 122. [CrossRef]
61. Choi, C.; Kim, M.; Choi, C.; Kim, M. Wettability Effects on Heat Transfer. In *Two Phase Flow, Phase Change and Numerical Modeling*; BoD–Books on Demand: Norderstedt, Germany, 2011. [CrossRef]
62. Caruana, R.; Marocco, L.; Liberati, P.; Guilizzoni, M. Experimental Analysis of the Effect of Limescale on the Wettability of Indirect Evaporative Cooling System Plates. *Fluids* **2024**, *9*, 76. [CrossRef]
63. Conrat, P.; Comino, F.; Castillo-González, J.; Navas-Martos, F.J.; Ruiz de Adana, M. Energy and Materials Analysis of Wet Channels Structures for Evaporative Cooling Systems Manufactured by FFF Technique with Foam Materials. *Appl. Therm. Eng.* **2024**, *256*, 124165. [CrossRef]
64. Castillo-González, J.; Comino, F.; Caruana, R.; Guilizzoni, M.; Conrat, P.; Ruiz de Adana, M.; Navas-Martos, F.J. Development of Innovative Thermoplastic Foam Materials Using Two Additive Manufacturing Technologies for Application in Evaporative Cooling Systems. *Polymers* **2024**, *16*, 3190. [CrossRef]
65. Chen, Y.; Wang, N.; Ola, O.; Xia, Y.; Zhu, Y. Porous Ceramics: Light in Weight but Heavy in Energy and Environment Technologies. *Mater. Sci. Eng. R Rep.* **2021**, *143*, 100589. [CrossRef]
66. Duan, Z.; Wang, M.; Dong, X.; Liu, J.; Zhao, X. Experimental and Numerical Investigation of Wicking and Evaporation Performance of Fibrous Materials for Evaporative Cooling. *Energy Build* **2022**, *255*, 111675. [CrossRef]
67. Tang, H.; Guo, C.; Xu, Q.; Zhao, D. Boosting Evaporative Cooling Performance with Microporous Aerogel. *Micromachines* **2023**, *14*, 219. [CrossRef] [PubMed]
68. Jiao, S.; McCarthy, J.J. A Synergistic Approach to Atmospheric Water Scavenging. *ACS Appl. Mater. Interfaces* **2023**, *15*, 7353–7358. [CrossRef]
69. Li, R.; Wang, W.; Shi, Y.; Wang, C.-T.; Wang, P.; Li, R.; Wang, W.; Shi, Y.; Wang, P.; Wang, C.-T. Advanced Material Design and Engineering for Water-Based Evaporative Cooling. *Adv. Mater.* **2024**, *36*, 2209460. [CrossRef]
70. Yamamoto, N.; Singh, J.; Dai, J. Multi-Functional Nano-Porous Ceramics1958. In Proceedings of the American Society for Composites Thirty-Third Technical Conference; American Society for Composites: Dayton, OH, USA, 2018; pp. 1958–1964. [CrossRef]
71. Stefaniak, Ł.; Rajski, K.; Danielewicz, J. Przegląd Zastosowania Nanopłynów Oraz Materiałów Porowatych w Pośrednim Chłodzeniu Wyparnym. *CIEPŁOWNICTWO Ogrzew. Went.* **2023**, *1*, 35–42. [CrossRef]
72. Zhao, X. Porous Materials for Direct and Indirect Evaporative Cooling in Buildings. In *Materials for Energy Efficiency and Thermal Comfort in Buildings*; Woodhead Publishing: Sawston, UK, 2010; pp. 399–426. [CrossRef]
73. Emdadi, Z.; Asim, N.; Yarmo, M.A.; Shamsudin, R.; Mohammad, M.; Sopian, K. Green Material Prospects for Passive Evaporative Cooling Systems: Geopolymers. *Energies* **2016**, *9*, 586. [CrossRef]
74. Doğramacı, P.A.; Aydın, D. Comparative Experimental Investigation of Novel Organic Materials for Direct Evaporative Cooling Applications in Hot-Dry Climate. *J. Build. Eng.* **2020**, *30*, 101240. [CrossRef]
75. He, S.; Chen, W.; Yang, W.; Zhao, X. Review of Hygroscopic Coating on Aluminum Fin Surface of Air Conditioning Heat Exchanger. *Appl. Sci.* **2021**, *11*, 5193. [CrossRef]
76. You, Y.; Wang, G.; Yang, B.; Guo, C.; Ma, Y.; Cheng, B. Study on Heat Transfer Characteristics of Indirect Evaporative Cooling System Based on Secondary Side Hydrophilic. *Energy Build* **2022**, *257*, 111704. [CrossRef]
77. Fathi, N.; Kim, J.; Jun, S.; King, R.M.; Amaya, M.; You, S.M. Evaporative Cooling Heat Transfer of Water From Hierarchically Porous Aluminum Coating. *Heat Transf. Eng.* **2018**, *39*, 410–421. [CrossRef]
78. Crook, B.; Willerton, L.; Smith, D.; Wilson, L.; Poran, V.; Helps, J.; McDermott, P. Legionella Risk in Evaporative Cooling Systems and Underlying Causes of Associated Breaches in Health and Safety Compliance. *Int. J. Hyg. Environ. Health* **2020**, *224*, 113425. [CrossRef]
79. Nocker, A.; Schulte-Illingheim, L.; Frösler, J.; Welp, L.; Sperber, O.; Hugo, A. Microbiological Examination of Water and Aerosols from Four Industrial Evaporative Cooling Systems in Regard to Risk of Legionella Emissions and Methodological Suggestions for Surveillance. *Int. J. Hyg. Environ. Health* **2020**, *229*, 113591. [CrossRef] [PubMed]

80. Johnston, J.D.; Cowger, A.E.; Weber, K.S. Bioaerosol and Microbial Exposures from Residential Evaporative Coolers and Their Potential Health Outcomes: A Review. *Indoor Air* **2022**, *32*, e13082. [CrossRef]
81. Szczęśniak, S.; Trusz-Zdybek, A.; Piekarska, K. Preliminary Sanitary Analysis of Supply and Exhaust Air of Ventilation Units Working at Special Rooms. *E3S Web Conf.* **2017**, *22*, 00171. [CrossRef]
82. Stefaniak, Ł.; Szczęśniak, S.; Walaszczyk, J.; Rajski, K.; Piekarska, K.; Danielewicz, J. Challenges and Future Directions in Evaporative Cooling: Balancing Sustainable Cooling with Microbial Safety. *Build Environ.* **2025**, *267*, 112292. [CrossRef]
83. Donlan, R.M.; Costerton, J.W. Biofilms: Survival Mechanisms of Clinically Relevant Microorganisms. *Clin. Microbiol. Rev.* **2002**, *15*, 167–193. [CrossRef]
84. Jamal, M.; Ahmad, W.; Andleeb, S.; Jalil, F.; Imran, M.; Nawaz, M.A.; Hussain, T.; Ali, M.; Rafiq, M.; Kamil, M.A. Bacterial Biofilm and Associated Infections. *J. Chin. Med. Assoc.* **2018**, *81*, 7–11. [CrossRef]
85. Takashima, M.; Shirai, F.; Sageshima, M.; Ikeda, N.; Okamoto, Y.; Dohi, Y. Distinctive Bacteria-Binding Property of Cloth Materials. *Am. J. Infect. Control* **2004**, *32*, 27–30. [CrossRef]
86. Ma, X.; Shi, W.; Yang, H. Study on Water Spraying Distribution to Improve the Energy Recovery Performance of Indirect Evaporative Coolers with Nozzle Arrangement Optimization. *Appl. Energy* **2022**, *318*, 119212. [CrossRef]
87. Ma, X.; Shi, W.; Yang, H. Improving the Performance of Indirect Evaporative Cooler for Energy Recovery from the Perspective of Nozzle Configuration: A CFD Model Analysis. *J. Build. Eng.* **2023**, *76*, 107195. [CrossRef]
88. Caruana, R.; De Antonellis, S.; Marocco, L.; Guilizzoni, M. Modeling of Indirect Evaporative Cooling Systems: A Review. *Fluids* **2023**, *8*, 303. [CrossRef]
89. Yang, H.; Rong, L.; Liu, X.; Liu, L.; Fan, M.; Pei, N. Experimental Research on Spray Evaporative Cooling System Applied to Air-Cooled Chiller Condenser. *Energy Rep.* **2020**, *6*, 906–913. [CrossRef]
90. Kim, H.J.; Ham, S.W.; Yoon, D.S.; Jeong, J.W. Cooling Performance Measurement of Two Cross-Flow Indirect Evaporative Coolers in General and Regenerative Operation Modes. *Appl. Energy* **2017**, *195*, 268–277. [CrossRef]
91. De Antonellis, S.; Joppolo, C.M.; Liberati, P.; Milani, S.; Molinaroli, L. Experimental Analysis of a Cross Flow Indirect Evaporative Cooling System. *Energy Build* **2016**, *121*, 130–138. [CrossRef]
92. Yang, H.; Shi, W.; Chen, Y.; Min, Y. Research Development of Indirect Evaporative Cooling Technology: An Updated Review. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111082. [CrossRef]
93. Al-Zubaydi, A.Y.T.; Hong, G. Experimental Study of a Novel Water-Spraying Configuration in Indirect Evaporative Cooling. *Appl. Therm. Eng.* **2019**, *151*, 283–293. [CrossRef]
94. Zhou, B.; Lv, J.; Zhu, M.; Wang, L.; Li, S.; Hu, E. Experiment for the Performance of a Thin Membrane Inclined Automatic Wicking Dew-Point Evaporative Cooling Device Based on Simulation Results. *Energy Build* **2024**, *308*, 114021. [CrossRef]
95. Guo, C.; Guo, W.; Zhou, Y.; Huang, T.; Zhang, P. Evaporative Wicking in Thin Porous Media. *Int. J. Heat Mass. Transf.* **2023**, *216*, 124536. [CrossRef]
96. Abada, D.; Maalouf, C.; Sotehi, O.; Rouag-Saffidine, D.; Polidori, G.; Boudjabi, A.F.; Derghout, Z. Performance Evaluation of Fabrics for Evaporative Cooling Applications. *Energy Build* **2022**, *266*, 112120. [CrossRef]
97. Duan, Z.; Zhan, C.; Zhao, X.; Dong, X. Experimental Study of a Counter-Flow Regenerative Evaporative Cooler. *Build Environ.* **2016**, *104*, 47–58. [CrossRef]
98. De Antonellis, S.; Joppolo, C.M.; Liberati, P. Performance Measurement of a Cross-Flow Indirect Evaporative Cooler: Effect of Water Nozzles and Airflows Arrangement. *Energy Build* **2019**, *184*, 114–121. [CrossRef]
99. Guilizzoni, M.; Milani, S.; Liberati, P.; De Antonellis, S. Effect of Plates Coating on Performance of an Indirect Evaporative Cooling System. *Int. J. Refrig.* **2019**, *104*, 367–375. [CrossRef]
100. Chen, Y.; Luo, Y.; Yang, H. Fresh Air Pre-Cooling and Energy Recovery by Using Indirect Evaporative Cooling in Hot and Humid Region—A Case Study in Hong Kong. *Energy Procedia* **2014**, *61*, 126–130. [CrossRef]
101. Khalid, O.; Ali, M.; Sheikh, N.A.; Ali, H.M.; Shehryar, M. Experimental Analysis of an Improved Maisotsenko Cycle Design under Low Velocity Conditions. *Appl. Therm. Eng.* **2016**, *95*, 288–295. [CrossRef]
102. Li, Y.; Jing, C. Multi-Objective Optimization of Counter-Flow Dew-Point Evaporative Coolers for Multi-Scenario Applications Using Non-Dominated Sorting Genetic Algorithm II. *Appl. Therm. Eng.* **2025**, *262*, 125292. [CrossRef]
103. Rosińska, W.; Jurasz, J.; Przestrzelska, K.; Wartalska, K.; Kaźmierczak, B. Climate Change's Ripple Effect on Water Supply Systems and the Water-Energy Nexus—A Review. *Water Resour. Ind.* **2024**, *32*, 100266. [CrossRef]
104. Żywiec, J.; Szpak, D.; Wartalska, K.; Grzegorzek, M. The Impact of Climate Change on the Failure of Water Supply Infrastructure: A Bibliometric Analysis of the Current State of Knowledge. *Water* **2024**, *16*, 1043. [CrossRef]
105. Wartalska, K.; Grzegorzek, M.; Bełcik, M.; Wdowikowski, M.; Kolanek, A.; Niemierka, E.; Jadwiszczak, P.; Kaźmierczak, B. The Potential of RainWater Harvesting Systems in Europe—Current State of Art and Future Perspectives. *Water Resour. Manag.* **2024**, *38*, 4657–4683. [CrossRef]

106. Przestrzelska, K.; Wartalska, K.; Rosińska, W.; Jurasz, J.; Kaźmierczak, B. Climate Resilient Cities: A Review of Blue-Green Solutions Worldwide. *Water Resour. Manag.* **2024**, *38*, 5885–5910. [CrossRef]
107. Hviid, C.A.; Zukowska-Tejsen, D.; Nielsen, V. Cooling of Schools—Results from a Demonstration Project Using Adiabatic Evaporative Cooling with Harvested Rainwater. *E3S Web Conf.* **2020**, *172*, 02003. [CrossRef]
108. Englart, S. Analysis of Rainwater Use in Membrane-Based Semi-Direct Evaporative Cooling of Air. *J. Build. Eng.* **2024**, *90*, 109409. [CrossRef]

Building and Environment 267 (2025) 112292

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Challenges and future directions in evaporative cooling: Balancing sustainable cooling with microbial safety

Łukasz Stefaniak *, Sylwia Szczęśniak, Juliusz Walaszczyk, Krzysztof Rajski, Katarzyna Piekarska, Jan Danielewicz

Faculty of Environmental Engineering, Wroclaw University of Science and Technology, 50377 Wroclaw, Poland

ARTICLE INFO

Keywords:
Liquid cooling
Legionella sp.
Cooling pads material
Indoor air quality
Biofilm

ABSTRACT

Evaporative cooling systems are gaining popularity due to their environmental benefits, particularly in reducing energy consumption and utilizing air (R-729) and water (R-718) as refrigerants. However, these systems are susceptible to microbial contamination, posing significant health risks, especially in environments where air is in direct contact with water. The article provides an in-depth analysis of the microbial risks associated with evaporative cooling systems, focusing on bacteria such as Legionella pneumophila, fungi, and other pathogens that can proliferate in the moist environments these systems create. While Legionella contamination is well-documented and frequently addressed, this study highlights the need for more comprehensive evaluation of other microbial risks. The research compares the microbial safety of evaporative cooling systems with that of traditional vapor compression cooling and examines the role of cooling pad materials and water quality in promoting microbial growth. It also underscores the limitations of current maintenance practices, which often overlook non-Legionella risks. To improve microbial safety, the paper proposes several mitigation strategies, including UV water treatment and heat exchanger surface modifications, to reduce microbial contamination. Additionally, the study calls for more detailed and consistent maintenance guidelines that cover a broader spectrum of microbial threats beyond Legionella, as well as regular monitoring of indoor air quality to ensure the safe operation of these systems in human-occupied spaces.

Ultimately, the findings emphasize that, with improved microbial safety protocols and regular maintenance, evaporative cooling systems can become a sustainable and safe alternative to conventional cooling technologies in various environments.

1. Introduction

Evaporative cooling (EC), an old concept that has found ingenious applications in modern, environmentally friendly engineering. At its core, it capitalizes on the simple principle that, when transitioning from a liquid to a gas, water absorbs heat from its surroundings. This mechanism is currently widely investigated to create a sustainable and energy-efficient cooling solution for the increasingly demanding building sector [1,2]. This type of cooling became an alternative to traditional air conditioning devices. As these are mainly based on a compressor cycle with gaseous refrigerants, they are not perceived as a sustainable solution for the future, especially in terms of the aspect of global warming [3].

Along with the great effort towards sustainable development, EC technology has been implemented in various sectors in the built environment. The IT sectors [4–6], agriculture [7–9], and the indoor thermal comfort sectors [8–10] are widely supported by EC technologies. Fig. 1 presents the application of EC in the built environment with a short description of the range of use. The popularity of EC technology is also seen in the publication activity (Fig. 2). Evaporative cooling is a highly developed and investigated branch of HVAC technologies. However, this sustainable technology faces a challenge in addressing microbial risk (due to air-water contact), which is not adequately described in the literature and guidelines [10–12] as should be. Fig. 2 confirms that the topic is discussed more than ten times less than the technology itself. However, it should be noted that in recent years, the number of publications on the relationship between EC and microbiological contamination has increased.

It should be noted that the ventilation and air conditioning system and the Air Handling Units (AHU) are contaminated even without the EC

* Corresponding author.
E-mail address: lukasz.stefaniak@pwr.edu.pl (Ł. Stefaniak).

https://doi.org/10.1016/j.buildenv.2024.112292
Received 29 August 2024; Received in revised form 17 October 2024; Accepted 7 November 2024
Available online 12 November 2024

part. Researchers provide evidence for existing primary air pollution, but also that there are internal sources of contamination [13,14]. Furthermore, cooling systems based on vapor compressor type devices, due to the ease of condensation achievement, are vulnerable to bacterial and fungal contamination [15,16].

Evaporative cooling technology is widely used for a variety of applications. Some EC methods can be used in air handling units to cool supply air and can affect microbial safety and, ultimately, indoor microbial safety. Other EC methods are used in evaporative condensers or cooling towers, usually located outside buildings. The evaporative condenser uses evaporative cooling to cool the refrigerant (on the hot side), which has a negative impact only on outdoor air microbial safety (Fig. 3). In the case of cooling towers, there are two ways to use the EC method (Fig. 3). Closed-circuit cooling towers use circulation water and ambient air to cool the working medium, which is contained in closed pipes. This solution has an impact on the safety of bacteria only in the outdoor air. The open-circuit cooling tower cools the working water by spraying it and directly contacting the ambient air. This causes contamination of both the outdoor air and the working water. However, inside the building, this chilled water is piped and does not come into contact with the air that people inhale. The typical locations of evaporative cooling applications are shown in Fig. 3. The EC device and cooling coil in the AHU are shown on a dotted line to emphasise that they can be used separately or in hybrid systems, which is very important when considering evaporative cooling as an alternative to energy-intensive compressor cooling.

The literature provides a wealth of articles on the construction, operation, and performance of the EC device, but little on the risk of microbial or bioaerosol. Review articles from last 5 years that tackle the evaporative cooling which is used to prepare cooled air that is supplied to cooled spaces are briefly described in Table 1. The focus and key finding were indicated. Also the microbial aspect is listed, but any of the reviews discusses the problem with microbial aspect.

Other articles that link construction, operation, and microbiological hazards are mainly cooling towers or evaporative condensers [17–20]. It should be emphasized that these devices do not contribute directly to indoor air pollution, only outdoor air (see Fig. 3). Health problems related to EC were extensively described by Johnston et al. [11]. Case studies were discussed in detail, and there is no more recent research to discuss. However, there is a lack of research on correlation between the type of EC and its influence on the quality of the supply air and, eventually, on the quality of the indoor air. The research would help to choose the proper EC system regarding the microbial quality of the supply air. The selection of effective cooling with minimal microbiological risk should be a key aspect of the design and operation of these devices.

Thus, this article concentrates strictly on air conditioning systems, with EC units, that supply cooled air directly to the room. It analyzes EC technology as a factor of potential influence negatively on the indoor air quality. It summarizes the aspect of microbial risk in terms of heat exchanger surface materials. Finally, mitigation and prevention strategies are discussed as the most important in creating a sustainable and effective cooling system that is safe for users and durable and environmentally friendly.

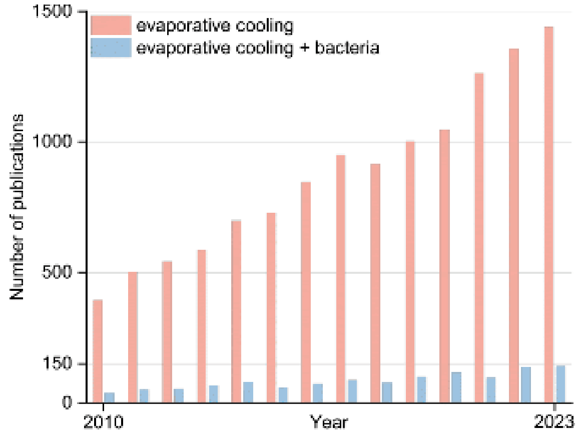


Fig. 2. Number of publications concerning tags evaporative cooling and bacteria, based on SCOPUS data base.

2. *Background*

EC technology can be divided into two main types: Direct Evaporative Cooling (DEC) (air is in direct contact with water) and Indirect Evaporative Cooling (IEC) (wet and dry channel are divided by heat exchanger walls). IEC can be further divided into regular IEC and Dewpoint Indirect Evaporative Cooling (DIEC) (where part of supply air is returned to the wet channels by perforation in heat exchanger walls (DIEC (a)) or by ventilation ducts (DIEC (b)). Schemes are shown in (Fig. 4). Each type presents a unique approach to cooling outdoor air for indoor environments. The specific description with working principles, psychometric representation, and a short microbial risk note are presented in Table 2. A red warning triangle indicates a place at risk for microbiological contamination.

Each technology presented in Fig. 4 is a development of the previous one with respect to microbial safety and the pursuit of the highest possible performance. DEC offers direct cooling but poses a significant microbial risk, IEC mitigates this risk with an indirect approach, but sacrifices some performance, and DIEC seeks to balance performance and contamination risk through innovative configurations. Each technology presents distinct advantages and disadvantages that must be considered in the context of specific requirements and constraints.

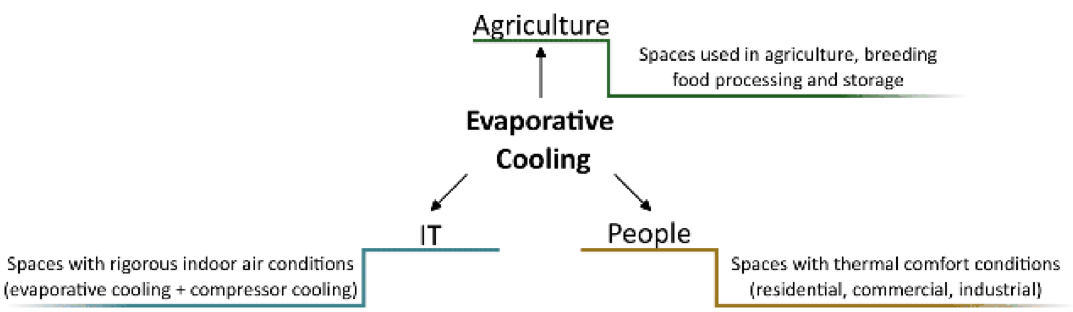


Fig. 1. Evaporative cooling application in built environment.

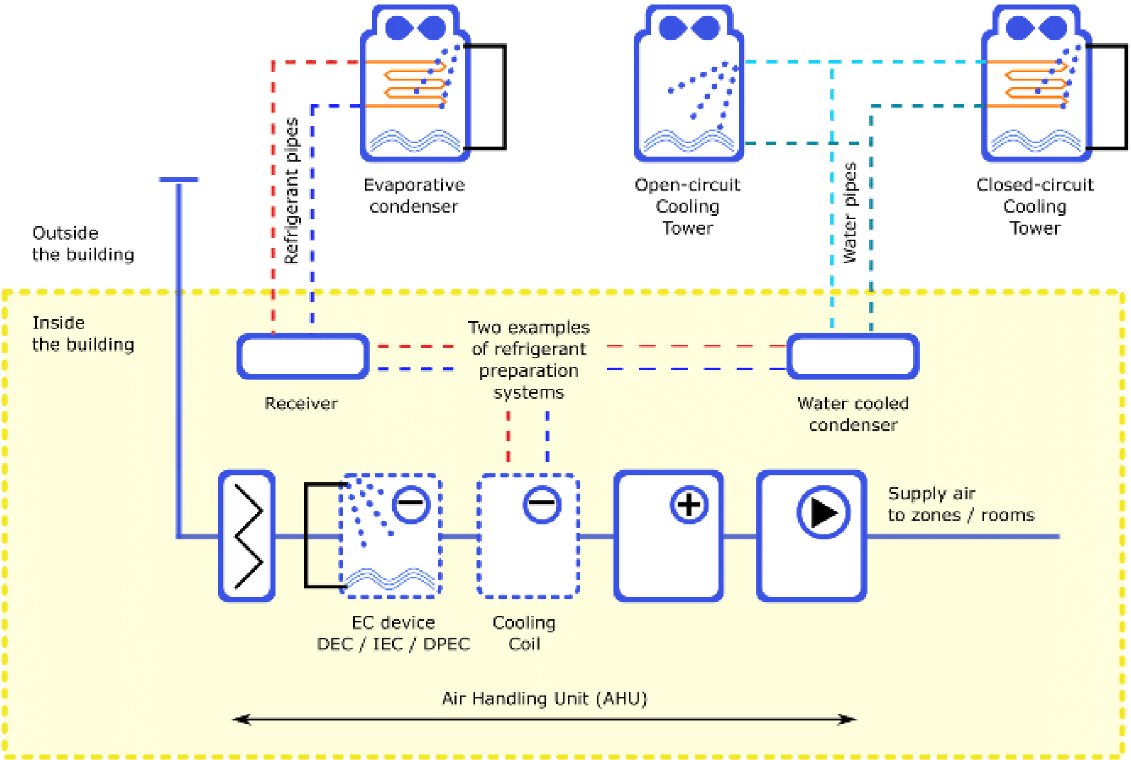


Fig. 3. Indoor and outdoor air contamination sources from EC technology.

Table 1
Brief description of recent review articles on evaporative cooling technology.

Source / Year	Year	Focus	Key finding	Microbial aspect
Yang et Al. [21]	2019	Enhanced evaporative cooling technologies	Pre-treat ambient air by dehumidification using membranes and dessicants increases cooling efficiency	Mentioned, not discussed
Yang et al. [22]	2021	Indirect evaporative cooling performance enhancement and materials for wet channel surface with high wettability	Porous materials are anticipated to be applied in evaporative cooling followed by intermittent water spraying as the water storage capacity is increased	Mentioned, not discussed
Cui et al. [23]	2021	Dew point evaporative cooling in energy, economic, and environmental aspect	The dew point evaporative cooling system could have 60–65% higher COP compared to the traditional AC unit.	No
Lv et al. [24]	2021	Indirect evaporative cooling – porous materials use	Heat and mass transfer of porous materials are crucial in terms of the evaporative cooling effect, and the process is usually simplified in models, but increasing computational power is promising and can help to improve models.	No
Tejero-Gonzalez and Franco Salas [25]	2021	Wetted porous media for evaporative cooling	When applying porous material onto the wet channel surface the balance between saturation effectiveness and pressure drop must be optimized	No
Sajjad et al. [26]	2021	Operating conditions and application of indirect evaporative cooling	Major design parameters are identified (system configuration, inlet airflow conditions, channel geometry, and evaporative material)	No
Zhu et al. [27]	2022	Dew point evaporative cooling applications in demand and supply side	Demand-side and supply-side application of dew point evaporative cooling	No
Abdullah et al. [28]	2023	Dehumidification systems integrated with evaporative cooling	Evaporative cooling systems can be used in hot and humid conditions however, membrane dehumidification is needed	No
Xiao and Liu [29]	2024	Dew point evaporative cooling integration with other systems	Materials and coating are discussed, which aim to promote full contact between water and air to improve the performance of the device.	No

3. Analysis and discussion

3.1. Indoor air contamination

The air that is treated and supplied to the indoor space may become contaminated in a primary and secondary way. Three main points of possible contamination are presented in Fig. 5 and described below: primary air contamination due to bioaerosols already existing in outdoor air; microbial contamination inside the EC device; and contamination related to the product air.

First, bioaerosols including bacteria and fungi can be simply transferred from the outdoor air, which is already contaminated. Air filters can be applied to minimize the problem. However, it is not a specific problem of EC, but of any ventilation or air conditioning system [14]. When discussing EC technology alone, it should not be an argument against its usage. Water can also be primarily contaminated. When no addition treatment is applied, microorganisms can be transferred with air to the wet channel.

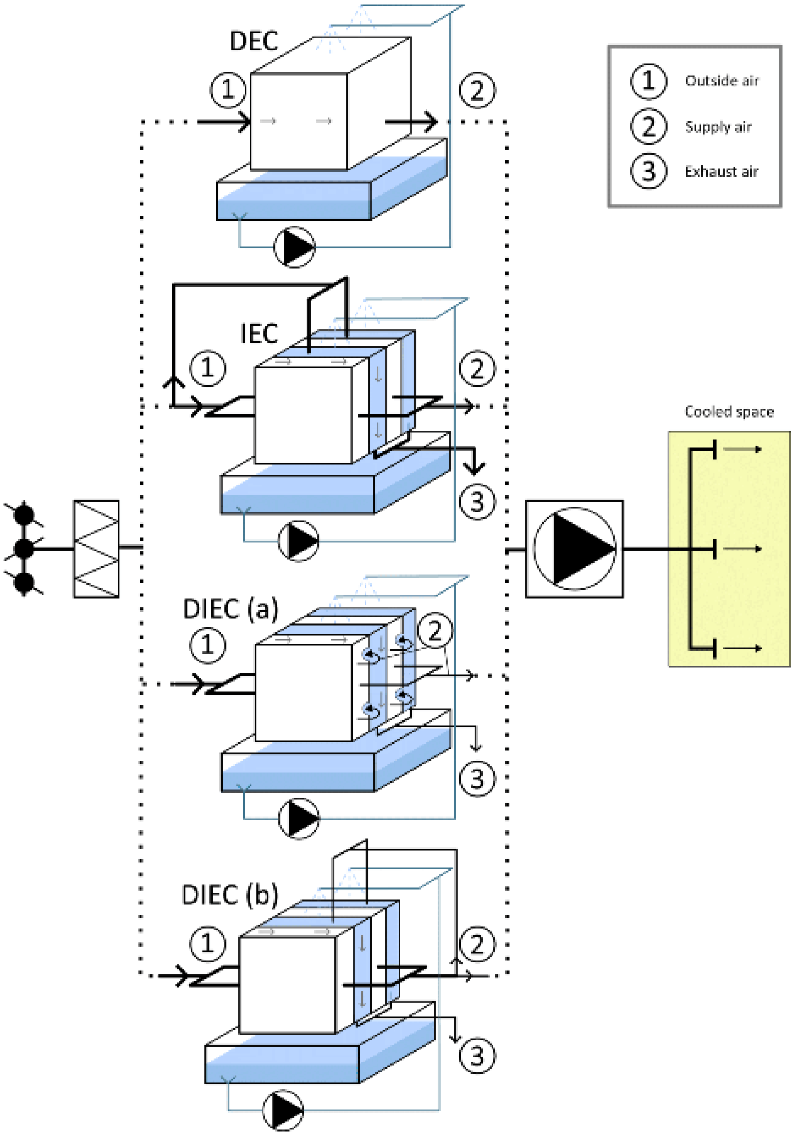


Fig. 4. Types of EC technology (DEC, IEC, DIEC) schemes.

Second, microbial contamination can occur in the device itself, like in a water tank or in a heat exchanger. Microorganisms that are already present in the air can reproduce on dry channel walls, which can be made of different materials. The material itself can support or resist reproduction, as discussed in Section 3.2. In the wet channel, both microorganisms can reproduce from primary water and air contamination. In theoretical papers, researchers neglect air leakages between wet and dry channels for the purpose of models and equations [38,39]. However, in experimental articles, researchers point out that there is a problem of air leakage between dry and wet channels, as is visible in the results on psychometric charts where the process lines deviate and some of the moisture is added to the dry channel [36,37]. To limit the possibility of air leakage, the proper construction of an EC device is needed. The wet channels should be placed on the suction side of the fan and the dry channel on the pressure side of the fan. Air leaks can be a source of transport of microorganisms between air handling units and devices sections [40].

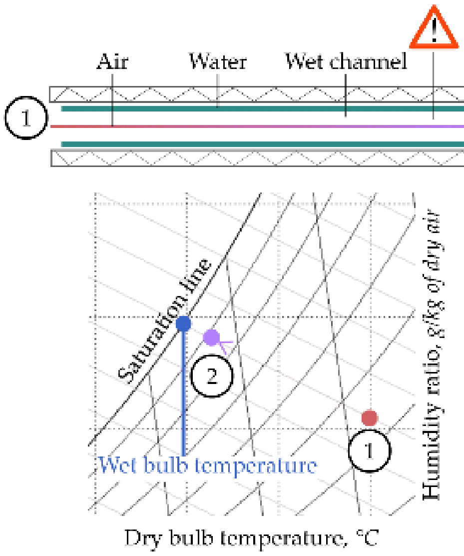
Eventually, the supplied air is transported to the cooled space through ventilation ducts. In this case, some of the present microorganisms can disperse through the ventilation system and settle on the surface of the ducts [41,42]. Part of the air that is returned to the wet channel can increase the presence of microorganisms in these channels.

Advances in EC technology are intended to enhance cooling efficiency and mitigate the potential for biological contamination. The latest IEC and DIEC systems are more efficient in terms of performance and should be safer in terms of microbiological risk. Nevertheless, there is a lack of articles or research reports that provide definitive confirmation of the microbiological safety of the new systems compared to the older membrane-free systems. In any case, the implementation of water purification systems is an effective method of maintaining clean air in EC [43].

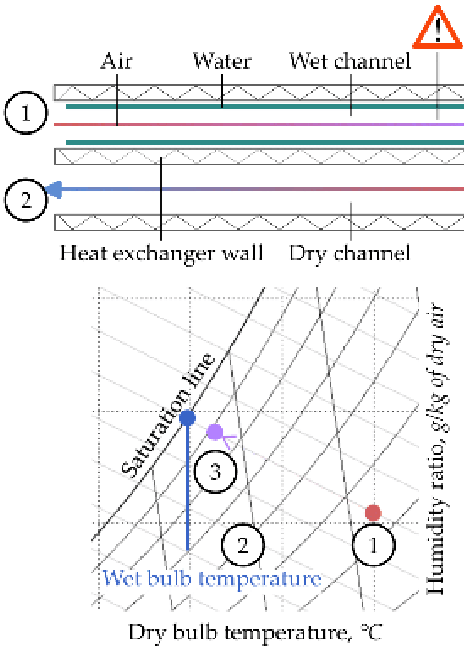
It is also important to note that coolers in typical compressor cooling systems are exposed to bioaerosol deposition, for example, on the cooling coils [15,16,44,45] or in the drip trays [46], where intermittent

Table 2
Evaporative cooling overview and microbial risk description [8].

Direct Evaporative Cooling (DEC)
Outside air (1) is directly in contact with water. The supplied air (2) is cooled and humidified. Cooling is limited to the wet bulb temperature.
The microbial risk is very high since the air after contact with water is transported through ventilation ducts. These can already be contaminated with, e.g. dust and the number of microorganisms can increase [30]. However, the air may also be additionally cleaned on a filter or thermally treated and finally, the air can be supplied directly to the cooled space.
Macher and Girman [31] experimentally proved that there is a correlation between sump contamination and indoor air quality. Macher et al. [32] used tracer bacteria (i.e. Micrococcus luteus) in an experiment that proves indoor air contamination.

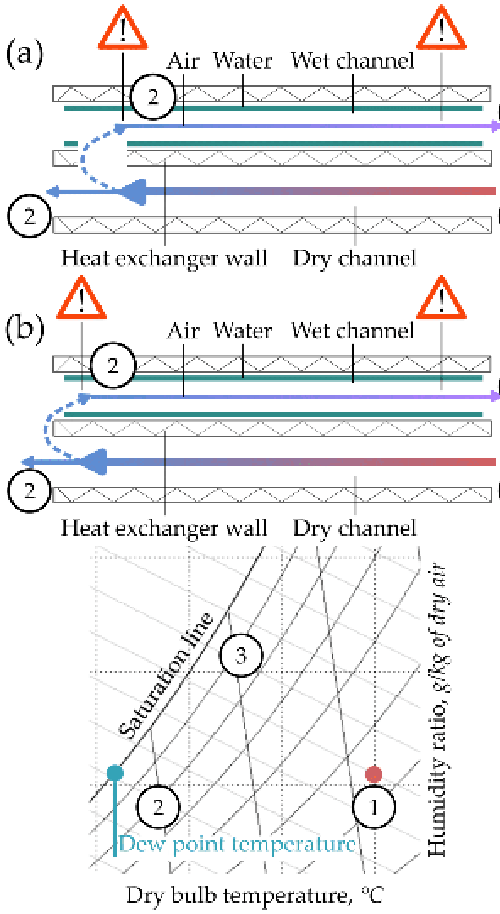


Indirect Evaporative Cooling (IEC)
Outside air (1) is cooled by indirect contact with the wet channel. Heat transfer occurs through the heat exchanger wall. The air supplied (2) is cooled without moisture addition. Cooling is limited to the wet bulb temperature.
IEC was developed to avoid the problem of microbial risk that occurred in DEC [33]. The introduction of heat exchangers lowers overall performance compared to EC. The possibility of microbial contamination of the supply air occurs when there are leakages between the wet and dry channels, which is indicated as the problem to be solved in the future [21]. More complex systems such as DEC or IEC with desiccant air drying are also reported to have air leakages that even influence the efficiency [34]. In addition attention should be paid to cracks that may occur in heat exchanger channels, as some porous materials are brittle [35]. Therefore, the correct configuration of the EC devices with respect to the pressure (dry channels on pressure side - wet channels on suction side) thus in respect to the fans, then proper maintenance, and service are required to ensure microbial safety.



(continued on next page)

Table 2 (*continued*)

Dewpoint Indirect Evaporative Cooling (DIEC) Outside air (1) is cooled by indirect contact with the wet channel. Part of the pre-cooled air (supply air) is then returned to the wet channel. Either by perforation in the heat exchanger (a) or by ducts outside the heat exchanger (b). Cooling is limited to the dewpoint temperature. DIEC as a development of IEC has to overcome the problem of low performance and at the same time ensure that the air stream supplied to the cooled space has no contact with water. However, in the case of solution (a), there is a very short distance between the wet and dry channels that can cause water droplets or splashes to flow into the dry channel. In case of system (b), there is a longer distance for water to travel back to the dry channel. As the researchers observes that some of the air from the wet channel gets to the dry channel [36,37], there is also a chance of contamination in the case of a DIEC device.	

or continuous condensation occurs depending on the temperature of the cooling air and the temperature of the refrigerant. Studies have confirmed that the climate and efficiency of the air filter affect the ecology of bacteria and fungi from outdoor to indoor air [16,47]. Researchers suggest [48,49] that EC technology that increases the relative humidity of the indoor air creates a favorable microclimate for the house dust mite. It should be emphasized that lowering the air temperature will always increase the relative humidity, unless a dehumidification process is engaged (by condensation on the cooling coil, etc.). Due to this, EC is used mainly in arid regions [50], where outdoor air generally has a low moisture content, and therefore it is more difficult to obtain a high relative humidity.

It should be noted that the recommended air relative humidity for occupied spaces with thermal comfort requirements is 40–60% [51] or 30–60% [52]. For data centers, the required air relative humidity is approximately 40–55% [53]. Research shows that keeping the relative humidity of the air below 80% significantly reduces the growth of bacteria in the filters [45] which contributes to safer HVAC systems operation. Steeman et al. [54] suggest that an increase in relative humidity in the indoor air can negatively influence the performance and operating time of an investigated IEC device if indoor air is used as working air to cool the supply air after water spray. In fact, construction limits the performance of IEC technology due to high humidity ratios.

EC technology should not be rejected on the basics of indoor air contamination. Technology is not a problem itself, because the microbial contamination in other air systems face similar challenges (wet cooling coil contamination, air humidification). The dehumidification process can be applied to the cooling coil unit and the EC [28] or any air conditioning system when necessary. However, traditional compressor cooling contributes to most of the energy consumption in the developing world, and here what is crucial is that EC systems need less energy for the same effect. Nevertheless, compressor cooling units achieves lower supply air temperatures and dehumidify the air. Combination of EC technology with regular compressor units can be a compromise in performance and energy consumption [55].

3.2. *Heat exchanger surface modification*

Surface modification is one of the current trends in the development of EC technologies [56]. Since the time when experiments demonstrated that surface roughness affects the heat transfer mechanism in spray cooling by influencing the liquid film thickness, bubble dynamics, and heat transfer rates, further experimental studies have been conducted to ascertain the principal condition governing such cooling [57]. Some studies have indicated that at larger film thicknesses, thermal inertia becomes the dominant factor, resulting in a reduction in the overall heat transfer coefficient. This observation led to the conclusion that water film thickness is a crucial parameter to determine the overall thermal performance [58]. Thus, the significant objective of modifying the surfaces of the heat exchanger walls on the wet side is to ensure a uniform

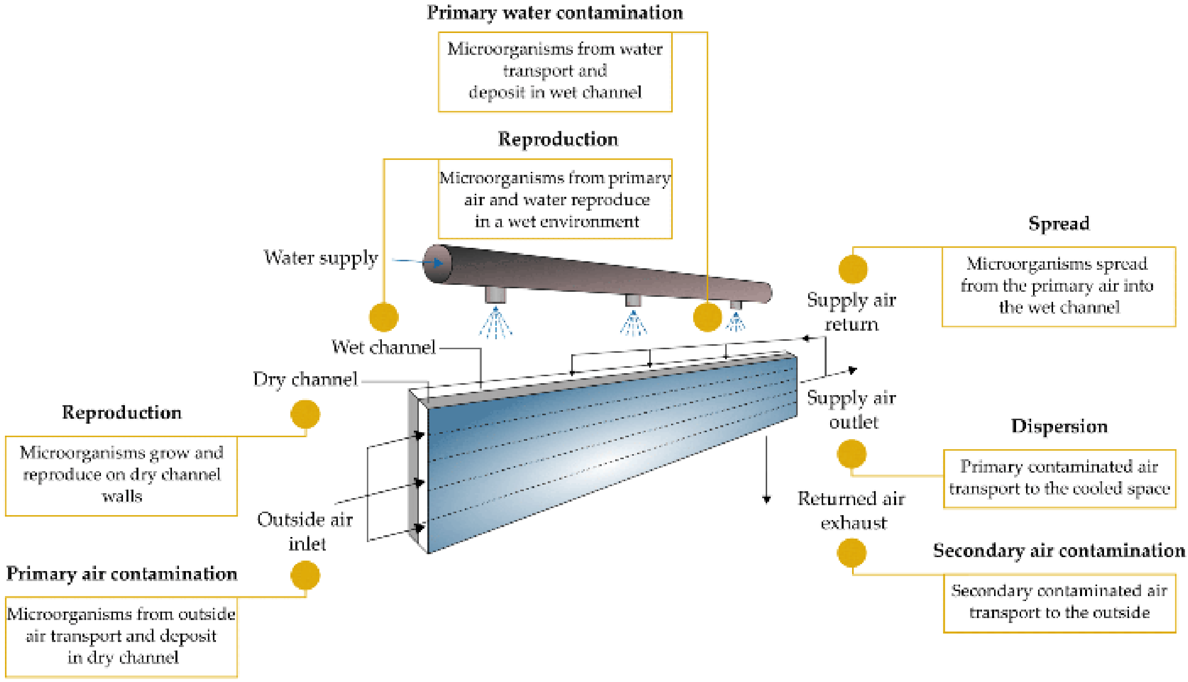


Fig. 5. Primary and secondary contamination in the DIEC device.

and as thin as possible water film layer across the entire wetted surface. In operational devices, a situation may arise where only a portion of the wet side wall is covered by a water film, restricting the area from which water can evaporate [59,60]. This limitation affects the potential of the evaporative cooling process. Furthermore, an excess of water on the walls can decrease the rate of heat transfer because of water's high specific heat, acting as an additional insulator limiting heat exchange between the dry and wet channels [61,62].

One of the consequences of maintaining a water film on the surface of an EC cooler is the formation and persistence of biofilm. The formation of biofilm is most often observed in humid, non-sterile environments, i.e., where water is present or flows through. The formation of the biofilm is the bacteria's adaptive response to the prevailing environmental conditions, which enables them to survive and proliferate. It should be noted that the formation of biofilms is not exclusive to bacteria; fungi, yeasts, protozoa, and other microorganisms are also capable of forming these structures [62]. A biofilm may be formed by microbial cells belonging to one or more species and may serve as a reservoir for a multitude of microorganisms, including those that are pathogenic or conditionally pathogenic [63–65].

The biofilm represents a potential microbial hazard, as larger fragments of the biofilm spontaneously detach from the surface after reaching a certain critical thickness. However, the optimal thickness for a given environment [66] or other conditions (e.g., material type) should be determined by experimentation.

It is also noteworthy that the adhesion of microorganisms to solid substrates is a consequence of Brownian motion, sedimentation, and convective transport, in addition to the motility of organisms with cilia and fimbriae. Consequently, the development of biofilm is dependent on the nature of the material on which they form [67].

The choice of material to build the heat exchanger is crucial and must consider the resistance to water and the structural rigidity. Not all materials used to coat the wet channel walls are waterproof. Waterproofing and ensuring structural rigidity are essential requirements for the material used in the construction of heat exchangers. Common materials include plastics, which are financially attractive and provide structural rigidity. The prevalence of this technology requires the construction of compact devices. A characteristic of indirect evaporative exchangers is the density of the channels, which leaves limited space for additional layering of material on the walls. In addition to a thin coverage, the material must be hydrophilic, allowing easy water evaporation from its surface [68]. However recent studies provide also evidence for water evaporation enhance by creating hydrophobic parts on hydrophilic surface of heat exchanger [69,70]. It is worth to mention that textiles made of natural or synthetic fibres are at risk of bacterial adhesion [71]. The relationship remains unclear and is debated. Some studies suggest that hydrophobic fibres promote bacterial adhesion due to a lower energy barrier [72,73], while others argue that hydrophilic fibres increase adhesion via interactions between hydroxyl groups [74,75]. Recent findings indicate that both superhydrophilic [76] and superhydrophobic [77] surfaces reduce bacterial adhesion, with moderate hydrophobicity leading to the highest adhesion [78].

In addition to construction materials, which do not influence microbial risk as much, research focused on surface modification materials. Six types of materials are presented in Table 3 with a brief description and division into subcategories of materials, where possible. Thermal conductivity, contamination risk, and replacement cost were analyzed. Replacement is considered when the surface is contaminated and cannot be cleaned. Graphical representation makes it easier to choose between performance, safety, and costs. Therefore, each parameter is evaluated from zero to three stars as shown in the legend in Table 3. The more stars the material obtains, the better it meets the requirements for heat exchanger surface material.

In summary, porous materials in evaporative cooling systems are chosen to create surfaces that efficiently absorb, store, and distribute supplied water. The selection of specific materials depends on factors such as the risk of contamination, the ease of cleaning, and the replacement costs, as described in the table. The choice should be made based on the application requirements and the desired balance between performance, safety, and maintenance, as shown in Table 3.

Table 3
Materials used in evaporative cooling for heat exchanger surface modification [26,27,71,79–83].

Property		Performance	Safety	Maintenance	Comments
Material type		Thermal conductivity	Contamination risk	Replacement cost	
Legend		★★★- high ★★☆- medium ★☆☆- low ☆☆☆- very low	★★★- very low ★★☆- low ★☆☆- medium ☆☆☆- high		
Metal	Wick	★★★	★★★	★☆☆	Exposed pores – easy to clean Problems with corrosion [80]
	Foam/Wool	★★★	★★★	★☆☆	Concealed pores – difficult to clean Problems with corrosion [80]
Fibre	Synthetic	☆☆☆	☆☆☆	★★★	Already contaminated with bacteria [71]
	Natural	☆☆☆	☆☆☆	★★★	Additional problems with e.g. mold formation [81]
	Cloth	☆☆☆	★★★	★★★	Resist bacteria formation in wetted area [26]
Ceramics		★★☆	☆☆☆	☆☆☆	Concealed pores – difficult to clean Low porosity does not provide measurable cooling [82]
Zeolite		☆☆☆	☆☆☆	☆☆☆	Concealed pores – difficult to clean
Carbon		★★☆	☆☆☆	★☆☆	Concealed pores – difficult to clean
No material		★★☆	★★★	–	Intermittent water supply helps to avoid bacteria growth without added extra porous material [27,83]

3.3. Mitigation and prevention strategies

The main working medium in EC systems is water. According to the principles of thermodynamics, the water absorbs the heat received from the air during the unit operation. As a consequence, the temperature of the water rises, thereby creating an environment that is conducive to the growth of microorganisms, both those that are present in the water and those that have settled on the surfaces of installation parts (ducts, heat exchangers, etc.). One of the most studied microbial contaminants that colonies water or air environments with high relative humidity is Legionella and its species. To current knowledge, the most well-studied species is Legionella pneumophila, which has been observed to survive best in aerosols at 65% relative humidity [84]. Studies have confirmed that the Legionellae proliferation occurs within a temperature range of 20 °C to 43 °C, with inactivation observed above 50 °C with decidual reduction times decreasing with increasing temperature [85]. Other studies indicate that Legionella pneumophila proliferates at temperatures between 25 °C and 42 °C, with an optimal growth temperature of 35 °C [86]. However, there are some Legionella species (L. non-pneumophila) that are adapted to low temperatures and predominate at 15 °C [85]. It is also crucial to highlight that the risk of proliferation is influenced not only by physical parameters, such as temperature and water pollution, but also by biotic parameters, including the presence of a biofilm or amoebae, which can enhance the survival or proliferation of Legionella [87]. Currently, there is a significant gap in our understanding of the factors that contribute to the survival or active growth of L. pneumophila in the environment. This range of parameters favours the growth of Legionella spp., and therefore the use of water for air cooling requires careful consideration with regard to the safety of the operation [88]. Yamamoto et al. [89] investigated an ultraviolet sterilize to treat water for the cooling tower. The research confirmed the effectiveness of UV treatment in controlling *Legionella sp.* that inhabit outdoor spaces. The authors also point out the importance of controlling other prokaryotic and eukaryotic microbes in water because they are symbiotic with *Legionella* sp. They pointed out that *Legionella sp.* in the aquatic environment is associated with algae, periphytes, amoebae, and heterotrophic bacteria. In addition, Yamamoto et al. [90] developed the research and investigated biocidal treatments. The use of bronopol and isothiazalon was shown to be applicable in *Legionella* sp. treatment but not in other microorganisms.

Kusnetsov et al. [91] provide research on *Legionella* sp. prevention strategies in water cooling systems. Improvement in water quality and treatment with biocides and the reduction in water temperature gave the best results. When the water temperature was below 20 °C *Legionella sp.* concentrations were below 1000 cfu/ dm^{-3} for several years. More important is that with a decrease in the water temperature, the performance of the device also increases. Duan et al. [92] tested water temperature in a range of 14.1–24.8 °C. The increase in water temperature from 14.1 °C to 24.8 °C resulted in decrease in wet bulb and dew point effectiveness around 16% and 11% respectively. Kim et al. [43] applied an ultraviolet water purification system to a DEC device with cooling pads. In fact, water contamination was significantly reduced. However, no clear correlation was found between water quality and air quality. Nevertheless, it was shown that pad contamination causes additional water contamination.

The choice of heat exchanger and its surface material is discussed in Table 3. It is a crucial point in the design of EC devices. It is also strictly related to maintenance and cleaning, which is an important part of the EC technology operation scheme. As stated previously, not only *Legionella sp.* is a threat but also other bacteria, fungi, bioaerosols, and microbes. However, *Legionella sp.* only was recognized best. As far back as 1991, Yamamoto et al. [90] published the first suggestions for *Legionella sp.* prevention. The cleaning procedure, the biocidal treatment and the monitoring of the water parameters were described. Later, Nocker et al. [93] shifted attention to the hygienic risk assessment of EC systems at a national level. In Germany, it is only assessed by determining the *Legionella sp.* concentrations. A similar situation exists in Australia where national guidelines focus on the control of *Legionella sp.* in specific types (like hospitals), while researchers suggest that they should cover more types of pathogens and buildings [49]. The research conducted by Masaka et al. [94] indicates that water mist systems (WMS) may be susceptible to colonization by opportunistic waterborne pathogens (OPPP), including *Legionella pneumophila, Pseudomonas aeruginosa, Mycobacterium avium, Naegleria fowleri* and *Acanthamoeba*. Such colonization may potentially pose a health risk if

OPPP-contaminated aerosols are released into the air.

Crook et al. [12] on the other hand, provide evidence of Legionella risk management failures. There are four main groups of failure types of meeting legal standards: risk assessment, written control scheme, implementation of control scheme, and record keeping. Therefore, more attention should be paid not only to legal standards development, but also to its fulfilment control. Eventually, Rangel et al. [10] have extensively investigated maintenance guidelines on the Legionella aspect. As a result, only a few of the investigated documents gave instructions that may help reduce *Legionella sp.* In those few, the information was not consistent.

3.4. *Alternative water sources in evaporative cooling*

Each of the EC technologies faces the problem of water consumption. With current limitations on access to fresh water due to climate change [95] and the energy demand or water treatment processes [96,97] water sources are important part of the discussion about EC technology. Along with the EC development, there are attempts to reduce water consumption. Especially, there is a trend in developing water collection technologies and finding alternative water sources, such as blue-green infrastructure to collect rainwater [98], greywater along with treatment methods [99], and salt and brackish water along with crystallization problem [100]. The need for alternative water sources is clearly visible, based on recent studies. The alternative sources of water proposed in the literature are summarized in Table 4. In addition, the microbiological aspects and comments on possible limitations in the use of different alternative water sources for EC technology are presented.

Table 4
Alternative water sources for different types of EC.

Source	EC type*	Water source	Microbial aspect	Comment
Hviid et al. [101]	IEC and regenerative IEC	Rainwater	UV disinfection was installed to eliminate possible bacterial contamination	The use of salt water effects in slightly lower cooling effectiveness
Englart [102]	Membrane-based semi-direct evaporative cooler		Small pore size of the membrane prevents air contamination	
McKenzie et al. [103]	Evaporatively pre-cooled condensing unit and evaporative-cooled condensing unit	Greywater	Disinfection can be used to reduce the risk of pathogens occurrence	Graywater, when treated, provide better water quality in terms of evaporative cooling requirements
Kabeel et al. [104]	DEC	Saline water	Not mentioned	Saline water can cause clogging in some cases
Yan et al. [105]	EC		Not mentioned	
Lefers et al. [106]	EC		Not mentioned	
Leung and Cheng [107]	EC	Condensate water	No treatment needed	Condensate water can be use as a supplement to fresh water with no extra treatment

*as the abbreviations and construction types differ in publications, authors provide evaporative cooling type name consistent with the source nomenclature.

4. Conclusion

In this article a comprehensive evaluation of the benefits and microbial risks associated with evaporative cooling systems is provided. This technology has gained momentum as a sustainable alternative to traditional vapor compression-based cooling systems. Evaporative coolers use water and air as refrigerants, offering lower energy consumption and reduced negative environmental impact compared to traditional cooling systems. However, EC systems pose significant challenges regarding microbial safety, particularly the risk of contamination by Legionella pneumophila and other pathogens, which thrive in the moist environments within these units.

The findings indicate that Legionella pneumophila is not the only microbial threat in evaporative cooling systems. While existing guidelines and standards focus heavily on Legionella pneumophila, this study highlights the importance of addressing other microbial risks, including bacteria, fungi, and molds, which can proliferate on wet surfaces, especially cooling pads and heat exchangers surfaces. The material of these components plays a crucial role, with some materials more prone to harboring microorganisms. Additionally, the design and operational factors, such as air-water contact and insufficient drainage, contribute to the overall risk of bioaerosol contamination in indoor environments.

This research points out that current maintenance practices are very often inadequate in fully mitigating microbial risks. This study recommends several specific interventions to enhance microbial safety, such as:

(i) UV Water Treatment: which can significantly reduce microbial contamination in the water used by evaporative coolers, ensuring safer air output;

(ii) Surface Modifications: EC device surfaces could be improved with antimicrobial coatings or materials that resist biofilm formation, reducing the risk of microbial growth;
(iii) System Design Optimization: redesigning systems to minimize air-water interaction, improving drainage, and preventing water stagnation can limit microbial proliferation;
(iv) Enhanced Maintenance Protocols: current guidelines need to be expanded and standardized across the industry to address a broader spectrum of microbial risks. This includes more frequent inspections, microbial monitoring, and thorough cleaning protocols, especially in high-risk environments such as healthcare facilities.

Furthermore, the study emphasizes the importance of ongoing research into the development of new materials for cooling pads and heat exchangers that are less conducive to microbial growth, as well as innovative strategies such as combining evaporative cooling with other technologies to maintain cooling efficiency while minimizing microbial risks.

While evaporative cooling offers an energy-efficient and environmentally friendly alternative to traditional cooling systems, the technology requires improved safety protocols to ensure its broader adoption in human-occupied spaces. Addressing microbial risks through targeted interventions, better materials, and more comprehensive guidelines is crucial for the future of this technology. Future research should focus on investigating non-Legionella microbial risks and refining mitigation strategies to ensure safe, long-term operation of evaporative cooling systems in various applications, including healthcare and residential buildings.

CRediT authorship contribution statement

Łukasz Stefaniak: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Sylwia Szczęśniak:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Juliusz Walaszczyk:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Krzysztof Rajski:** Writing – review & editing, Supervision, Formal analysis. **Katarzyna Piekarska:** Writing – review & editing, Supervision, Formal analysis. **Jan Danielewicz:** Writing – review & editing, Supervision, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

[1] R.H. Mohammed, M. El-Morsi, O. Abdelaziz, Indirect evaporative cooling for buildings: a comprehensive patents review, J. Build. Eng. 50 (2022) 104158, https://doi.org/10.1016/J.JOBE.2022.104158.
[2] M. Kalsia, A. Sharma, R. Kaushik, R.S. Dondapati, Evaporative cooling technologies: conceptual review study, Evergreen 10 (2023) 421–429, https://doi.org/10.5109/6781102.
[3] S. Szczęśniak, Ł. Stefaniak, Global warming potential of new gaseous refrigerants used in chillers in HVAC systems, Energ. (Basel) 15 (2022), https://doi.org/10.3390/en15165999.
[4] T.A. Ndukaife, A.G.A. Nnanna, Optimization of water consumption in hybrid evaporative cooling air conditioning systems for data center cooling applications, Heat Transf. Eng. 40 (2019) 559–573, https://doi.org/10.1080/01457632.2018.1436418.
[5] Palmowska A. Analiza warunków cieplno-wilgotnościowych w Data Center. CIEPŁOWNICTWO, OGRZEWNICTWO, WENTYLACJA 2022;1:17–23. https://doi.org/10.15199/9.2022.4.3.
[6] T. Sun, X. Huang, C. Liang, R. Liu, Y. Yan, Energy consumption and energy saving analysis of air-conditioning systems of data centers in typical cities in China, Sustainability 15 (2023) 7826, https://doi.org/10.3390/su15107826.
[7] S. Ghani, E.M.A.A. El-Bialy, F. Bakochristou, M. Mohamed Rashwan, A. Mohamed Abdelhalim, S. Mohammad Ismail, et al., Experimental and numerical investigation of the thermal performance of evaporative cooled greenhouses in hot and arid climates, Sci. Technol. Built. Environ. 26 (2020) 141–160, https://doi.org/10.1080/23744731.2019.1634421.
[8] H.M.U. Raza, M. Sultan, M. Bahrami, A.A. Khan, Experimental investigation of evaporative cooling systems for agricultural storage and livestock air-conditioning in Pakistan, Build. Simul. 14 (2021) 617–631, https://doi.org/10.1007/s12273-020-0678-2.
[9] D. Rehman, E. McGarrigle, L. Glicksman, E. Verploegen, A heat and mass transport model of clay pot evaporative coolers for vegetable storage, Int. J. Heat Mass Transf. 162 (2020) 120270, https://doi.org/10.1016/j.ijheatmasstransfer.2020.120270.
[10] K.M. Rangel, G. Delclos, R. Emery, E. Symanski, Assessing maintenance of evaporative cooling systems in legionellosis outbreaks, J. Occup. Environ. Hyg. 8 (2011) 249–265, https://doi.org/10.1080/15459624.2011.565409.
[11] J.D. Johnston, A.F. Cowger, K.S. Weber, Bioaerosol and microbial exposures from residential evaporative coolers and their potential health outcomes: a review, Indoor Air 32 (2022) e13082, https://doi.org/10.1111/INA.13082.
[12] B. Crook, L. Willerton, D. Smith, L. Wilson, V. Poran, J. Helps, et al., Legionella risk in evaporative cooling systems and underlying causes of associated breaches in health and safety compliance, Int. J. Hyg. Environ. Health 224 (2020) 113425, https://doi.org/10.1016/J.IJHEH.2019.113425.
[13] K. Piekarska, A. Trusz, S. Szczęśniak, Bacteria and fungi in two air handling units with air recirculating module, Energ. Build. 178 (2018) 154–164, https://doi.org/10.1016/j.enbuild.2018.08.036.
[14] S. Szczęśniak, A. Trusz-Zdybek, K. Piekarska, Preliminary sanitary analysis of supply and exhaust air of ventilation units working at special rooms, E3S Web Conferen. 22 (2017) 00171, https://doi.org/10.1051/e3sconf/20172200171.
[15] A. Bakker, J.A. Siegel, M.J. Mendell, J. Peccia, Building and environmental factors that influence bacterial and fungal loading on air conditioning cooling coils, Indoor Air 28 (2018) 689–696, https://doi.org/10.1111/ina.12474.
[16] A. Bakker, J.A. Siegel, M.J. Mendell, A.J. Prussin, L.C. Marr, J. Peccia, Bacterial and fungal ecology on air conditioning cooling coils is influenced by climate and building factors, Indoor Air 30 (2020) 326–334, https://doi.org/10.1111/ina.12632.
[17] M. Campaña, R. del Hoyo, A. Monleón-Getino, J. Checa, Predicting Legionella contamination in cooling towers and evaporative condensers from microbiological and physicochemical parameters, Int. J. Hyg. Environ. Health 248 (2023) 114117, https://doi.org/10.1016/J.IJHEH.2023.114117.
[18] D.O. Schwake, A. Alum, M. Abbaszadegan, Legionella occurrence beyond cooling towers and premise plumbing, Microorganisms 9 (2021) 2543, https://doi.org/10.3390/MICROORGANISMS9122543. Page 2543 2021;9.
[19] R.L. Brigmon, C.E. Turick, A.S. Knox, C.E. Burckhalter, The impact of storms on legionella pneumophila in cooling tower water, implications for human health, Front. Microbiol. 11 (2020) 543589, https://doi.org/10.3389/FMICB.2020.543589/BIBTEX.
[20] A.T. Paniagua, K. Paranjape, M. Hu, E. Bédard, S.P. Faucher, Impact of temperature on Legionella pneumophila, its protozoan host cells, and the microbial diversity of the biofilm community of a pilot cooling tower, Sci. Tot. Environ. 712 (2020) 136131, https://doi.org/10.1016/J.SCITOTENV.2019.136131.
[21] Y. Yang, G. Cui, C.Q. Lan, Developments in evaporative cooling and enhanced evaporative cooling - a review, Renew. Sustain. Energy Rev. 113 (2019) 109230, https://doi.org/10.1016/j.rser.2019.06.037.
[22] H. Yang, W. Shi, Y. Chen, Y Min, Research development of indirect evaporative cooling technology: an updated review, Renew. Sustain. Energy Rev. 145 (2021) 111082, https://doi.org/10.1016/j.rser.2021.111082.
[23] Y. Cui, J. Zhu, S. Zoras, L. Liu, Review of the recent advances in dew point evaporative cooling technology: 3E (energy, economic and environmental) assessments, Renew. Sustain. Energy Rev. 148 (2021) 111345, https://doi.org/10.1016/j.rser.2021.111345.
[24] J. Lv, H. Xu, M. Zhu, Y. Dai, H. Liu, Z. Li, The performance and model of porous materials in the indirect evaporative cooling system: a review, J. Build. Eng. 41 (2021) 102741, https://doi.org/10.1016/j.jobe.2021.102741.
[25] A. Tejero-González, A. Franco-Salas, Optimal operation of evaporative cooling pads: a review, Renew. Sustain. Energy Rev. 151 (2021) 111632, https://doi.org/10.1016/J.RSER.2021.111632.
[26] U. Sajjad, N. Abbas, K. Hamid, S. Abbas, I. Hussain, S.M. Ammar, et al., A review of recent advances in indirect evaporative cooling technology, Int. Commun. Heat Mass Transf. 122 (2021) 105140, https://doi.org/10.1016/j.icheatmasstransfer.2021.105140.
[27] G. Zhu, T. Wen, Q. Wang, X. Xu, A review of dew-point evaporative cooling: recent advances and future development, Appl. Energ. 312 (2022) 118785, https://doi.org/10.1016/j.apenergy.2022.118785.
[28] S. Abdullah, M.N.B.M. Zubir, Muhamad MR Bin, K.M.S. Newaz, H.F. Öztop, M. S. Alam, et al., Technological development of evaporative cooling systems and its integration with air dehumidification processes: a review, Energ. Build. 283 (2023) 112805, https://doi.org/10.1016/J.ENBUILD.2023.112805.

[29] X. Xiao, J. Liu, A state-of-art review of dew point evaporative cooling technology and integrated applications, Renew. Sustain. Energy Rev. 191 (2024) 114142, https://doi.org/10.1016/J.RSER.2023.114142.
[30] A. Li, Z. Liu, X. Zhu, Y. Liu, Q. Wang, The effect of air-conditioning parameters and deposition dust on microbial growth in supply air ducts, Energ. Build. 42 (2010) 449–454, https://doi.org/10.1016/j.enbuild.2009.10.013.
[31] J. Macher, J. Girman, Multiplication of microorganisms in an evaporative air cooler and possible indoor air contamination, Environ. Int. 16 (1990) 203–211, https://doi.org/10.1016/0160-4120(90)90114-L.
[32] J.M. Macher, J.R. Girman, L.A. Alevantis, Limited water-to-air bacterial transfer from a residential evaporative air cooler, Environ. Int. 21 (1995) 761–764, https://doi.org/10.1016/0160-4120(95)00088-2.
[33] F.J. Rey Martinez, E. Velasco Gómez, R. Herrero Martin, J. Martinez Gutiérrez, F Varela Diez, Comparative study of two different evaporative systems: an indirect evaporative cooler and a semi-indirect ceramic evaporative cooler, Energ. Build. 36 (2004) 696–708, https://doi.org/10.1016/j.enbuild.2003.10.010.
[34] H.T. El-Dessouky, H.M. Ettouney, W. Bouhamra, A novel air conditioning system: membrane air drying and evaporative cooling, Chem. Eng. Res. Des. 78 (2000) 999–1009, https://doi.org/10.1205/026387600528111.
[35] M.C. Ndukwu, S.I. Manuwa, Review of research and application of evaporative cooling in preservation of fresh agricultural produce, Int. J. Agricult. Biolog. Eng. 7 (2014) 85–102, https://doi.org/10.25165/IJABE.V7I5.1174.
[36] H.T. El-Dessouky, H.M. Ettouney, W. Bouhamra, A novel air conditioning system: membrane air drying and evaporative cooling, Chem. Eng. Res. Des. 78 (2000) 999–1009, https://doi.org/10.1205/026387600528111.
[37] Y. Al Horr, B. Tashtoush, N. Chilengwe, M Musthafa, Operational mode optimization of indirect evaporative cooling in hot climates, Case Stud. Therm. Eng. 18 (2020) 100574, https://doi.org/10.1016/J.CSITE.2019.100574.
[38] W. Gao, W. Worek, V. Konduru, K. Adensin, Numerical study on performance of a desiccant cooling system with indirect evaporative cooler, Energ. Build. 86 (2015) 16–24, https://doi.org/10.1016/J.ENBUILD.2014.09.049.
[39] A.E. Kabeel, M. Abdelgaied, R. Sathyamurthy, T. Arunkumar, Performance improvement of a hybrid air conditioning system using the indirect evaporative cooler with internal baffles as a pre-cooling unit, Alexandr. Eng. J. 56 (2017) 395–403, https://doi.org/10.1016/J.AEJ.2017.04.005.
[40] P. Szałański, W. Cepiński, M.A. Sayegh, Leakage in air handling units, the effects on the transmission of airborne infections, Build. Environ. 233 (2023) 110074, https://doi.org/10.1016/J.BUILDENV.2023.110074.
[41] M. Gołofit-Szymczak, A. Ławniczek-Wałczyk, R.L. Górny, Narażenie pracowników konserwujących instalacje wentylacyjne na szkodliwe czynniki mikrobiologiczne, Medycyna Pracy Worker. Health Saf. 64 (2014) 613–623, https://doi.org/10.13075/MP.5893.2013.0066.
[42] H.H. Hussain, N.T. Ibraheem, N.K.F. Al-Rubaey, M.M. Radhi, N.K.K. Hindi, R.H. K. AL-Jubori, A review of airborne contaminated microorganisms associated with human diseases, Med. J. Babyl. 19 (2022) 115–122, https://doi.org/10.4103/MJBL.MJBL_20_22.
[43] W. Kim, H.W. Dong, J. Park, M. Sung, J.W. Jeong, Impact of an Ultraviolet Reactor on the Improvement of Air Quality Leaving a Direct Evaporative Cooler, Sustainability 10 (2018) 1123, https://doi.org/10.3390/SU10041123. Vol 10, Page 1123 2018.
[44] D.F. Geary, American Society of Heating, Refrigerating and Air-conditioning Engineers Guideline 12-2000: minimizing the risk of legionellosis associated with building water systems, Legionella (2014) 376–384, https://doi.org/10.1128/9781555817985.CH77.
[45] M. Möritz, H. Peters, B. Nipko, H. Rüden, Capability of air filters to retain airborne bacteria and molds in heating, ventilating and air-conditioning (HVAC) systems, Int. J. Hyg. Environ. Health 203 (2001) 401–409, https://doi.org/10.1078/1438-4639-00054.
[46] P. Hugenholtz, J.A. Fuerst, Heterotrophic bacteria in an air-handling system, Appl. Environ. Microbiol. 58 (1992) 3914–3920, https://doi.org/10.1128/AEM.58.12.3914-3920.1992.
[47] P.C. Kemp, H.G. Neumeister-Kemp, B. Esposito, G. Lysek, F. Murray, Changes in airborne fungi from the outdoors to indoor air; large HVAC systems in nonproblem buildings in two different climates, AIHA J. 64 (2003) 269–275, https://doi.org/10.1080/15428110308984817.
[48] A.R. Ellingson, R.A. LeDoux, P.K. Vedanthan, R.W. Weber, The prevalence of dermatophagoides mite allergen in colorado homes utilizing central evaporative coolers, J. Allerg. Clin. Immunol. 96 (1995) 473–479, https://doi.org/10.1016/S0091-6749(95)70289-X.
[49] C.H. Vanlaar, S.H. Downs, T.Z. Mitakakis, J.D. Leuppi, N.G. Car, J.K. Peat, et al., Predictors of house-dust-mite allergen concentrations in dry regions in Australia, Allergy 56 (2001) 1211–1215, https://doi.org/10.1034/J.1398-9995.2001.00085.X.
[50] R. Boukhanouf, H.G. Ibrahim, A. Alharbi, M. Kanzari, Investigation of an evaporative cooler for buildings in hot and dry climates, J. Clean Energ. Technolog. (2014) 221–225, https://doi.org/10.7763/JOCET.2014.V2.127.
[51] E.M. Sterling, A. Arundel, T.D. Sterling, Criteria for human exposure to humidity in occupied buildings, ASHRAE Trans. 91 (1985) 611–622.
[52] ASHRAE, Humidifiers. 2020 ASHRAE Handbook–HVAC Systems and Equipment, 2020.
[53] Data Center Economizer Contamination and Humidity Study n.d. https://escholarship.org/uc/item/8fm831xf (accessed January 4, 2024).
[54] M. Steeman, A. Janssens, M. De Paepe, Performance evaluation of indirect evaporative cooling using whole-building hygrothermal simulations, Appl. Therm. Eng. 29 (2009) 2870–2875, https://doi.org/10.1016/J.APPLTHERMALENG.2009.02.004.
[55] Q. Chen, M.K. Ja, M. Burhan, M.W. Shahzad, D. Ybyraiymkul, H. Zheng, et al., Experimental study of a sustainable cooling process hybridizing indirect evaporative cooling and mechanical vapor compression, Energ. Rep. 8 (2022) 7945–7956, https://doi.org/10.1016/J.EGYR.2022.06.019.
[56] I. Stefaniak, K. Rajski, J. Danielewicz, Przegląd zastosowania nanopłynów oraz materiałów porowatych w pośrednim chłodzeniu wyparnym, CIEPŁOWNICTWO, OGRZEWNICTWO, WENTYLACJA 1 (2023) 35–42, https://doi.org/10.15199/9.2023.12.5.
[57] M.R. Pais, L.C. Chow, E.T. Mahefkey, Surface roughness and its effects on the heat transfer mechanism in spray cooling, J. Heat Transf. 114 (1992) 211–219, https://doi.org/10.1115/1.2911248.
[58] S. Saha, J. Khan, T. Farouk, Numerical study of evaporation assisted hybrid cooling for thermal powerplant application, Appl. Therm. Eng. 166 (2020) 114677, https://doi.org/10.1016/J.APPLTHERMALENG.2019.114677.
[59] X. Ma, W. Shi, H. Yang, Spray parameter analysis and performance optimization of indirect evaporative cooler considering surface wettability, J. Build. Eng. 82 (2024) 108175, https://doi.org/10.1016/J.JOBE.2023.108175.
[60] M. Yang, H. Ma, S. Ma, A. Nong, Y. Zhang, Y. Ma, Effect of surface wettability on air parameters and performance of indirect evaporative cooler in the presence of primary air condensation, J. Build. Eng. 45 (2022) 103535, https://doi.org/10.1016/J.JOBE.2021.103535.
[61] A.G. Pautsch, T.A. Shedd, G.F. Nellis, Thickness measurements of the thin film in spray evaporative cooling, in: Thermomechanical Phenomena in Electronic Systems -Proceedings of the Intersociety Conference 1, 2004, pp. 70–76, https://doi.org/10.1109/ITHERM.2004.1319156.
[62] K. Czaczyk, K. Wojciechowska, Tworzenie biofilmów bakteryjnych - istota zjawiska i mechanizmy oddziaływań, Biotechnologia (2003).
[63] M. Jamal, W. Ahmad, S. Andleeb, F. Jalil, M. Imran, M.A. Nawaz, et al., Bacterial biofilm and associated infections, J. Chin. Med. Assoc. 81 (2018) 7–11, https://doi.org/10.1016/J.JCMA.2017.07.012.
[64] R.M. Donlan, J.W. Costerton, Biofilms: survival mechanisms of clinically relevant microorganisms, Clin. Microbiol. Rev. 15 (2002) 167–193, https://doi.org/10.1128/CMR.15.2.167-193.2002.
[65] M.R. Parsek, P.K. Singh, Bacterial biofilms: an emerging link to disease pathogenesis, Annu. Rev. Microbiol. 57 (2003) 677–701, https://doi.org/10.1146/ANNUREV.MICRO.57.030502.090720.
[66] C. Picioreanu, M. van Loosdrecht, J. Heijnen, Two-dimensional model of biofilm detachment caused by internal stress from liquid flow, Biotechnol. Bioeng. 72 (2000) 205–218, https://doi.org/10.1002/1097-0290(20000120)72:2<3C205::AID-BIT9>3E3.0.CO;2-L.
[67] D. Mara, N. Horan, Handbook of water and wastewater microbiology. Handbook of Water and Wastewater Microbiology, 2003, pp. 1–819, https://doi.org/10.1016/B978-0-12-470100-7.X5000-6.
[68] Y. You, G. Wang, B. Yang, C. Guo, Y. Ma, B. Cheng, Study on heat transfer characteristics of indirect evaporative cooling system based on secondary side hydrophilic, Energ. Build. 257 (2022) 111704, https://doi.org/10.1016/J.ENBUILD.2021.111704.
[69] Y. Guo, X. Zhao, F. Zhao, Z. Jiao, X. Zhou, G. Yu, Tailoring surface wetting states for ultrafast solar-driven water evaporation, Energ. Environ. Sci. 13 (2020) 2087–2095, https://doi.org/10.1039/D0EE00399A.
[70] Z. Kang, A. Shahzad, J. Fan, Evaporative cooling enhanced by fibrovascular capillary structures, Int. J. Therm. Sci. 202 (2024) 109058, https://doi.org/10.1016/J.IJTHERMALSCI.2024.109058.
[71] N. Čuk, B. Simončič, R. Fink, B. Tomšič, Bacterial adhesion to natural and synthetic fibre-forming polymers: influence of material properties, Polym. (Basel) 16 (2024) 2409, https://doi.org/10.3390/POLYM16172409. Vol 16, Page 2409 2024.
[72] A. Møllebjerg, L.G. Palmén, K. Gori, R.L. Meyer, The bacterial life cycle in textiles is governed by fiber hydrophobicity, Microbiol. Spectr. 9 (2021), https://doi.org/10.1128/SPECTRUM.01185-21.
[73] P. Gu, N. Fan, Y. Wang, J. Wang, P. Müller-Buschbaum, Q Zhong, Linear control of moisture permeability and anti-adhesion of bacteria in a broad temperature region realized by cross-linking thermoresponsive microgels onto cotton fabrics, ACS Appl. Mater. Interface. 11 (2019) 30269–30277, https://doi.org/10.1021/ACSAMI.9B09294.
[74] S. Bajpai, V. Bajpai, A. Dey, S. Ghosh, M.K. Jha, Study of adherence kinetics of Escherichia coli on cotton knitted fabrics, India. Chem. Eng. 61 (2019) 296–308, https://doi.org/10.1080/00194506.2018.1554455.
[75] T. Hemmatian, H. Lee, J. Kim, Bacteria adhesion of textiles influenced by wettability and pore characteristics of fibrous substrates, Polym. (Basel) 13 (2021) 223, https://doi.org/10.3390/POLYM13020223. Page 223 2021;13.
[76] M. Takashima, F. Shirai, M. Sageshima, N. Ikeda, Y. Okamoto, Y. Dohi, Distinctive bacteria-binding property of cloth materials, Am. J. Infect. Control 32 (2004) 27–30, https://doi.org/10.1016/j.ajic.2003.05.003.
[77] Y. Jiang, Y.J. Yin, X.C. Zha, X.Q. Dou, C.L. Feng, Wettability regulated gram-negative bacterial adhesion on biomimetic hierarchical structures, Chin. Chem. Lett. 28 (2017) 813–817, https://doi.org/10.1016/J.CCLET.2016.08.002.
[78] Y. Yuan, M.P. Hays, P.R. Hardwidge, J. Kim, Surface characteristics influencing bacterial adhesion to polymeric substrates, RSC Adv. 7 (2017) 14254–14261, https://doi.org/10.1039/C7RA01571B.
[79] X. Zhao, Porous materials for direct and indirect evaporative cooling in buildings, Mater. Energy Effici. Therm. Comfor. Build. (2010) 399–426, https://doi.org/10.1533/9781845699277.2.399.

[80] M. Alodan, A. Al-Faraj, Design and evaluation of Galvanized metal sheets as evaporative cooling pads, J. King Saud Univ. - Eng. Sci. (2005).
[81] E. Sofia, N. Putra, E.A. Kosasih, Development of indirect evaporative cooler based on a finned heat pipe with a natural-fiber cooling pad, Heliyon 8 (2022) e12508, https://doi.org/10.1016/j.heliyon.2022.e12508.
[82] E. Ibrahim, L. Shao, S.B. Riffat, Performance of porous ceramic evaporators for building cooling application, Energ. Build. 35 (2003) 941–949, https://doi.org/10.1016/S0378-7788(03)00019-7.
[83] M.W. Shahzad, J. Lin, Xu B Bin, L. Dala, Q. Chen, M. Burhan, et al., A spatiotemporal indirect evaporative cooler enabled by transiently interceding water mist, Energy 217 (2021) 119352, https://doi.org/10.1016/j.energy.2020.119352.
[84] P. Hambleton, M.G. Broster, P.J. Dennis, R. Henstridge, R. Fitzgeorge, J. W. Conlan, Survival of virulent Legionella pneumophila in aerosols, Epidemiol. Infect. 90 (1983) 451–460, https://doi.org/10.1017/S0022172400029090.
[85] R. Schulze-Röbbecke, M. Rödder, M. Exner, Vermehrungs- und Abtötungstemperaturen natürlich vorkommender Legionellen [Multiplication and killing temperatures of naturally occurring legionellas], Zentralbl Bakteriol Mikrobiol Hyg B Umwelthyg Krankenhaushyg Arbeitshyg Prav Med 184 (1987) 495–500.
[86] A.M. Spagnolo, M.L. Cristina, B. Casini, F. Perdelli, Legionella pneumophila in healthcare facilities, Rev. Res. Med. Microbiol. 24 (2013) 70–80, https://doi.org/10.1097/MRM.0B013E328362FE66.
[87] M.V. Storey, N.J. Ashbolt, T.A. Stenström, Biofilms, thermophilic amoebae and Legionella pneumophila - a quantitative risk assessment for distributed water, Water Sci. Technol. 50 (2004) 77–82, https://doi.org/10.2166/WST.2004.0023.
[88] N. Wéry, V. Bru-Adan, C. Minervini, J.P. Delgénes, L. Garrelly, J.J. Godon, Dynamics of Legionella spp. and bacterial populations during the proliferation of L. pneumophila in a cooling tower facility, Appl. Environ. Microbiol. 74 (2008) 3030–3037, https://doi.org/10.1128/AEM.02760-07.
[89] H. Yamamoto, M. Ikedo, E. Yabuuchi, I. Urakami, K. Nakano, Effects of FLONLIZER®, ultraviolet sterilizer, on legionella species inhabiting cooling tower water, Microbiol. Immunol. 31 (1987) 745–752, https://doi.org/10.1111/J.1348-0421.1987.TB03136.X.
[90] H. Yamamoto, T. Ezaki, M. Ikedo, Y. Eiko, Effects of biocidal treatments to inhibit the growth of legionellae and other microorganisms in cooling towers, Microbiol. Immunol. 35 (1991) 795–802, https://doi.org/10.1111/J.1348-0421.1991.TB01612.X.
[91] J.M. Kusnetsov, A.I. Tulkki, H.E. Ahonen, P.J. Martikainen, Efficacy of three prevention strategies against legionella in cooling water systems, J Appl Microbiol 82 (1997) 763–768, https://doi.org/10.1046/J.1365-2672.1997.00151.X.
[92] Z. Duan, C. Zhan, X. Zhao, X. Dong, Experimental study of a counter-flow regenerative evaporative cooler, Build. Environ. 104 (2016) 47–58, https://doi.org/10.1016/j.buildenv.2016.04.029.
[93] A. Nocker, L. Schulte-Illingheim, J. Frösler, L. Welp, O. Sperber, A. Hugo, Microbiological examination of water and aerosols from four industrial evaporative cooling systems in regard to risk of Legionella emissions and methodological suggestions for surveillance, Int. J. Hyg. Environ. Health 229 (2020) 113591, https://doi.org/10.1016/J.IJHEH.2020.113591.
[94] E. Masaka, S. Reed, M. Davidson, J. Oosthuizen, Opportunistic premise plumbing pathogens. A potential health risk in water mist systems used as a cooling intervention, Pathogens 10 (2021) 462, https://doi.org/10.3390/PATHOGENS10040462/S1.
[95] J. Żywiec, D. Szpak, K. Wartalska, M. Grzegorzek, The impact of climate change on the failure of water supply infrastructure: a bibliometric analysis of the current state of knowledge, Water (Basel) 16 (2024) 1043, https://doi.org/10.3390/W16071043. Vol 16, Page 1043 2024.
[96] M. Grzegorzek, K. Wartalska, B. Kaźmierczak, Review of water treatment methods with a focus on energy consumption, Int. Commun. Heat Mass Transf. 143 (2023) 106674, https://doi.org/10.1016/J.ICHEATMASSTRANSFER.2023.106674.
[97] A.K. Plappally, V.J.H Lienhard, Energy requirements for water production, treatment, end use, reclamation, and disposal, Renew. Sustain. Energy Rev. 16 (2012) 4818–4848, https://doi.org/10.1016/J.RSER.2012.05.022.
[98] K. Przestrzelska, W. Katarzyna, W. Rosińska, J. Jakub, B. Kaźmierczak, Climate resilient cities: a review of blue-green solutions worldwide, Water Res.our. Manage. (2024) 1–26, https://doi.org/10.1007/S11269-024-03950-5, 2024.
[99] E. Reynaert, É. Sylvestre, E. Morgenroth, T.R. Julian, Greywater recycling for diverse collection scales and appliances: enteric pathogen log-removal targets and treatment trains, Water Res. 264 (2024) 122216, https://doi.org/10.1016/J.WATRES.2024.122216.
[100] R. Li, W. Wang, Y. Shi, C.-T. Wang, P. Wang, R. Li, et al., Advanced material design and engineering for water-based evaporative cooling, Adv. Mater. 36 (2024) 2209460, https://doi.org/10.1002/ADMA.202209460.
[101] C.A. Hviid, D. Zukowska-Tejsen, V. Nielsen, Cooling of schools – results from a demonstration project using adiabatic evaporative cooling with harvested rainwater, E3S Web Conferen. 172 (2020) 02003, https://doi.org/10.1051/E3SCONF/202017202003.
[102] S. Englart, Analysis of rainwater use in membrane-based semi-direct evaporative cooling of air, J. Build. Eng. 90 (2024) 109409, https://doi.org/10.1016/J.JOBE.2024.109409.
[103] E.R. McKenzie, T.E. Pistochini, F.J. Loge, M.P. Modera, An investigation of coupling evaporative cooling and decentralized graywater treatment in the residential sector, Build. Environ. 68 (2013) 215–224, https://doi.org/10.1016/J.BUILDENV.2013.07.007.
[104] A.E. Kabeel, M.M. Bassuoni, A simplified experimentally tested theoretical model to reduce water consumption of a direct evaporative cooler for dry climates, Int. J. Refrigerat. 82 (2017) 487–494, https://doi.org/10.1016/J.IJREFRIG.2017.06.010.
[105] M. Yan, S. He, M. Gao, M. Xu, J. Miao, X. Huang, et al., Comparative study on the cooling performance of evaporative cooling systems using seawater and freshwater, Int. J. Refrigerat. 121 (2021) 23–32, https://doi.org/10.1016/J.IJREFRIG.2020.10.003.
[106] R.M. Lefers, P.A. Davies, N.V. Fedoroff, N. Almadhoun, M.A. Tester, T Leiknes, Proof of concept: Pozzolan bricks for saline water evaporative cooling in controlled environment agriculture, Appl. Eng. Agric. 34 (2018) 929–937, https://doi.org/10.13031/aea.13013.
[107] Y.-K. Leung, K Wai Eric Cheng, Carbon footprint reduction by reclaiming condensed water, Sustainability 16 (2024) 3867, https://doi.org/10.3390/SU16093867. Vol 16, Page 3867 2024.

energies

MDPI

Article

The Possibility of Intermittent Water Spray Implementation in a Non-Porous Indirect Evaporative Cooler

Łukasz Stefaniak *, Juliusz Walaszczyk, Michał Karpuk, Krzysztof Rajski and Jan Danielewicz

Faculty of Environmental Engineering, Wrocław University of Science and Technology, 50377 Wrocław, Poland
* Correspondence: lukasz.stefaniak@pwr.edu.pl

Abstract: Evaporative cooling is a sustainable and energy-efficient technology based on water evaporation to achieve cooling. It uses air (R-729) and water (R-718) as refrigerants, so its effect on global warming is limited. Recent research focuses development of porous heat exchanger surfaces to be used in evaporative cooling technology with intermittent water spray. However, non-porous surfaces were not investigated. Here, we present the possibility of implementing intermittent water spray in a non-porous indirect evaporative cooler. The experimental results show that it increases the cooling capacity when compared to the constant water spray for chosen outdoor air parameters (20–30 °C and 40–50% relative humidity). Also, the time after the outlet air temperature achieves minimum value (4–6 min) is presented for a certain non-porous heat exchanger. The maximum cooling capacity obtained without spraying is 25–64% higher than the cooling capacity in steady-state conditions under constant water spraying. The regression model approach is employed to describe the observation. The results introduce a new path in evaporative cooling technology development. They also create the possibility of improving the effectiveness of existing systems by modifying only the water system management, without any changes in construction or replacing the heat exchanger.

Keywords: air conditioning; natural refrigerants; sustainable cooling; cooling performance; energy efficiency

check for updates

Academic Editors: Tadeusz Bohdal and Marcin Kruzel

Received: 23 January 2025
Revised: 3 February 2025
Accepted: 10 February 2025
Published: 12 February 2025

Citation: Stefaniak, Ł.; Walaszczyk, J.; Karpuk, M.; Rajski, K.; Danielewicz, J. The Possibility of Intermittent Water Spray Implementation in a Non-Porous Indirect Evaporative Cooler. *Energies* **2025**, *18*, 882. https://doi.org/10.3390/en18040882

1. Introduction

The rising global temperature and frequent extreme heat events present significant challenges to the cooling sector [1,2], particularly in ensuring energy-efficient and environmentally friendly air conditioning solutions [3,4]. Conventional air conditioning systems, predominantly based on vapor compression cycles, pose multiple challenges. Their average energy efficiency ratio (EER) is around 5, with advanced systems reaching an EER greater than 10 [5]. Despite this progress, these systems rely mostly on synthetic refrigerants, which have considerable short- and long-term environmental repercussions, including high global warming potential (GWP) [6]. This has driven researchers to explore alternative cooling technologies that are sustainable, energy-efficient, and less reliant on environmentally harmful refrigerants [7–9].

1.1. Evaporative Cooling Technology

Evaporative cooling (EC) has emerged as a promising alternative to traditional cooling systems. It offers low-cost and reliable solutions using natural refrigerants such as air and water (R-718 and R-729) [10–12]. In direct evaporative cooling (DEC), warm air passes through a water-saturated medium, where the evaporation of water absorbs heat from the air, resulting in cooler, more humid air. However, conventional DEC, since it adds moisture to treated air, has limited applicability in many scenarios, particularly in humid climates [13]. To overcome these limitations, indirect evaporative cooling (IEC) was developed. IEC systems cool air without adding moisture by transferring heat between separate air and water streams, keeping the moisture content of the supply air at the same level as the outside air. Despite their advantages, IEC systems are limited by their inability to cool air below the wet bulb temperature of the inlet air. To enhance the efficiency of IEC systems, researchers have introduced dew point indirect evaporative cooling (DIEC), which takes advantage of sensible and latent heat transfer mechanisms. By recirculating precooled air into the wet channel, DIEC systems achieve supply air temperatures below the wet bulb temperature of the inlet air, significantly improving cooling performance. While substantial progress has been made in understanding and developing these technologies, there remains a critical need to explore innovative techniques to further improve their efficiency, particularly in addressing the heat exchanger material and operational challenges of non-porous indirect evaporative coolers. The schemes of EC types with short descriptions are presented in Figure 1.

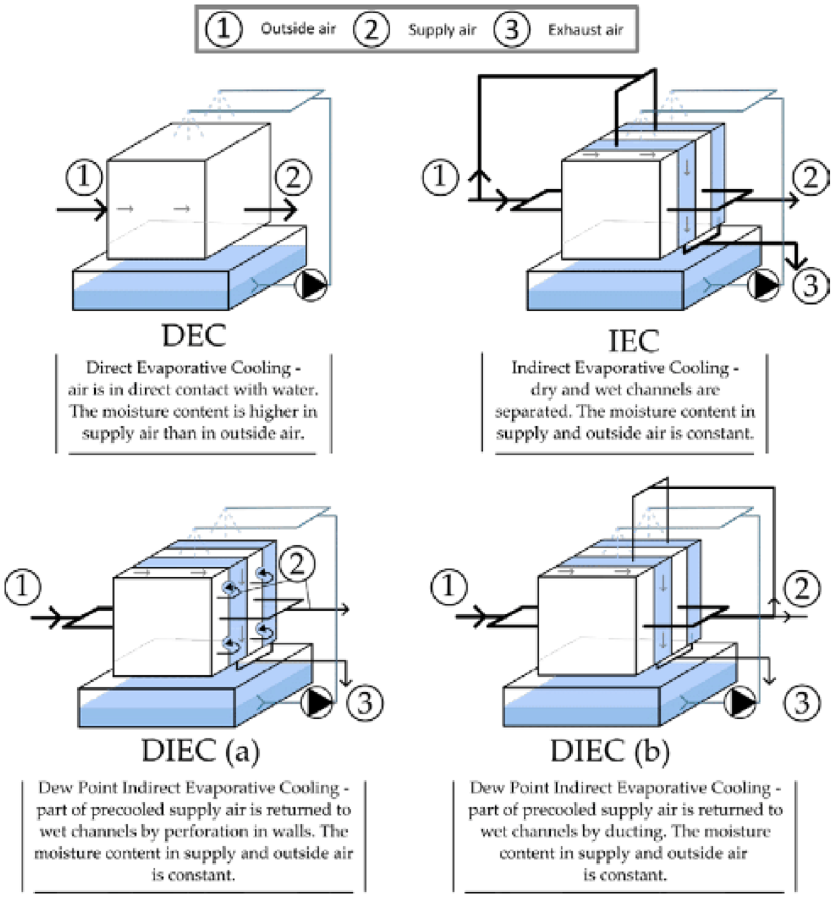


Figure 1. Evaporative cooling technology schemes, based on [14].

1.2. Heat Exchanger Material

Heat exchanger materials play a crucial role in the performance and durability of IEC and DIEC systems. These systems rely on heat exchangers to transfer energy between primary (dry) and secondary (wet) air streams, using both sensible and latent heat. The material used for heat exchangers affects thermal conductivity, water retention, and corrosion resistance, all of which are critical for efficiency and lifespan.

An important goal of modifying the surface of the wet side exchanger walls is to ensure an even and possibly thin layer of water film on the entire heat exchanger surface. Non-porous materials are commonly used, as they are easy to maintain and safer in terms of microbial risk [14], which is crucial in HVAC systems [15]. In an operating device, a situation can occur when only part of the wall on the wet side is covered with a water film, which limits the area from which the water evaporates [16]. Therefore, the potential of the evaporative cooling process is limited. Also, there cannot be too much water on the walls. Due to its high specific heat, water increases thermal inertia and becomes an additional insulator on the heat-exchange path between the dry and wet channels [16]. The graphical representation of the problems with the water film on the wet channel side is shown in Figure 2. It is also necessary to take into account the type of material used to make the exchanger itself. Not all materials used to cover the walls of the wet channel are waterproof. And it is precisely the waterproofness and ensuring the rigidity of the structure that are required from the material from which the heat exchanger is built. Currently, plastic walls are used, which are attractive in financial terms and, at the same time, ensure the rigidity of the structure. Aluminum is also often used, as it has very good heat conduction properties (between the dry and wet channels). Currently, the aim of the exchanger design is to have the thinnest walls possible with high thermal conductivity and high wettability on the wet channel side. This affects mainly the size of devices for indirect evaporative cooling.

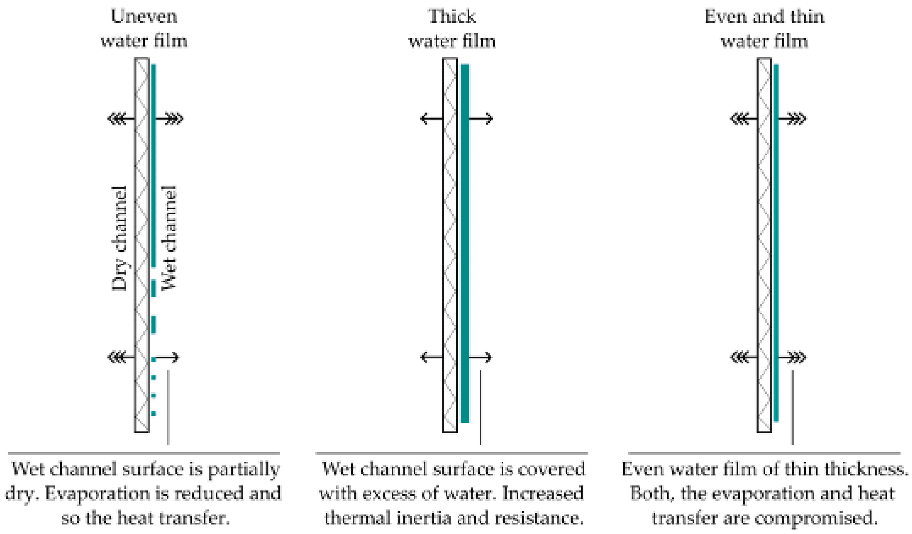


Figure 2. Wet channel surface water film, based on [17].

However, aluminum alloys, plastics, composites, and steel face the problem of water storage feature. Therefore, plates coating [18–20] and porous materials [21,22] are widely used. The reason is the idea of limiting the operating time of spray water pumps. In a situation where water is stored on the walls of the wet channel, there is no need for a continuous supply of water by pumps. As a result, the demand for electrical energy is reduced, and thus, the balance of energy supplied to the system becomes more favorable.

1.3. Intermittent Water System Operation

The development of IEC systems has focused on the modification of heat exchangers by integrating porous materials. These materials improve water distribution, improve surface wettability, and minimize water splashing, while also providing the heat exchanger with the ability to store water [23–25]. This allowed the introduction of the intermittent water system operation. This advancement is particularly significant in the context of global water shortages and rising costs of water treatment [26]. Energy savings are also important when the pump operation time is reduced [24], as the world aims to reduce electricity consumption and become independent of, e.g., energy imports [26]. Intermittent water supply, in particular, has emerged as an effective approach to improving the efficiency of DIEC systems equipped with porous heat exchangers.

For example, Xu et al. [25] proved energy savings (50–70% reduction in electricity consumption) and an increase in the coefficient of performance (COP) by 100–160% when employing the Coolmax® (Taipei, Taiwan) material layer for heat exchanger walls with an intermittent water supply. The system operated with water supply durations of 15 or 60 s in 10 min cycles. Sun et al. [27] investigated various intermittent spray algorithms, ranging from 8 to 45 s of spray time with pump pauses of 1 to 3 min, using porous ceramic tubular heat exchangers. Shi et al. [28] investigated a plate-type porous IEC system with a sintered nickel layer. The pump could remain stopped for up to 2105 s, leading to a 95% reduction in pump operation time and a 117% improvement in COP. In a follow-up study conducted in 2022, Shi et al. [29] expanded this research by optimizing pump stop intervals to range from 1270 to 2410 s, achieving more than double the COP compared to continuous water supply.

In general, intermittent water system operation has proven to be a promising approach to improving the energy efficiency and performance of DIEC coolers. When the pump operation time is reduced, the COP parameter especially is increased as the energy consumption is reduced. Combined with increased effectiveness, this is a recent path of investigation in EC technology.

1.4. Research Gap

As a recent advance in EC technology, intermittent water spraying is investigated in various publications. Based on the research presented in Table 1, all of them investigate a porous heat exchanger surface. The types of these surfaces are also listed, as they are important in terms of water storage capacities and the potential application of intermittent water spraying [16,20]. The water spray intervals examined in the publications of Table 1 are presented in Figure 3. The authors identified the research gap in the field of intermittent water spraying in heat exchangers with non-porous heat exchanger surface.

Table 1. Intermittent water supply investigation, with focus on heat exchanger surface type.

Year	Source	Type *	Porous Heat Exchanger Surface	Surface Type
2017	Xu et al. [25]	E	Yes	Fabric
2017	Wang et al. [30]	E	Yes	Ceramics
2020	Sun et al. [27]	E	Yes	Ceramics
2021	Elahi et al. [31]	E	Yes	-
2021	Chen et al. [32]	E	Yes	Plant fiber–polymer composite
2022	Shi et al. [29]	T/E	Yes	Stainless steel + sintered porous nickel
2022	Shi et al. [28]	E	Yes	Stainless steel + sintered porous nickel
2023	Shi et al. [33]	E	Yes	Stainless steel + sintered porous nickel
2023	Chen et al. [34]	E	Yes	Fiber fabric
2023	Chen et al. [35]	E	Yes	TiO_2/SiO_2 nano-coated polypropylene
2024	Chen et al. [19]	E	Yes	TiO_2/SiO_2 nano-coated polypropylene
2024	Khan et al. [36]	E	Yes	SuperKool cellulose cooling pad

* E—experimental; T—theoretical.

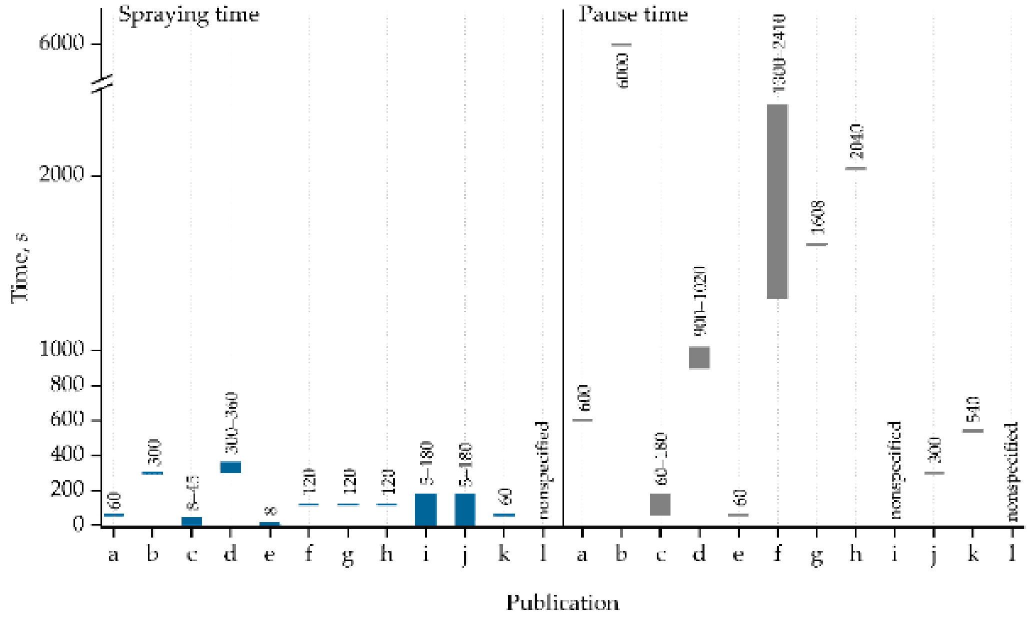


Figure 3. Water system operation intervals for publications: a [25], b [30], c [27], d [31], e [32], f [29], g [28], h [33], i [34], j [35], k [19], l [36].

1.5. *Objective and Novelty of the Study*

The idea of our work is to present experimental data on the process of drying of the non-porous heat exchanger after the water system shuts off. As stated above, papers tackling the idea of intermittent water spraying have already set water systems' pause time. However, there are insufficient experiments or analyses on how the heat exchanger will operate when no more water is sprayed in a longer period of time.

The authors provide results for an experimental investigation on the performance of DIEC when the water supply was shut off after achieving a steady-state condition. Three inlet air temperatures (20, 25, and 30 °C) were evaluated, and for each temperature, three relative humidity values were investigated (40, 45, and 50%). The device was observed for more than 70 min after the supply system was turned off. This resulted in an observation on DIEC with non-porous heat exchanger operation when drying.

The results presented in this study can initiate further investigation on evaporative cooling devices with non-porous surfaces but with upgraded water supply systems (intermittent spraying).

2. Materials and Methods

In this section, the authors describe the experimental setup in detail, selected experimental parameters and a regression model. A schematic and an actual photograph of the test rig are provided, along with details on the specifications and placement of the measuring instruments.

2.1. *Test Rig*

The performance evaluation was carried out using a prototype test rig. A real photo and a schematic diagram of the device, including the arrangement of measurement instruments, is shown in Figure 4. The rig consists of a cooling coil, a heater, and a humidifier, enabling air treatment independent of outdoor conditions. Two fans with inverters are installed.

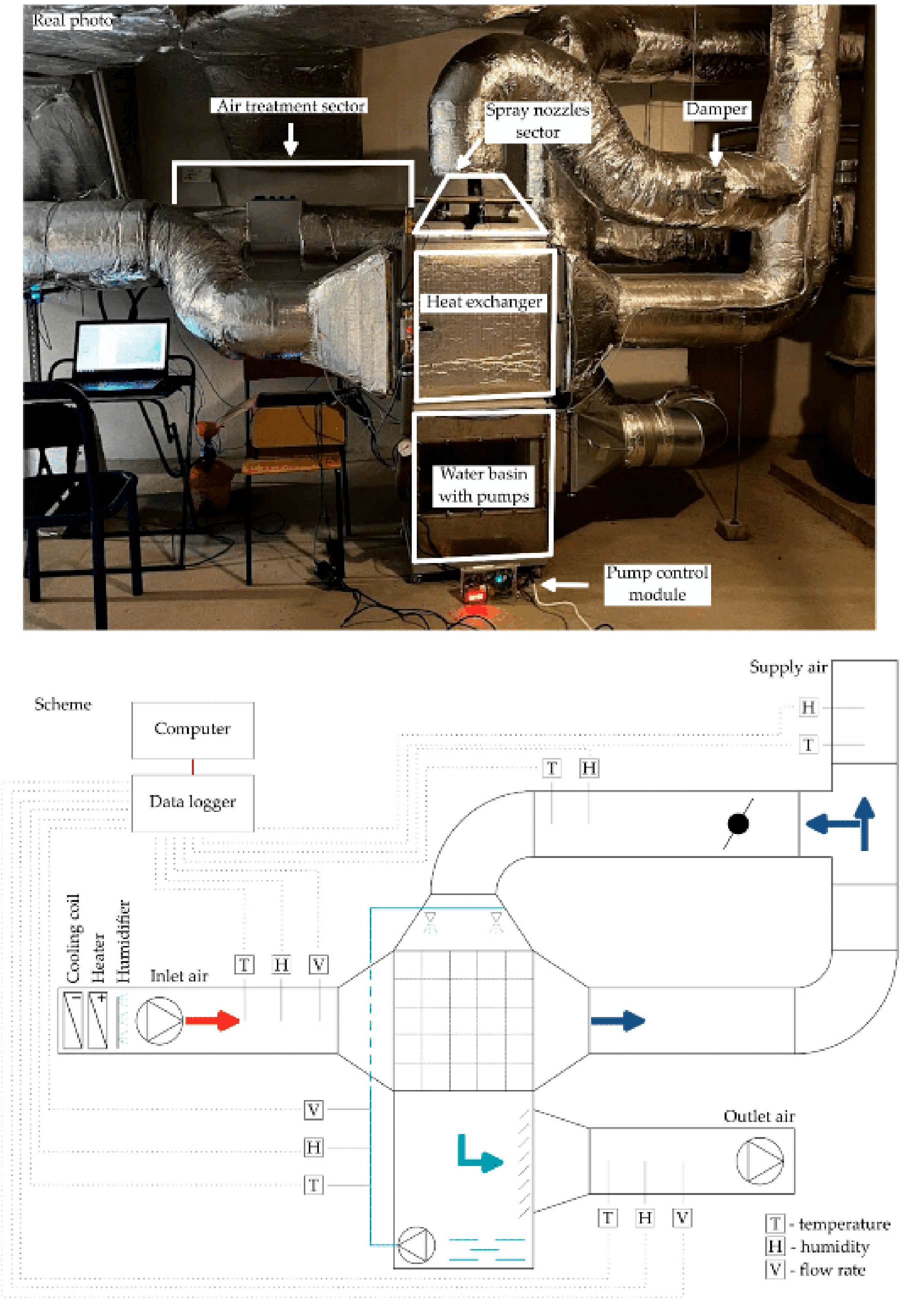


Figure 4. Experimental device real photo and schematic configuration (red arrow—inlet air, blue—supply air, teal—outlet air).

2.1.1. Airflow Organization

The rig, which is thermally insulated, operates as a cross-flow DIEC with a horizontal air inlet. Air is supplied directly from the outside, above the roof. The temperature and moisture content can be changed before entering the heat exchanger. The air is then cooled in the device. A portion of the cooled supply air is recirculated and transported vertically into the wet channel from the top. An adjustable damper can be used to regulate the purge ratio. The remaining supply air is delivered to the cooled space, while the outlet air is exhausted through a droplet eliminator outside the building. The air is supplied by fans of type JETTEC 250/2400F by Harmann Ventilators with inverters of type SV004iC5-1F by LG, Cheoan, Korea.

2.1.2. Heat Exchanger

The heat exchanger consists of 115 alternately arranged non-hydrophilic polymer plates, forming wet and dry channels. The real photo of a part of the heat exchanger is presented in Figure 5. Both the wet and dry channel dimensions are 500 × 500 mm. The height of both channels is 2 mm. The side walls of the heat exchanger are insulated with mineral wool to minimize the influence of the surrounding.

Figure 5. Real photo of the heat exchanger, dry channels.

2.1.3. Water System

The water is supplied to the heat exchanger by two serially connected pumps of type DC50E-24150S. Then, it is sprayed with four full cone nozzles of type BETE WL–½ 120 BSP (Figure 6) located 140 mm above the heat exchanger. The excess water is collected in a reservoir at the bottom of the rig, where the pumps are mounted. In the wet channel, air and water flow in parallel. The water pipes are also insulated.

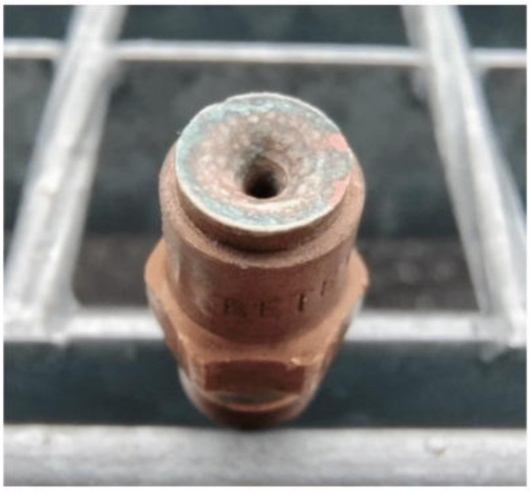


Figure 6. Nozzle used in the experiment (BETE WL–½ 120 BSP).

2.1.4. Measurements

Temperature (T), relative humidity (H), and volumetric flow rate (V) measurements were taken at the locations marked in Figure 4, with data recorded every second. To ensure steady-state conditions, the rig was operated for at least 45 min before data collection. The steady state was confirmed when the temperature fluctuations remained within ±1% and the relative humidity fluctuations within ±5% over a 5-minute period, as described in previous studies [26,29,36]. The specifications of the measuring devices used in the experiment are presented in Table 2.

Table 2. Measurement device specifications.

	Parameter	Instrument	Accuracy
Air	Temperature	Sensirion SHT25	±0.2 °C
	Relative humidity	Sensirion SHT25	1.8% (RH 10–90%), 3% (RH 90–100%)
	Flow rate (inlet)	SMAY IRIS 250	5%
	Flow rate (outlet)	Lindab FMU-FMDRU 250-200	5%
Water	Temperature	WIKA TF37 Pt100/4/F0,15	±(0.15 + 0.002 t)
	Flow rate	IFM SM6004 magnetic-inductive flow meter	±(2% MW * + 0.5% MEW **)

* measured value, ** final value of the measuring range.

2.1.5. Parameter Setting

The aim of the paper was to investigate the operation of the DIEC with a nonporous heat exchanger after the water supply is stopped. Its purpose was to evaluate whether there is a possibility of intermittent water spraying in the hydrophobic heat exchanger. Inlet air parameters were chosen according to what is observed in a temperate climate in Europe [37,38]. Also, high relative humidity (50%) was evaluated, as evaporative cooling is claimed to work best in arid climate [39]. Table 3 presents all experimental parameters.

Table 3. Experimental parameters.

Parameter	Value	Unit
Inlet air temperature	20, 25, 30	°C
Inlet air relative humidity	40, 45, 50	%
Water flow rate	5.94	L/min
Inlet air flow rate	540	m^3/h
Purge ratio	35	%
Air velocity in dry channel	2.0	m/s

2.2. Regression Model

Our paper is focused on the cooling performance after the water system shuts off. Inlet air parameters and air flow rates are constant during the operation with the water system turned off; therefore, the crucial parameter observed and measured is the outlet air temperature from the dry channel (T_2). Outlet air temperature changes with time during the drying process and affects cooling performance over time. Predictions about outlet air temperature during the drying phase will provide essential data to evaluate cooling performance for different inlet air parameters. For that reason, a regression model was developed. It aims to predict the time series of the outlet air temperature from the DIEC device. Also, a regression model of outlet air relative humidity (RH_2) was developed, as in [40].

The measurement time-series data were affected by short-term fluctuations. Therefore, the Simple Moving Average (SMA) was used to smooth the data and reduce noise [41–43]. The averaging data points over a 1200 s period of experiment for each parameter were used for model preparations. The statistical model was prepared, based on the assumption that T2 (dry channel outlet temperature) and RH2 (dry channel outlet relative humidity) depend on T1 (inlet air temperature), RH1 (inlet air relative humidity), and time τ, what can be described as Equations (1) and (2).

$$T_2 = f(T_1, RH_1, \tau), \tag{1}$$

$$RH_2 = f(T_1, RH_1, \tau), \tag{2}$$

2.2.1. Operation After Water System Turnoff

In order to understand the model and the approach of the authors, the description of the operation of the system after the water system is turned off is crucial. In every parameter setting investigated, the same shape of the supply air temperature T_2 chart was observed (Figure 7). The water system turnoff is at $\tau = 0$ s. T_2 value was measured over a 40 minute period of time. In further analysis, the data were presented for shorter period of time (1200 s). This is due to the fact that after point 4, there are no significant changes in temperature T_2

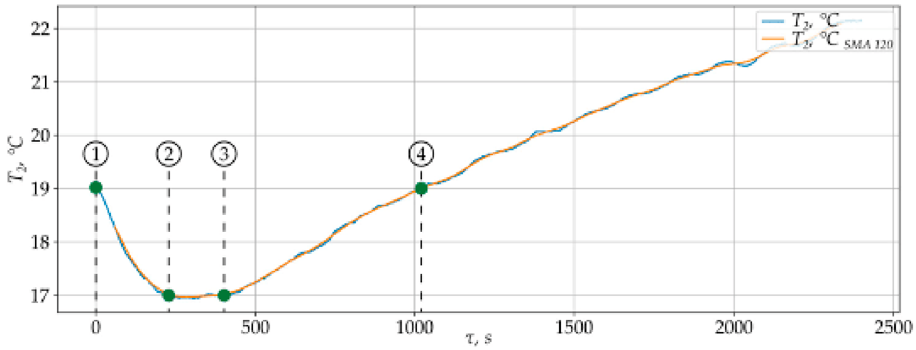


Figure 7. Supply air temperature after water system turnoff, example for inlet air temperature 25 °C and inlet air relative humidity 45%.

The chart can be divided by 4 points (as visible in Figure 7):

1. Turnoff of the water system;
2. Lowest T_2 value is achieved;
3. T_2 value starts to increase;
4. T_2 is equal to the T_2 in $\tau = 0$ s.

From point 1 to 2, a significant T_2 drop is observed (in the example, the drop achieves 2 K). At the same time, there is an increase in cooling power as a direct result of T_2 drop. In point 2, the minimum T_2 value is achieved, and it is stable up to point 3. After that, the T_2 starts to increase, and in point 4, it achieves a temperature equal to that of point 1.

The time between points 1 and 4 can be used to utilize lower supply air temperature. At the same time, the energy consumption is reduced, as the water pumping system does not operate.

As this observation is promising in terms of energy consumption and efficiency of the system itself, the authors focused on T_2 characteristics.

2.2.2. Regression Analysis

As described previously, the drying process of the DIEC device consists of two processes: (i) when T_2 rapidly decreases; (ii) increase back to its original value at point 4. The time between points 1 and 4 is crucial for an increase in cooling performance due to shut-off of the water system. Based on the data measured for the first 1200 s after the water system is shut off, the authors prepared a regression model [44,45].

The process (i), when T_2 is decreasing, can be described as a general form of differential equation, as Equation (3),

$$dT_2 \sim -T_2 d\tau, \tag{3}$$

which means that decreasing T_2 is related to time. The solution of that differential equation is in the form of an exponential relation, as shown in Equation (4).

$$T_2 = a \cdot e^{-b\tau}, \tag{4}$$

A similar relation was applied for the relative humidity of the outlet air.

The process (ii), when T_2 is increasing back, can be described as a logistic function, as in Equation (5),

$$f(x) = \frac{1}{1 + e^{-x}}, \tag{5}$$

which has value ½ at x = 0 and value 1 when x approaches infinity. The logistic function has a similar shape as T_2 when increasing (point 2 and 4 in Figure 7), especially when T_2 drifts towards T_1 as a final point of the drying process (point 3 to 4 in Figure 7). Eventually, the proposed form of the logistic function is presented in Equation (6),

$$\frac{c}{1 + d \cdot e^{-f(\tau-\tau_0)}}, \tag{6}$$

where τ_0 is a time when T_2 has a minimum value.

The processes (i) and (ii) were combined into an additive regression model of T_2 and RH_2 in relation to time τ in Equation (7):

$$\left(a \cdot e^{-b\cdot\tau} + \frac{c}{1 + d \cdot e^{-f(\tau-\tau_0)}}\right), \tag{7}$$

It was also presented in relation to T_1 and RH_1, as described in Equation (8):

$$C_1 \cdot T_1 + C_2 \cdot \sqrt{T_1 \cdot RH_1} + C_3 \cdot RH_1, \tag{8}$$

Finally, the additive regression model of T_2 was established in the form of Equation (9) and the model of RH_2 in the form of Equation (10).

$$T_2(\tau, T_1, RH_1) = A + B \cdot \left(a \cdot e^{-b\cdot\tau} + \frac{c}{1 + d \cdot e^{-f(\tau-\tau_0)}}\right) + C_1 \cdot T_1 + C_2 \cdot \sqrt{T_1 \cdot RH_1} + C_3 \cdot RH_1, \tag{9}$$

$$RH_2(\tau, T_1, RH_1) = \widetilde{A} + \widetilde{B} \cdot \left(\widetilde{a} \cdot e^{-\widetilde{b}\cdot\tau} + \frac{\widetilde{c}}{1 + \widetilde{d} \cdot e^{-\widetilde{f}(\tau-\tau_0)}}\right) + \widetilde{C}_1 \cdot T_1 + \widetilde{C}_2 \cdot \sqrt{T_1 \cdot RH_1} + \widetilde{C}_3 \cdot RH_1, \tag{10}$$

The point τ_0, when T_2 has the lowest value in each time series was also modelled in Equation (11).

$$\tau_0 = a_0 + a_{T_1} \cdot T_1 + a_{T_1 RH_1} \cdot \sqrt{RH_1 \cdot T_1} + a_{RH_1} \cdot RH_1, \tag{11}$$

Parameters a_0, a_{T1}, a_{T1RH1}, a_{RH1} for Eq. 11 were established (Table 4).

Table 4. Parameters for Equation (11).

a_0	a_{T1}	a_{T1RH1}	a_{RH1}
348.7261	71.3488	−111.0783	41.6207

The parameters of T_2 (Equation (9)) and RH_2 (Equation (10)) models (with empirical t t_{emp}) were calculated based on nonlinear least squares method and are presented in Table 5 and Table 6, respectively.

Table 5. Parameters for T_2 model (Equation (9)).

Parameter		Standard Deviation	95% Confidence Interval		t_{emp}
a	4.2129	1.4395	3.0125	5.8915	4.29
b	0.0059	0.0021	0.0041	0.0084	14.41
c	23.2458	5.2116	18.6112	29.0345	14.15
d	0.4185	0.2749	0.2258	0.7756	1.41
f	0.0009	0.0010	0.0004	0.0024	7.28
A	−27.2041	0.1240	−27.4473	−26.9610	−219.32
B	1.0215	0.0059	1.0100	1.0331	173.41
C_1	0.0693	0.0199	0.0302	0.1084	3.48
C_2	1.1074	0.0296	1.0493	1.1654	37.41
C_3	−0.2654	0.0112	−0.2874	−0.2434	−23.64

Table 6. Parameters for RH_2 model (Equation (10)).

Parameter		Standard Deviation	95% Confidence Interval		t_{emp}
a	53.9280	3.6521	50.3995	57.7037	58.93
b	0.0003	0.0000	0.0002	0.0003	74.39
c	20.8809	3.9974	17.2628	25.2575	15.97
d	0.0691	0.0081	0.0615	0.0777	22.77
f	0.0108	0.0013	0.0096	0.0122	36.91
A	−52.9753	0.4150	−53.7880	−52.1620	−127.73
B	0.9666	0.0060	0.9560	0.9770	174.04
C_1	1.9228	0.0690	1.7880	2.0580	27.96
C_2	−2.2500	0.1020	50.3995	57.7037	58.93
C_3	1.8252	0.0390	0.0002	0.0003	74.39

All parameters in Tables 5 and 6 are significant, because t_{emp} was higher than $t_\alpha \approx 2$ (except for d in Table 5) (for n = 1200 samples for every inlet air parameter tested), i.e., higher than critical t value in t-Distribution with significance level of 0.05. The determination coefficient R^2 of the T_2 model is 0.980, and R^2 of the RH_2 model is 0.907. That is, the model explains approximately 98.0 percent of the variability in the outlet temperature and approximately 90.7 percent of the variability in the outlet relative humidity.

3. Results and Discussion

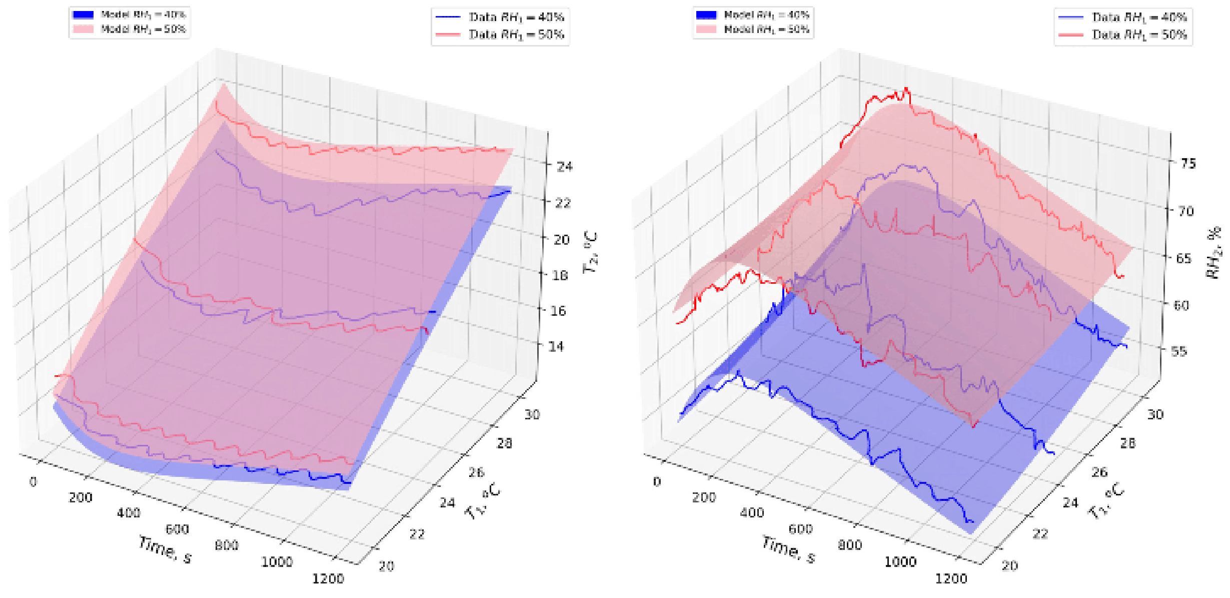
The main idea of the article is to evaluate the operation of the non-porous DIEC heat exchanger after the water system is turned off. In this part, we present the effect of stopping the water supply on the performance of the examined system.

3.1. Supply Air Parameters

Figure 8a represents the outlet air temperature (T_2), and Figure 8b represents the outlet air relative humidity (RH_2) as a function of the same parameters: time (τ), inlet air temperature (T_1), and inlet relative humidity (RH_1). In both cases, the experimental and modeled data are presented. The shapes of the graphs are strictly correlated, as the moisture content is constant (the heat exchanger is indirect, and there is no condensation observed). Therefore, the decrease in temperature results in an increase in relative humidity.

In Figure 8a, along the τ axis, there is a visible trend just after the water system stops (at τ = 0 s). T_2 values experience a sharp decline at the initial stages of operation, followed by achieving the lowest temperature, and steadily increase as the system approaches steady state. Further on, along the T_1 axis, higher inlet temperatures lead to higher stabilized outlet temperatures, while lower inlet relative humidity (RH_1) enhances the cooling performance

(T_2 is lower). Also, with the increase in T_1, there is a greater distance between surfaces for RH_1 = 40% and RH_1 = 50%. This suggests that in lower inlet air temperatures (T_1), inlet air relative humidity (RH_1) does not influence the supply air temperature (T_2) as much as in the case of higher T_1.



(**a**) (**b**)

Figure 8. Experimental (lines) and modelled (surface) values for (**a**) supply air temperature (T_2); (**b**) relative humidity (RH_2).

Overall, higher RH_1 results in reduced cooling performance (higher T_2), while lower T_1 enhances the cooling effect (lower T_2). The general trend (described in Figure 7) is observed across the investigated parameters.

3.2. *Cooling Capacity*

Cooling capacities were presented for three specific situations. Figure 9 on surface Q_1 (red) presents the cooling capacity achieved in steady-state conditions, when constant spraying is used. Therefore, it is the result for point 1 (also for point 4, as T_2 in point 1 is equal to T_2 in point 4) in Figure 7. Figure 9 on surface Q_2 (green) represents the maximum cooling capacity that can be achieved due to the T_2 drop after the water system is turned off. It is calculated for the minimum T_2 value. The last surface Q_3 (blue) in Figure 9 is the result of the average value between points 1 and 4 in Figure 7. It represents the average cooling capacity that can be achieved in time after the water system is turned off, and T_2 will fall down and rise up to the same temperature as in τ = 0 s.

The shape of the surfaces is similar in every case. The location of the blue surface (Q_3) is not exactly in the middle between the Q_1 and Q_2 surface. Therefore, when utilizing the effect after the water system turnoff, it is possible to achieve a cooling capacity close to the maximum possible cooling capacity (the difference is about 100 W).

The results are consistent with the general knowledge on evaporative cooling. The higher the temperature and the lower the relative humidity, the higher the cooling capacity. This trend is consistent in every case described. It is worth noting that the authors investigated relatively low temperatures as well, and still there was cooling potential, even at

20 °C as the inlet air temperature. It is a promising result in terms of using evaporative cooling in relatively low temperatures and high relative humidities.

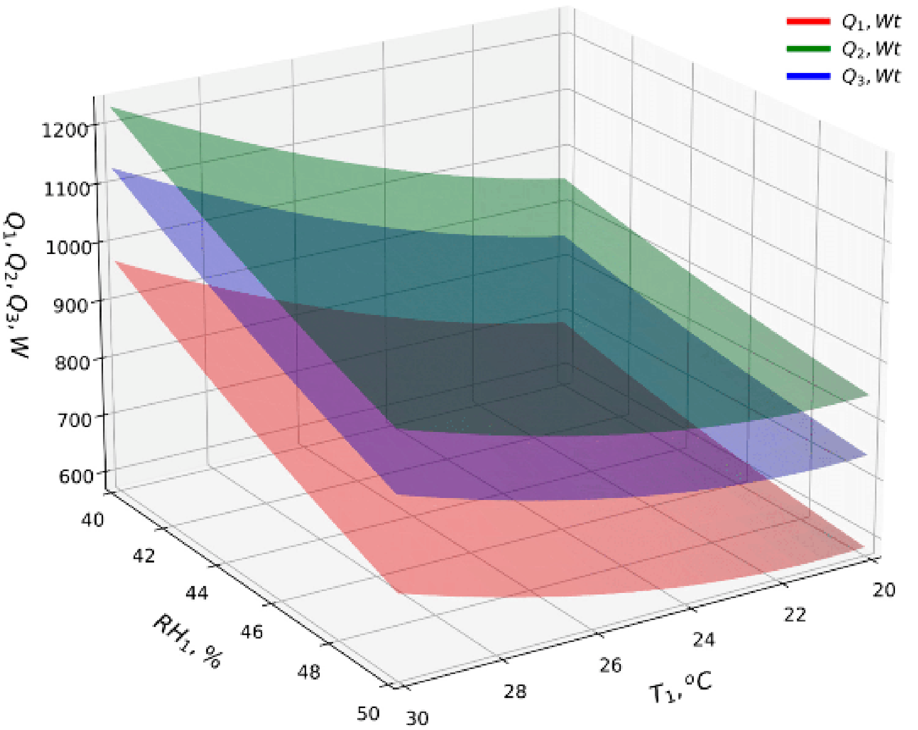


Figure 9. Cooling capacity modeled values: Q_1 in steady-state conditions under constant spraying (point 1 in Figure 7); Q_2 maximum value when T_2 achieves its minimum (point 2 in Figure 7); Q_3 average value for period from points 1 to 4 in Figure 7.

3.3. *Minimum Supply Air Temperature (T_2)*

The experiment resulted in an interesting finding about the system achieving minimum supply air temperature (T_2). The time it takes the system to achieve the minimum value is presented in Table 7. Generally, it is between 4 and 6 min, independent of the inlet air parameters. It can be an indicator for further development of the experiment that from the point of achieving minimum T_2 value, a certain amount of time should pass, and spraying should be turned on again to keep the T_2 at the lower level than in the constant spraying conditions. Overall, it shows that an intermittent water supply can be implemented to increase the performance of the DIEC.

Table 7. Time to achieve minimum supply air temperature.

T_1, °C	RH_1, %	Time to Achieve Minimum T_2, s
20	40	315
	45	339
	50	314
25	40	261
	45	307
	50	308
30	40	322
	45	320
	50	254

The supply air temperature (T_2) achieved by the investigated device under varying inlet air parameters (inlet air temperature (T_1) and relative humidity (RH_1)) is presented in Figure 10. The results indicate that the supply air temperature is strongly influenced by the inlet air conditions. Specifically, T_2 decreases with lower values of T_1 and higher RH_1.

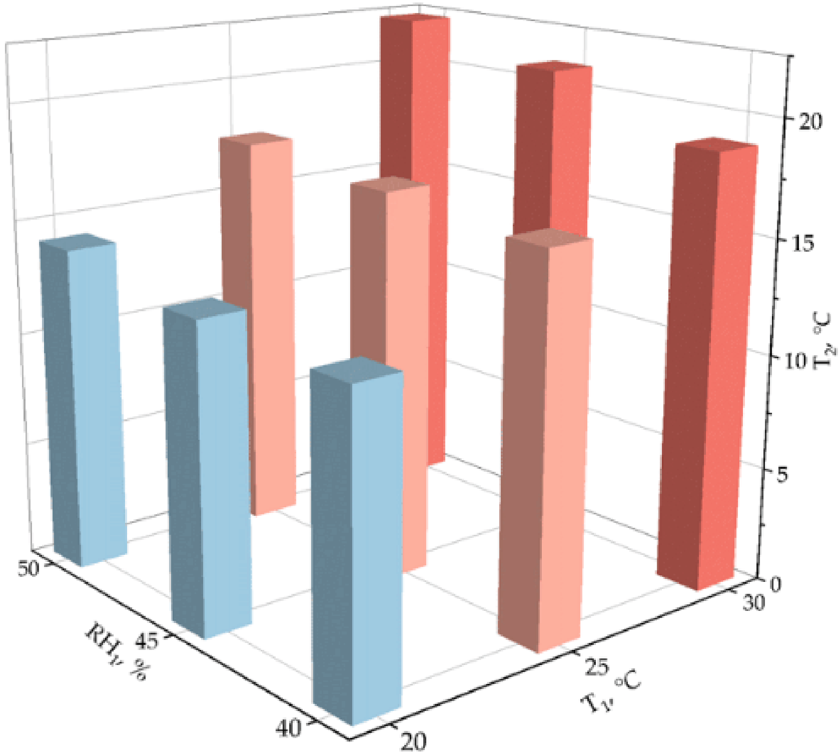


Figure 10. Supply air temperature (T_2) for different inlet air (T_1) parameters.

The temperature difference between T_1 and T_2 represents how much the inlet air can be cooled down. For T_1 = 20 °C, the difference is in a range of 5.9–7.0 K; for T_1 = 25 °C, 7.5–8.6 K; and for T_1 = 30 °C, 7.8–11.1 K. Overall, these results provide data about the suitability of dew point indirect evaporative cooling for climates with moderate to high relative humidity and demonstrate its potential for energy-efficient cooling, particularly in regions where the inlet air conditions fall within the optimal operating range for this technology.

4. Conclusions

This research addresses a significant gap by focusing on non-porous heat exchanger surfaces, demonstrating the potential for intermittent water supply application. The following conclusions may be drawn from the experiment:

- The experimental findings reveal that in the investigated device, after the water system is turned off, the supply air temperature (T_2) decreases initially by 5.9–11.1 K, stabilizes at a minimum value, and then gradually rises back to the initial temperature. This characteristic offers an opportunity for optimizing intermittent water spraying cycles.
- The investigated system can also work in moderate climate conditions.
- Evaporative cooling devices with non-porous surfaces but with upgraded water supply system (intermittent spraying) have great potential for improvements in terms of energy efficiency (water pump pause time can achieve up to around 1000 s).

- The findings suggest that there is a specific time (4–6 min) after water system turnoff when the cooling capacity achieves maximum value. Optimized pause time in intermittent water supply can enhance DIEC performance, providing a basis for future research.
- Future studies can focus on developing control systems for intermittent spraying to maximize performance and energy efficiency in varying climatic conditions.

Author Contributions: Conceptualization, Ł.S., J.W. and J.D.; methodology, Ł.S., J.W. and M.K.; software, M.K.; validation, M.K.; formal analysis, Ł.S., J.W. and M.K.; investigation, Ł.S.; resources, Ł.S. and K.R.; data curation, Ł.S., J.W. and M.K.; writing—original draft preparation, Ł.S., J.W. and M.K.; writing—review and editing, Ł.S., J.W., M.K., K.R. and J.D.; visualization, Ł.S., J.W. and M.K.; supervision, K.R. and J.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Tahir, F.; Al-Ghamdi, S.G. Climatic Change Impacts on the Energy Requirements for the Built Environment Sector. *Energy Rep.* **2023**, *9*, 670–676. [CrossRef]
2. Labriet, M.; Joshi, S.R.; Vielle, M.; Holden, P.B.; Edwards, N.R.; Kanudia, A.; Loulou, R.; Babonneau, F. Worldwide Impacts of Climate Change on Energy for Heating and Cooling. *Mitig. Adapt. Strateg. Glob. Change* **2015**, *20*, 1111–1136. [CrossRef]
3. Szcześniak, S. Systemy Wentylacji i Klimatyzacji Budynków w Kontekście Neutralności Węglowej. *Ciepłownictwo Ogrzewnictwo Wentylacja* **2024**, *1*, 33–40. [CrossRef]
4. Dhawan, V.; Shah, N.; Dreyfuss, G.; Zaelke, D.; Osho, Z.; Murphy, A.; Seth, S. *Low Carbon Development Pathways for Cooling: Leveraging Kigali Amendment Across Residential Applications*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2023. [CrossRef]
5. Shahzad, M.W.; Burhan, M.; Ybyraiymkul, D.; Oh, S.J.; Ng, K.C. An Improved Indirect Evaporative Cooler Experimental Investigation. *Appl. Energy* **2019**, *256*, 113934. [CrossRef]
6. Szcześniak, S.; Stefaniak, Ł. Global Warming Potential of New Gaseous Refrigerants Used in Chillers in HVAC Systems. *Energies* **2022**, *15*, 5999. [CrossRef]
7. Lundgren-Kownacki, K.; Hornyanszky, E.D.; Chu, T.A.; Olsson, J.A.; Becker, P. Challenges of Using Air Conditioning in an Increasingly Hot Climate. *Int. J. Biometeorol.* **2018**, *62*, 401–412. [CrossRef] [PubMed]
8. Ismail, M.; Yebiyo, M.; Chaer, I. A Review of Recent Advances in Emerging Alternative Heating and Cooling Technologies. *Energies* **2021**, *14*, 502. [CrossRef]
9. Pezzutto, S.; Quaglini, G.; Riviere, P.; Kranzl, L.; Novelli, A.; Zambito, A.; Wilczynski, E. Screening of Cooling Technologies in Europe: Alternatives to Vapour Compression and Possible Market Developments. *Sustainability* **2022**, *14*, 2971. [CrossRef]
10. Xiao, X.; Liu, J. A State-of-Art Review of Dew Point Evaporative Cooling Technology and Integrated Applications. *Renew. Sustain. Energy Rev.* **2024**, *191*, 114142. [CrossRef]
11. Lai, L.; Wang, X.; Hu, E.; Choon Ng, K. A Vision of Dew Point Evaporative Cooling: Opportunities and Challenges. *Appl. Therm. Eng.* **2024**, *244*, 122683. [CrossRef]
12. Li, R.; Wang, W.; Shi, Y.; Wang, C.-T.; Wang, P.; Li, R.; Wang, W.; Shi, Y.; Wang, P.; Wang, C.-T. Advanced Material Design and Engineering for Water-Based Evaporative Cooling. *Adv. Mater.* **2024**, *36*, 2209460. [CrossRef] [PubMed]
13. Yang, Y.; Cui, G.; Lan, C.Q. Developments in Evaporative Cooling and Enhanced Evaporative Cooling—A Review. *Renew. Sustain. Energy Rev.* **2019**, *113*, 109230. [CrossRef]
14. Stefaniak, Ł.; Szcześniak, S.; Walaszczyk, J.; Rajski, K.; Piekarska, K.; Danielewicz, J. Challenges and Future Directions in Evaporative Cooling: Balancing Sustainable Cooling with Microbial Safety. *Build Environ.* **2025**, *267*, 112292. [CrossRef]
15. Gorlach, J.; Gazda, D.; Trusz, A.; Walaszczyk, J.J.; Szczęsniak, S.; Piekarska, K. Ventilation and Air Conditioning Systems Are a Source of Antibiotic-Resistant Bacteria—A Review. *Build Environ.* **2025**, *271*, 112583. [CrossRef]
16. Yang, H.; Shi, W.; Chen, Y.; Min, Y. Research Development of Indirect Evaporative Cooling Technology: An Updated Review. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111082. [CrossRef]

17. Stefaniak, Ł.; Rajski, K.; Danielewicz, J. Przegląd Zastosowania Nanopłynów Oraz Materiałów Porowatych w Pośrednim Chłodzeniu Wyparnym. *Ciepłownictwo Ogrzewnictwo Wentylacja* **2023**, *1*, 35–42. [CrossRef]
18. Guilizzoni, M.; Milani, S.; Liberati, P.; De Antonellis, S. Effect of Plates Coating on Performance of an Indirect Evaporative Cooling System. *Int. J. Refrig.* **2019**, *104*, 367–375. [CrossRef]
19. Chen, Y.; Liu, L.; Yan, H.; Tao, Q.; Fan, Y. Study of a Nano-Coated Hydrophilic Polymer for Indirect Evaporative Cooler from Wetting, Thermal and Corrosion Resistance Performance. *Appl. Therm. Eng.* **2024**, *257*, 124180. [CrossRef]
20. You, Y.; Wang, G.; Yang, B.; Guo, C.; Ma, Y.; Cheng, B. Study on Heat Transfer Characteristics of Indirect Evaporative Cooling System Based on Secondary Side Hydrophilic. *Energy Build.* **2022**, *257*, 111704. [CrossRef]
21. Zhao, X. Porous Materials for Direct and Indirect Evaporative Cooling in Buildings. In *Materials for Energy Efficiency and Thermal Comfort in Buildings*; Elsevier: Amsterdam, The Netherlands, 2010; pp. 399–426.
22. Wijaksana, H.; Winaya, I.N.S.; Sucipta, M.; Ghurri, A. An Overview of Different Indirect and Semi-Indirect Evaporative Cooling System for Study Potency of Nanopore Skinless Bamboo as An Evaporative Cooling New Porous Material. *J. Adv. Res. Fluid Mech. Therm. Sci.* **2020**, *76*, 109–116. [CrossRef]
23. Sofia, E.; Putra, N. Evaporative Cooling Innovations—A Review. In *AIP Conference Proceedings*; AIP Publishing: New York, NY, USA, 2020; p. 020036.
24. Sofia, E.; Putra, N.; Kosasih, E.A. Development of Indirect Evaporative Cooler Based on a Finned Heat Pipe with a Natural-Fiber Cooling Pad. *Heliyon* **2022**, *8*, e12508. [CrossRef] [PubMed]
25. Xu, P.; Ma, X.; Zhao, X.; Fancey, K. Experimental Investigation of a Super Performance Dew Point Air Cooler. *Appl. Energy* **2017**, *203*, 761–777. [CrossRef]
26. Grzegorzek, M.; Wartalska, K.; Kaźmierczak, B. Review of Water Treatment Methods with a Focus on Energy Consumption. *Int. Commun. Heat Mass Transf.* **2023**, *143*, 106674. [CrossRef]
27. Sun, T.; Huang, X.; Chen, Y.; Zhang, H. Experimental Investigation of Water Spraying in an Indirect Evaporative Cooler from Nozzle Type and Spray Strategy Perspectives. *Energy Build.* **2020**, *214*, 109871. [CrossRef]
28. Shi, W.; Min, Y.; Ma, X.; Chen, Y.; Yang, H. Performance Evaluation of a Novel Plate-Type Porous Indirect Evaporative Cooling System: An Experimental Study. *J. Build. Eng.* **2022**, *48*, 103898. [CrossRef]
29. Shi, W.; Min, Y.; Ma, X.; Chen, Y.; Yang, H. Dynamic Performance Evaluation of Porous Indirect Evaporative Cooling System with Intermittent Spraying Strategies. *Appl. Energy* **2022**, *311*, 118598. [CrossRef]
30. Wang, F.; Sun, T.; Huang, X.; Chen, Y.; Yang, H. Experimental Research on a Novel Porous Ceramic Tube Type Indirect Evaporative Cooler. *Appl. Therm. Eng.* **2017**, *125*, 1191–1199. [CrossRef]
31. Elahi, S.H.; Farhani, S.D. Increasing Evaporative Cooler Efficiency by Controlling Water Pump Run and off Times. *Int. Commun. Heat Mass Transf.* **2021**, *127*, 105525. [CrossRef]
32. Chen, Y.; Huang, X.; Sun, T.; Chu, J. Experimental Study of Plant Fiber-Polymer Composite for Indirect Evaporative Cooler Application. *Appl. Therm. Eng.* **2021**, *199*, 117543. [CrossRef]
33. Shi, W.; Yang, H.; Ma, X.; Liu, X. A Novel Indirect Evaporative Cooler with Porous Media under Dual Spraying Modes: A Comparative Analysis from Energy, Exergy, and Environmental Perspectives. *J. Build. Eng.* **2023**, *76*, 106874. [CrossRef]
34. Chen, Y.; Yan, H.; Min, Y. Visualized Study of Wetting Enhancement and Thermal Performance of Fiber-Coated Indirect Evaporative Cooler. *Appl. Therm. Eng.* **2023**, *221*, 119904. [CrossRef]
35. Chen, Y.; Yan, H.; Pan, Y. Wetting and Evaporative Performance Analysis of Wet Channels in Indirect Evaporative Cooler with Hydrophilic Nano-Coating. *Appl. Therm. Eng.* **2023**, *229*, 120622. [CrossRef]
36. Khan, I.; Khalid, W.; Ali, H.M.; Sajid, M.; Ali, Z.; Ali, M. An Experimental Investigation on the Novel Hybrid Indirect Direct Evaporative Cooling System. *Int. Commun. Heat Mass Transf.* **2024**, *155*, 107503. [CrossRef]
37. Szczęśniak, S.; Stefaniak, Ł.; Kanaś, P.; Małyszko, M.; Jaskóła, W.; Brzeźniak, K. O Potrzebie Zmian Parametrów Obliczeniowych Powietrza Zewnętrznego Na Przykładzie Miasta Wrocław. *Ciepłownictwo Ogrzewnictwo Wentylacja* **2023**, *1*, 13–20. [CrossRef]
38. Szczęśniak, S.; Karpuk, M.; Stefaniak, Ł.; Grabka, A.; Michalak, W.; Jaskóła, W.; Maciewicz, M. Obowiązujące Normy Na Tle Rzeczywistych Wartości Temperatury Powietrza Zewnętrznego w Polsce. *Ciepłownictwo Ogrzewnictwo Wentylacja* **2024**, *1*, 22–31. [CrossRef]
39. Abd Manaf, I.; Durrani, F.; Eftekhari, M. A Review of Desiccant Evaporative Cooling Systems in Hot and Humid Climates. *Adv. Build. Energy Res.* **2021**, *15*, 1–42. [CrossRef]
40. Pakari, A.; Ghani, S. Regression Models for Performance Prediction of Counter Flow Dew Point Evaporative Cooling Systems. *Energy Convers. Manag.* **2019**, *185*, 562–573. [CrossRef]
41. Montgomery, D.; Jennings, C.; Kulahci, M. *Introduction to Time Series Analysis and Forecasting*, 2nd ed.; John Wiley & Sons, Inc.: New York, NY, USA, 2015.
42. Fuller, W. *Introduction to Statistical Time Series*, 2nd ed.; John Wiley & Sons, Inc.: New York, NY, USA, 1996.
43. Simonoff, J.S. *Smoothing Methods in Statistics*; Springer: New York, NY, USA, 1996; ISBN 978-1-4612-8472-7.

44. Darlington, R.; Hayes, A. *Regression Analysis and Linear Models. Concepts, Applications, and Implementation*; The Guilford Press: New York, NY, USA, 2017.
45. Montgomery, D.; Peck, E.; Vinning, G. *Introduction to Linear Regression Analysis*, 5th ed.; John Wiley & Sons, Inc.: New York, NY, USA, 2012.

Journal of Building Engineering 105 (2025) 112585

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Experimental performance analysis of non-porous indirect evaporative coolers under intermittent water spraying conditions

Łukasz Stefaniak, Juliusz Walaszczyk, Jan Danielewicz, Krzysztof Rajski *

Faculty of Environmental Engineering, Wrocław University of Science and Technology, 50377, Wrocław, Poland

A R T I C L E I N F O

Keywords:
Air conditioning
Indirect evaporative cooling
Intermittent water spraying
Natural refrigerants
Energy-efficient technology

A B S T R A C T

Faced with extreme global heat, the demand for efficient air conditioning is critical, especially using environmentally friendly technologies such as natural refrigerants. It makes the exploration of traditional solutions, such as evaporative cooling (EC), crucial. Our study investigates the performance of dewpoint indirect evaporative cooling (DIEC) systems, focusing on non-porous heat exchangers with intermittent water supply to enhance cooling efficiency and reduce energy consumption. In this experimental study, we evaluated key performance indicators of the DIEC system, including dew point and wet bulb effectiveness, cooling power, and coefficient of performance (COP), under various water spraying intervals (30 s, 60 s, 90 s of spraying and constant spraying) and different inlet air velocities (1.6 m/s, 2.0 m/s and 2.5 m/s). The results indicate that an intermittent water supply significantly reduces electrical energy consumption without compromising system performance. Notably, the highest COP, ranging from 50 to 107, was observed during the shortest 30-s spraying intervals, compared to a COP of approximately 20 during constant spraying. These findings highlight the effectiveness of optimizing water management strategies in DIEC systems. The adoption of intermittent water supply in DIEC devices with non-porous heat exchangers offers a viable and sustainable path to improving air conditioning efficiency, making it a promising solution for addressing the growing demand for environmentally friendly cooling technologies.

1. Introduction

The world is facing extreme heat phenomena that push the cooling sector to its limits. Only 10 % of the 2.8 billion people living in the hottest parts of the world have access to cooling in their homes [1]. The impact of these changes is also highly visible in the mortality rate among the elderly. For people over 65 years of age, the number of heat-related deaths has increased by 60 % (comparing 2019–2021 to 2002–2004 time period) [2]. Therefore, there is an emerging challenge for the cooling sector to ensure the demand for air conditioning with the highest efficiency and the lowest environmental impact possible.

Shahzad et al. [3] indicate that the market average energy efficiency ratio (EER) for the available air conditioners is around 5. At the same time, the available equipment can achieve an EER greater than 10. Not only is the low effectiveness of cooling devices raising concerns. Most residential cooling devices are based on vapor compression systems. These use refrigerants that have significant environmental impacts, both in the short and long term [4].

Regarding challenges, evaporative cooling (EC) is widely presented as a solution [5]. It provides relatively inexpensive and reliable

* Corresponding author.
E-mail address: krzysztof.rajski@pwr.edu.pl (K. Rajski).

https://doi.org/10.1016/j.jobe.2025.112585
Received 20 December 2024; Received in revised form 10 March 2025; Accepted 3 April 2025
Available online 4 April 2025

devices with natural refrigerants air and water (R-718 and R-729). What is more it can be easily combined with renewable energy sources (e.g. solar energy [6–9]). Although EC is discussed [10–14], it still lacks investigation in some branches. The research result is presented in Fig. 1. The systems are divided into EC, which is the most general and broad term for the technology. However, due to the addition of moisture content to the treated air, the technology has not been perceived as promising. Next, indirect evaporative coolers (IEC) are then introduced. They have emerged as a solution to reduce air temperature without introducing moisture into conditioned spaces. The fundamental principle behind IEC lies in the separation of air and water streams, which allows heat transfer from the primary air (outside air) to a wet channel without compromising the dryness of the primary air. However, it is not possible to cool the air below the wet bulb temperature of the outside air. To address these challenges and enhance the efficiency of IEC units, the concept of dewpoint indirect evaporative cooling (DIEC) has been introduced. Unlike conventional IEC, DIEC involves sensible and latent heat transfer. The pre-cooled air, returned into the wet channel, absorbs heat energy from the primary air due to temperature differences. This innovation enables the achievement of supply air temperatures below the wet bulb temperature of the outlet air, marking a significant improvement in performance.

1.1. Role of water in IEC

Indirect evaporative coolers are devices designed to reduce air temperature using the cooling effect of water evaporation without introducing moisture into the conditioned space. It is possible due to the separation of air streams. Heat from the primary air (outside air) is transferred through the wall of the heat exchanger into the wet channel. Primary air lowers its temperature by releasing heat through the heat exchanger wall into the wet channel, intensifying the evaporation of water. Primary air remains dry because water does not mix with it. However, the cooling medium absorbs heat and undergoes evaporation. This phase change from liquid to vapor consumes heat, resulting in a cooler secondary air stream. Therefore, it is the temperature difference caused by evaporation that is the main factor driving the cooling process. Conventional IEC units have faced challenges in commercialization over the years due to restrictions in supply air temperature, and the high manufacturing cost [11].

Therefore, DIEC devices were introduced. The scheme of the device is shown in Fig. 2 (a). Design improvements provide the possibility of obtaining the supply air temperature below the wet bulb temperature of the inlet air. However, the role of water remains the same. It is the airflow organization that made the improvement. Since many air flow arrangements have been investigated, the focus has shifted to water in the following aspects: temperature, flow, and strategies to optimize water usage, either through the application of porous materials or intermittent water supply.

1.2. Water temperature and flow

In the case of DIEC, the water temperature that is supplied to the device must be taken into consideration. In case of porous heat exchangers, tap water can be used directly to moisten the heat exchanger. The porous material stores the supplied water and there is no need for a water reservoir, as drip is limited to a minimum. In this case, the water source is not influenced by the environment where the device is placed.

However, for non-porous heat exchangers water is supplied by nozzles and there is a water reservoir at the bottom. Water is in closed circuit and in the same environment as the cooling device. The treated air temperature approaches the dew point temperature, as shown in Fig. 2 (b). The water temperature, however, can be at the temperature on the line between the dry and wet bulb temperature of the outside air. Or, when there are additional heat gains, water can achieve temperatures much higher than the outside air temperature [15,16]. It results in a decrease in effectiveness and an increase in product air temperature [17]. The problem occurs because these devices are placed mainly on roofs and no additional shading or insulation is provided. The above roof temperatures, which are widely underestimated, are known to have a great influence on the performance of HVAC devices [18,19].

However, the influence of chilled water is examined in the literature for non-porous [20] and porous [21] heat exchanger surfaces. The results confirm that lowering the spray water temperature can significantly increase the performance of the evaporative cooler. Systems supplied with chilled water can have potential applications even in high humidity climates. However, electric energy consumption to prepare chilled water should be taken into consideration as it can exceed the gains.

The water flow rate has also been extensively discussed as it impacts the overall performance of evaporative coolers. The aim is to fully wet the heat transfer surface with water without creating an excess of water film on the surface. The extensive analysis of this aspect was carried out by De Anonellis et al. [22]. The main finding was that performance is highly influenced by the water flow rate but not so much by the nozzle organization and type. The water flow rate should also be considered with regard to the secondary air stream parameters (which has direct contact with water). The drier the air, the higher the water flow rate is required to maintain satisfactory performance.

Fig. 1. Evaporative cooling development with its limitations and research gaps.

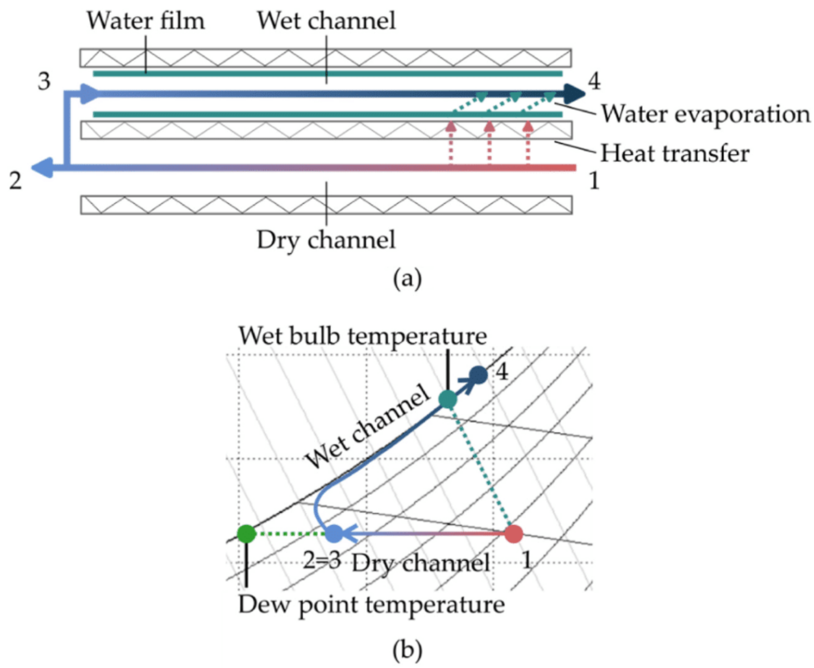


Fig. 2. DIEC scheme (a) and a psychometric representation (b).

1.3. Porous materials and intermittent water supply

The development aimed at modification of heat exchangers by application of porous materials. It allows to distribute water evenly, increase wettability, and decrease splashing [23]. At the same time, heat exchanger gain the ability to store water. With regard to water

Table 1
Performance of IEC coolers from 2010 regarding type of water supply and type of research (T – theoretical, E – experimental, wet bulb effectiveness defined as in Eq. (1), dew point effectiveness defines as in Eq. (2)).

Year	Source	Water supply	Type	Effectiveness	
			–	Wet bulb	Dew point
2010	Hasan [31]	Constant	T	1.09–1.36	0.70–0.84
2010	Riangvilaikul et al. [32]	Constant	E	1.00–1.15	0.63–0.85
2010	Riangvilaikul et al. [33]	Constant	T	1.00–1.15	0.60–0.90
2011	Bruno [34]	Constant	E	0.93–1.29	0.57–0.83
2011	Zhan et al. [35]	Constant	T/E	1.13–1.36	0.74–0.93
2013	Lee et al. [17]	Constant	E	1.18–1.22	0.75–0.90
2014	Jradi et al. [36]	Constant	T/E	0.70–1.17	0.43–0.78
2016	Kabeel et al. [37]	Constant	T/E	0.76–1.37	0.52–0.94
2016	Xu et al. [38]	Constant	E	1.03	0.69
2017	Xu et al. [25]	Intermittent	E	1.00–1.28	0.67–0.76
2017	Duan et al. [39]	Constant	T/E	0.98	–
2018	Cui et al. [40]	Constant	E	0.80–1.01	0.60–0.80
2018	Wang et al. [41]	Constant	T	0.70–1.22	0.47–0.93
2018	Boukhanouf et al. [42]	Constant	T/E	0.5–1.12	–
2019	Alharbi et al. [43]	Constant	T/E	1.02–1.10	0.71–0.86
2019	Liu et al. [44]	Constant	T/E	0.75–1.08	0.43–0.77
2020	Rajski et al. [45]	Constant	T	0.4–1.05	–
2020	Sun et al. [26]	Intermittent	E	0.68–1.34	–
2021	Chu et al. [46]	Constant	E	1.06	0.76
2021	Elahi et al. [47]	Intermittent	E	0.63–0.92	–
2022	Sofia et al. [23]	Constant	E	0.20–0.91	0.15–0.69
2022	Shi et al. [28]	Intermittent	T/E	0.3–0.69	–
2022	Shi et al. [27]	Intermittent	E	0.52–0.68	–
2023	Chen et al. [48]	Intermittent	E	–	–
2023	Chen et al. [49]	Intermittent	E	–	–
2024	Chen et al. [50]	Intermittent	E	0.74–0.81	–
2024	Khan et al. [51]	Intermittent	E	0.23–0.85	0.13–0.81

shortages and high costs of water treatment [24] the approach to minimize water supply occurs in the literature as a way to improve the performance of DIEC [17]. Eventually, intermittent water supply has been applied to DIEC coolers with porous layers on the heat exchanger. Xu et al. [25] achieved a significant decrease in electricity use (50–70 %) and an increase in COP (100–160 %) by applying the Coolmax® wet material layer. The water supply time was 15 or 60 s for each 10 min cycle. Sun et al. [26] investigated different intermittent spray algorithms (8–45 s spray time for 1 and 3 min water pump pause) for porous ceramic tubular heat exchanger. The change is claimed to have no contribution to water savings, but the energy consumed by the pump is reduced as the operating time is shorter. In 2021 Shi et al. [27] evaluated plate type porous IEC (sintered layer of nickel) for an intermittent water supply operation. The longest measured interval without pump operation was 2105 s. This results in almost 95 % reduction in operation time of the water system, and also in an increase in COP of more than 117 %. Later in 2022 Shi et al. [28] performed a similar investigation and the non-operating time of the water system was between 1270 and 2410 s. The increase in COP has been significant compared to the constant water supply (more than two times). In general, intermittent operation of the water system contributes to better performance and reduced energy consumption.

1.4. Research gap, objectives, and novelty of the study

1.4.1. Research gap

As a recent technology, the DIEC system is divided into devices with porous and non-porous heat exchanger surfaces. Based on the research presented in Tables 1 and it is clear that since 2010 eight publications have tackled the idea of operating an intermittant water system (most of them are from the last few years). More precise research leads to the conclusion that porous materials are investigated in terms of possible water storage capacities and the potential application of intermittent water spray [27–30]. Water spraying intervals examined in publications from Table 1 are presented in Fig. 3. It is visible that spraying periods generally do not exceed 3 min (only one investigation analyze 5–6 min perios). At the same time, there is no clear correlation in pump off period, when the heat exchenger works without further spraying. The time differs significantly, ranging from 1 min up to over 40 min. Still, overall observation is that pump on time is shorter than pump off time in every case. Thus, the authors identified a research gap for intermittant water supply for DIEC devices with non-porous heat exchanger.

1.4.2. Objectives

In a typical experimental device, the water distribution system consists of a water pump, piping, nozzles, and a water tank. Water pump operation is constant, or when porous surfaces are applied to the heat exchanger, the operation is intermittent.

The aim of this paper is to investigate the effect of intermittent spraying on the cooling performance of DIEC systems with a non-porous heat exchanger (scheme of examined device is shown in Fig. 4) and to assess the potential benefits in terms of energy efficiency. The experimental device's water distribution system has been upgraded with an additional pump operation control module. It allows the time to be set when the heat exchanger is sprayed. The time of pump shutdown is also set. Thus, there is no need for manual control, which decreases the uncertainties in spray time.

Based on the water system operation intervals for porous heat exchangers (Fig. 3) and tests, the authors decided to investigate three spray times (30s, 60s, and 90s) with 7 min pump shut off. Three spray periods are chosen because there are no data on the wettability of non-porous heat exchangers. Still, those are in the range of previously used intervals. The shut-off time was chosen between four

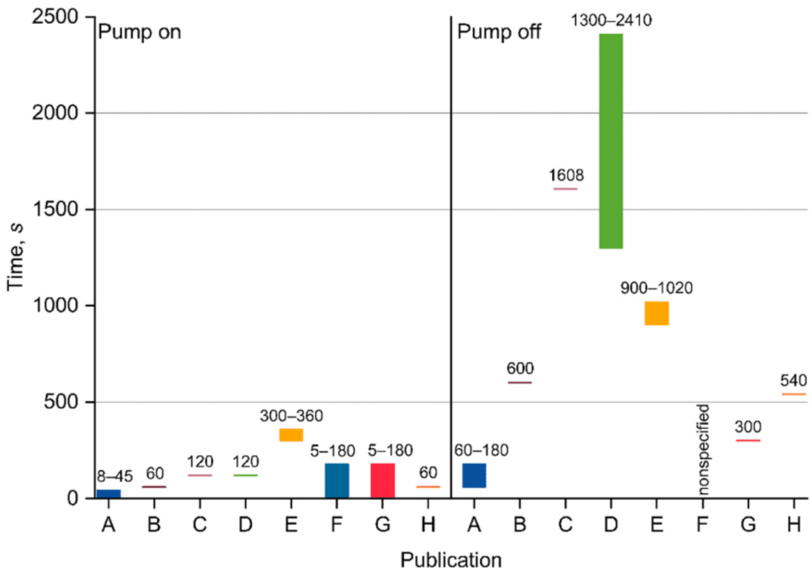


Fig. 3. Water system operation intervals for publications: A [26]; *B* [25]; *C* [27]; *D* [28]; *E* [47]; *F* [48]; *G* [49]; *H* [50].

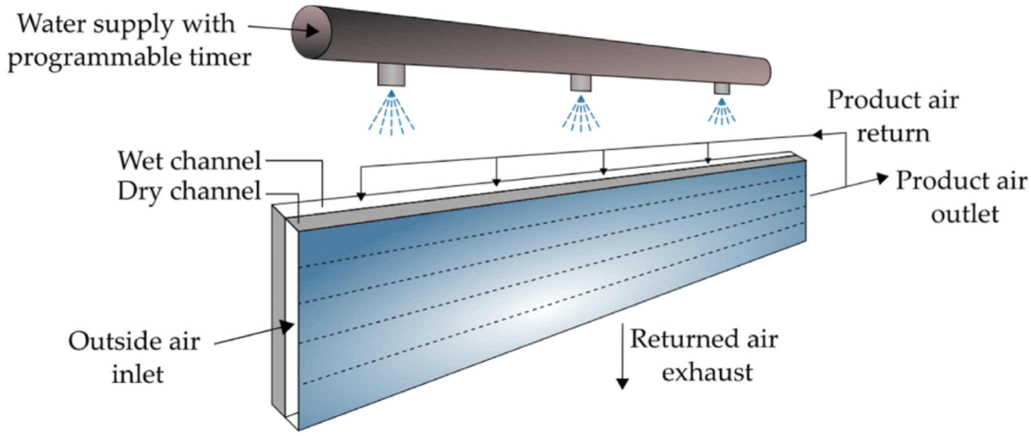


Fig. 4. Evaluated DIEC scheme with airflow and water supply organization.

shortest periods (60s, 300s, 540s, and 600s) as the non-porous layer is predicted to have lower water storage performance.

1.4.3. *Novelty of the study*

Unlike previous studies that mainly focus on porous heat exchangers, this study focuses on non-porous heat exchangers, which is a novel approach in the context of improving the performance of DIEC systems. As non-porous heat exchangers are less exposed to bacterial growth (as no pores are present) [30] or mold formation [52]. Additionally, costs increase as porous materials need an additional water-resistant coating to separate wet and dry channels [53].

Thus, the aim is to evaluate the benefits that can be achieved for non-porous heat exchangers by water supply system modification.

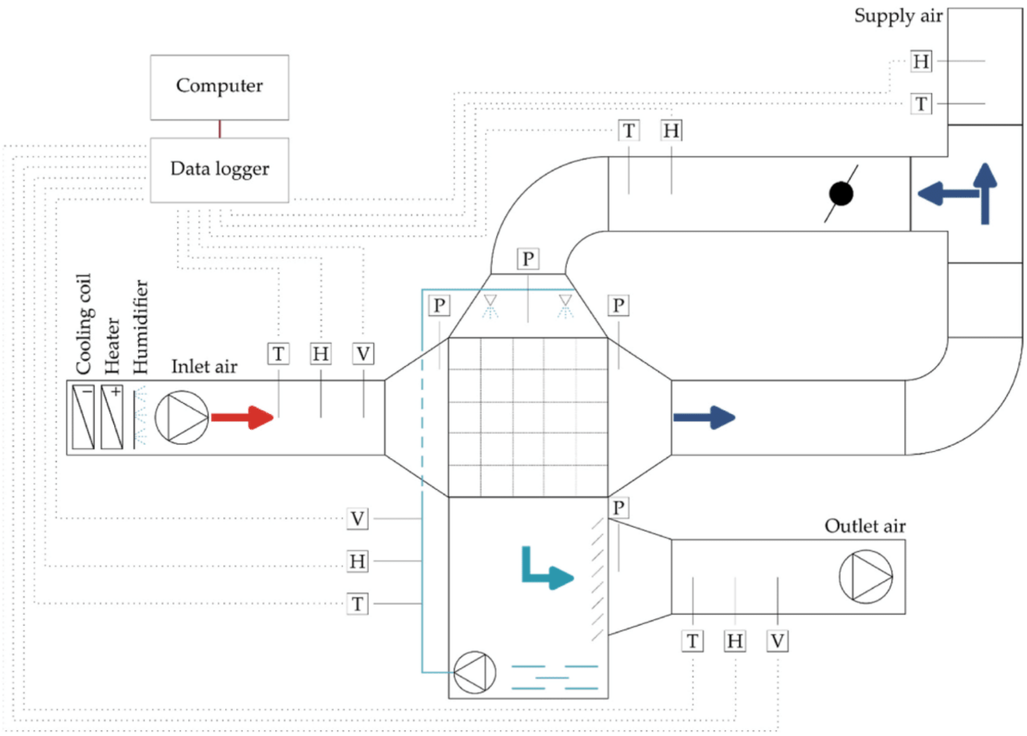


Fig. 5. Experimental device schematic configuration.

2. Methods

In this section, the authors present experimental setup, selected performance indicators, and power demand calculation. Scheme and a real photography of the test rig are presented with the specification and localisation of the measuring devices. System performance indicators are briefly described and discussed to precisely define the parameters chosen for each formula.

2.1. Experimental setup

Performance evaluation was conducted on a prototype test rig. The device schematic arrangement with the location of measurement devices is shown in Fig. 5. It is equipped with a cooling coil, heater, and a humidifier that allows to treat the air independently on the outdoor air parameters. Two fans are equipped with inverters that ensure stable air flow.

The real photography of the test rig is shown in Fig. 6 (a) (the test rig is thermally insulated). It is a cross-flow DIEC with horizontal inlet air delivery. Part of the cooled supply air is returned and transported vertically into the wet channel from the top (damper allows to regulate the returned air flow). Eventually, the outlet air is exhausted through the droplet eliminator. The rest of the supply air is supplied to the cooled space.

The wet and dry channels are made of 115 nonhydrophilic polymer plates arranged alternately (shown in Fig. 6 (b)). The water supply system is equipped with two serially connected pumps that can operate in a defined time manner using an adjustable timer relay

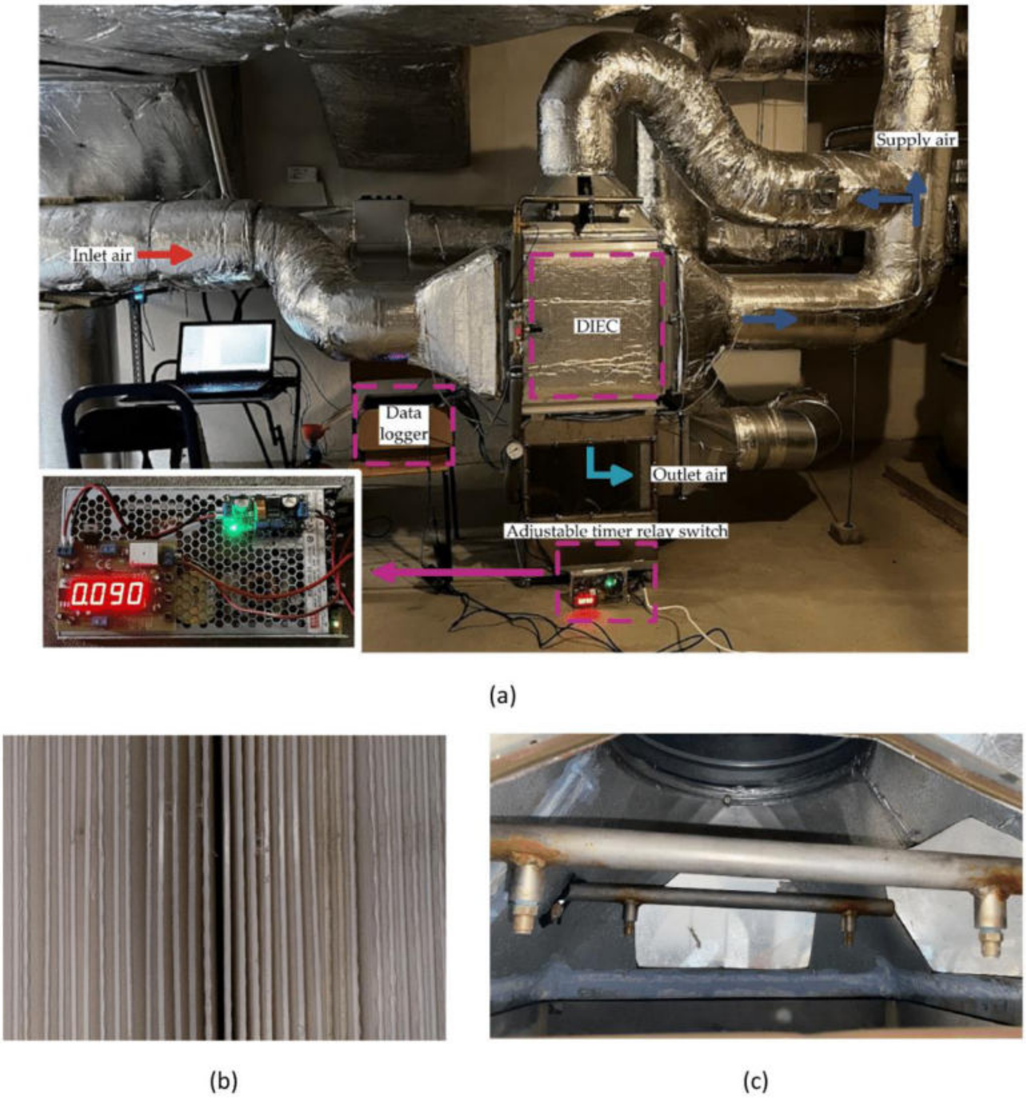


Fig. 6. Real photo of the: (a) test rig; (b) heat exchanger (wet channels); (c) spraying system.

switch. Water is supplied with four nozzles from the top of the heat exchanger as shown in Fig. 6 (c). Water is stored in water reservoir at the bottom of the device. Air and water in wet channel are arranged in a parallel flow manner.

The specification of the test rig is presented in Table 2. Temperature (T), relative humidity (H) and volumetric flow (V) are measured in the places specified in Fig. 5. All data are recorded every second. To achieve steady state conditions test rig was operating for at least 45 min before the measurements started. The steady state is recognized when the fluctuation of measured temperature and relative humidity is within a deviation of ± 1 % and ± 5 % for 5 min respectively [27,54,55]. Additionally, pressure drop was measured manually for the heat exchanger (P) with instrument nozzles and impulse lines installed in points (P). The specifications of the measurement devices are presented in Table 3.

2.2. EC system performance indicators

2.2.1. Wet bulb effectiveness

The DEC system can cool air at constant enthalpy up to inlet air wet-bulb temperature [56]. Therefore the efficiency of DEC device can be calculated by Eq. (1)

$$\eta_{wb} = \frac{t_1 - t_2}{t_1 - t_1^{wb}} \tag{1}$$

Eq. (1) can also be used to describe the efficiency of the IEC device [56]. It is suitable when inlet air is supplied simultaneously in the wet and dry channels (inlet air has the same parameters at the entrance to each channel type). In both systems, inlet air wet bulb temperature is in the denominator.

2.2.2. Dew point effectiveness

Many researchers investigated the system where air from dry channel returns to the wet channel. The return of air from the dry to wet channel improves DIEC system performance and the inlet air can be cooled below its wet bulb temperature. Thus, it is more appropriate to describe investigated heat exchanger efficiency related to the dew point, instead of the wet-bulb temperature. This can be expressed as Eq. (2) [57] and the following formula is used for further calculations.

$$\eta_{dp} = \frac{t_1 - t_2}{t_1 - t_1^{dp}} \tag{2}$$

2.2.3. COP

The COP in this paper was calculated for an IEC system similar to that described in Ref. [57]. However, in this research the authors decided to expand the equation used by Zhou et al. [57] and calculate the COP based on Eq. (3). Additionally, it includes the water pump system power demand. This approach seems to be the most comprehensive for future implementation in commercial applications.

$$COP = \frac{Q_{sensible}}{W} = \frac{(V_p - V_s)\rho c_p (t_1 - t_2)}{W_{pumps} + W_{fans}} \tag{3}$$

2.2.4. Parameter setting

The purpose of the study was to evaluate the operation of the intermittent water system in a non-porous heat exchanger. Thus, the authors chose to investigate typical design parameters that are currently observed in a temperate, central Europe climate [58,59]. The

Table 2
Specifications and dimensions of the main components in the investigated device.

	Description	Data	Units
Heat exchanger	Wet channel dimensions	500x500	mm
	Dry channel dimensions	500x500	mm
	Wet channel height	2	mm
	Dry channel height	2	mm
	Number of plates	115	–
Nozzles	Type	BETE WL – ½ 120 BSP	–
	Shape	Full cone	–
	Number	4	–
	Height above heat exchanger	140	mm
	Operating pressure	2	bar
Air	Average dry channel air flow	468, 540, 684	m^3/h
	Purge ratio	35	%
	Fans	JETTEC 250/2400F	–
	Fans inverters	SV004iC5-1F	–
Water	Water flow rate[a]	5.94	l/min
	Pumps	DC50E-24150S	–

[a] Constant operation.

Table 3
Measuring devices specification.

Parameter		Instrument	Accuracy
Air	Temperature	Sensirion SHT25	±0.2 °C
	Relative humidity		1.8 % (RH 10–90 %), 3 % (RH 90–100 %)
	Flow rate (inlet)	SMAY IRIS 250	5 %
	Flow rate (outlet)	Lindab FMU-FMDRU 250-200	5 %
	Pressure drop	Testo 435	±0.02 hPa
Water	Temperature	WIKA TF37 Pt100/4/F0,15	±(0.15 + 0.002 t)
	Flow rate	IFM SM6004 magnetic-inductive flow meter	±(2 % MW[a]+0.5 % MEW[b])

[a] Measured value.
[b] Final value of the measuring range.

experiment was conducted in quasi-constant inlet air parameters. Overall parameter setting is shown in Table 4.

2.2.5. *Uncertainty analysis*

The uncertainty of measurements was evaluated according to Bureau International des Poids et Mesures (BIPM) guidline [60]. In this paper, all measurement uncertainties are expressed in the form of standard deviation.

For measurements, that were stabilised during the experiment, such as airflow, the arithmetic mean was calculated as the best available estimate of the expected value of the particular quantity. In these cases, the standard uncertainty was derived from the experimental standard deviation of the mean, denoted as $u(\overline{x})$, and was calculated using Eq. (4).

$$\boldsymbol{u}(\overline{\boldsymbol{x}}) = \sqrt{\frac{\mathbf{1}}{\boldsymbol{n}(\boldsymbol{n}-\mathbf{1})}\sum_{j=1}^{n}(\boldsymbol{x}_j-\overline{\boldsymbol{x}})^2} \tag{4}$$

If lower bound a_- and upper bound a_+ values were available, for example, in cases related to the accuracy of sensors as specified by the manufacturer, the standard uncertainty $u(x_1)$ was calculated using Eq. (5).

$$\boldsymbol{u}(\boldsymbol{x}_1) = \sqrt{\frac{(\boldsymbol{a}_+-\boldsymbol{a}_-)^2}{\mathbf{12}}} \tag{5}$$

Uncertainty components related to the mean and accuracy of the sensors were combined into the overall uncertainty using Eq. (6).

$$\boldsymbol{u}(\boldsymbol{x}) = \sqrt{\boldsymbol{u}^2(\overline{\boldsymbol{x}})+\boldsymbol{u}^2(\boldsymbol{x}_1)} \tag{6}$$

When a quantity, for example cooling capacity, was calculated based on a mathematical function f, and arguments x_i in function f can be treated as independent, the combined standard uncertainty was calculated using Eq. (7), where N is the number of arguments in function.

$$\boldsymbol{u}_c(\boldsymbol{y}) = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial f}{\partial \boldsymbol{x}_i}\right)^2 \boldsymbol{u}^2(\boldsymbol{x}_i)} \tag{7}$$

In general, all uncertainties in this paper are expressed as standard uncertainties derived from standard deviations. Based on general Eq. (7) there were developed detailed equations for wet bulb effectiveness, dew point effectiveness, and COP uncertainties, denotes as Eq. (8), Eq. (9), and Eq. (10) respectively.

$$u_c(\eta_{wb}) = \sqrt{\left(\frac{t_2-t_1^{wb}}{\left(t_1-t_1^{wb}\right)^2}\right)^2 u^2(t_1)+\left(\frac{-1}{t_1-t_1^{wb}}\right)^2 u^2(t_2)+\left(\frac{t_1-t_2}{\left(t_1-t_1^{wb}\right)^2}\right)^2 u^2\left(t_1^{wb}\right)} \tag{8}$$

$$u_c(\eta_{dp}) = \sqrt{\left(\frac{t_2-t_1^{dp}}{\left(t_1-t_1^{dp}\right)^2}\right)^2 u^2(t_1)+\left(\frac{1}{t_1^{dp}-t_1}\right)^2 u^2(t_2)+\left(\frac{t_1-t_2}{\left(t_1-t_1^{dp}\right)^2}\right)^2 u^2\left(t_1^{dp}\right)} \tag{9}$$

Table 4
Parameter setting during experiment.

Parameter	Inlet air temperature, °C	Inlet air relative humidity, %	Water flow rate, l/min	Spray time, s	Pause time, s	Air velocity in dry channel, m/s
Value	30	40	5.94	30, 60, 90	420	1.6, 2.0, 2.5

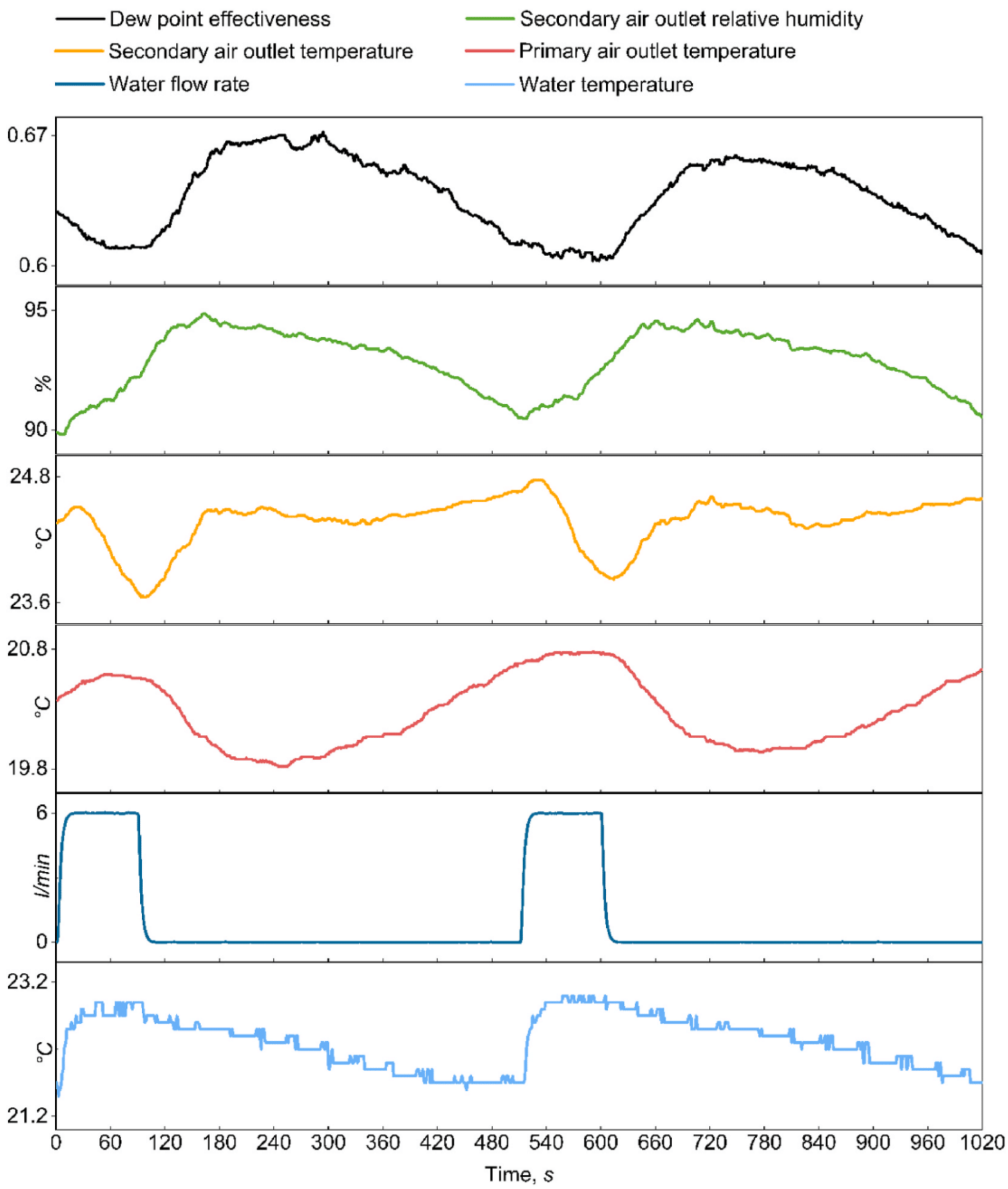


Fig. 7. Selected experimental parameters.

$$u_c(COP) = \sqrt{\left(\frac{1}{W}\right)^2 u^2(Q_{sensible}) + \left(\frac{-Q_{sensible}}{W^2}\right)^2 u^2(W)} \quad (10)$$

Final uncertainty results were in relatively range 2.6–3.1 % for wet bulb effectiveness, 3.2–3.7 % for dew point effectiveness, and 5.3–10.4 % for COP.

3. Results and discussion

The article focusses on the possibility of intermittent water system operation for non-porous heat exchanger. The main idea is to shorten the pump working time and analyze how it influences the effectiveness of the device.

Fig. 7 presents a sample of experimental data to show the parameters change for intermittent water system operation. While spraying, there is an increase in secondary air relative humidity. At the same time, the secondary air outlet temperature is decreasing relatively fast. This means that air in the wet channel inflates the heat transfer potential for heat flow from the dry to the wet channel through the internal wall of the DIEC. At 90 s and 600 s of the presented time window, when the water pump system stops, the secondary air temperature stops decreasing. If the water pump system still operates, the temperature will still decrease. Thus it is predictable that heat transfer potential due to temperature difference between dry and wet channels can be far grater at longer than 90 s spraying.

For about 300 s before water spraying was switched on, the primary air outlet temperature has risen. After the water pump system started, the primary air temperature growth was tempered. Coupled with (a) switching off of the water pump system, (b) relatively low secondary air outlet temperature, and (c) relatively high primary air outlet temperature, there was an intense heat transfer from dry to wet channel. What was shown in Fig. 7, after (a), (b) and (c) coincidence, the primary air was cooled down and the secondary air was heated up most intensive. This was also confirmed in the effectiveness of the dew point shown at the top of Fig. 7.

It is seen that, while spraying, part of the cooling potential is lost as the secondary outlet air does not gain as much heat as when there is no spraying. As an effect, the dew point effectiveness is higher when there is no water supply to the heat exchanger for certain period of time. Possible causes and effects of intermittent water spray regime are discussed in Table 5.

An important finding is presented in Fig. 8 (results for inlet air temperature 30 °C, relative humidity 40 %, water spraying pause time 420 s, and dry channel air velocity 2.0 m/s). The results are presented for the chosen dry channel air velocity (2.0 m/s) as high velocities are recently examined and claimed to negatively influence the performance [63]. Both, for constant and intermittent water system operation, there is a reduction in treated air average dry bulb temperature. For constant water system operation, it is 8.5 K. For intermittent spraying, it is more, from 9.7 up to 10.4 K. The difference between those is significant and confirms that the improvement in water system management suggested by the authors has a positive effect on the device performance.

The authors evaluated whether there is an influence on two typical performance indicators dew point and wet bulb effectiveness. The results are presented in Fig. 9. For constant water system operation, dew point and wet bulb effectiveness values are below 0.60 and 0.85 respectively. For intermittent operation, dew point effectiveness is in a range of 0.59–0.72 and wet bulb effectiveness 0.86–1.04. Comparison of results with other publications [25–28], which investigate intermittent water system operation with porous heat exchanger surfaces, shows that the results are in the range. Regarding extreme values in Table 1, wet bulb efficiency was claimed to be 0.2–1.37 and dew point effectiveness 0.13–0.94. Despite the differences in construction and operation parameters, the results are within the range of performance of other researchers.

Results for constant spraying are presented to be a reference to the intermittent spraying for the examined heat exchanger. For intermittent spraying, the higher the air velocity in the dry channel, the lower the effectiveness. It is consistent with what is generally observed by other researchers [64]. Moreover, numerical studies suggests that primary air velocity in the heat exchanger should be less than 1.5 m/s [38,65,66]. Some of them, which are validated using experiment suggest the velocity to be below 2.5 m/s [33]. So the results are presented for 1.6, 2.0, and 2,5 m/s. For first two air velocities, the effectiveness decreases when the spray time increases. While for the highest velocity, effectiveness is increasing with increased spray time. The fact is directly connected with changing ratio of air and water supplied to the heat exchanger. The experiments confirms that when the water to air ratio increases the effectiveness decreases [67,68].

Eventually, the average cooling power was calculated. It is an important result that not only the possibility of intermittent water spray for non-porous heat exchangers exists, but also it improves the performance. As presented in Fig. 10, there is an increase in average cooling power of the device for each velocity when compared to the constant spraying. For constant operation, it was calculated to be in a range 598–1215 W. For other variants, it was in a range of 1012–1236 W (for 30 s), 937–1257 W (for 60 s) and 1109–1289 W (for 90 s). In every scenario, the cooling power for intermittent water spray is higher when compared to constant water spray.

As stated earlier, the authors decided to evaluate the COP of the device. Actual COP values and pump operation time are presented in Fig. 11. The difference between constant and intermittent operation is clearly visible and significant. Variant with constant water spray achieved only a COP value around 20. For other variants, the indicator achieves values 2–5 times higher.

Table 5
Intermittent water spray regime causes and effects discussion.

Feature	Spraying regime		Description
	Constant	Intermittent	
Causes			
Water film thickness	Increased	Reduced	The thickness of the water layer formed on the heat exchanger surface. A thicker film increases thermal resistance and thermal inertia [61], reducing heat transfer.
Secondary air saturation at inlet	Increased	Reduced	The level of moisture in the air entering the heat exchanger wet channels. Secondary air has contact with water droplets before entering the heat exchanger. Higher saturation limits evaporation and cooling [52].
Circuit water temperature	Increased	Reduced	The heat generated by the pump and the reduced heat transfer increase water temperature in constant spraying. It effects in lower thermal performance [62].
Temperature equalization time	Reduced	Increased	The time it takes for the temperatures within the system to stabilize. Increased water temperature while constant spraying heat up heat exchanger plates, reducing performance.
Effects			
Heat Transfer	Reduced	Increased	A thicker water film and higher air saturation reduce heat transfer in constant spraying.
Overall cooling efficiency	Reduced	Increased	Intermittent spraying allows for better utilization of evaporation energy [28].

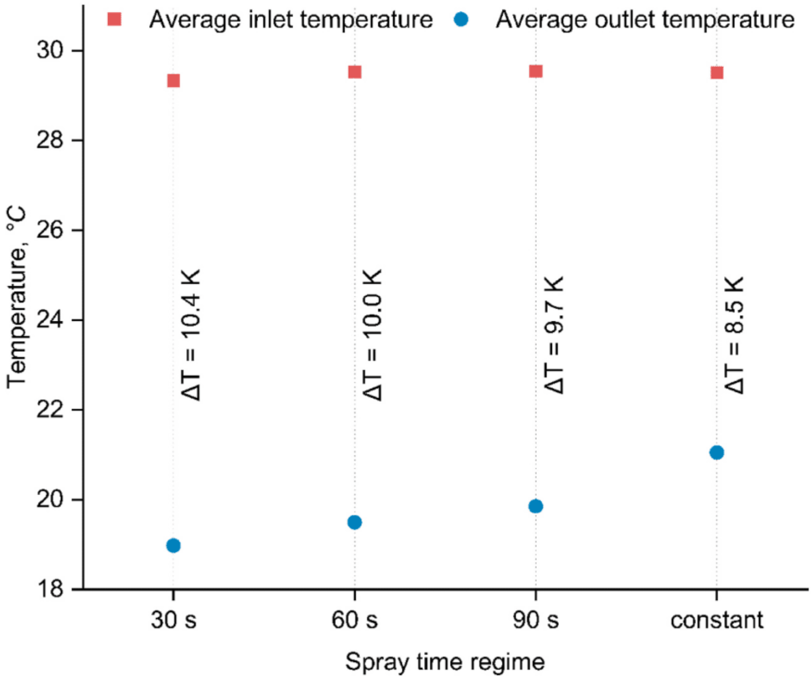


Fig. 8. Average inlet and outlet temperature for dry channel.

The growth in cooling power is the minor factor that improves the COP (the cooling power increase is not that significant in most cases, when compared to constant spray regime). It is the reduction in electric energy consumption that matters. Fans are needless to move the air, so it is the pumping system, that needs to be revised. In the investigated case, for intermittent spray regime, pumps operated only for 4–10.5 min for an hour of work. Pump work time was reduced more than five times. The inverse correlation between pump operation time and the COP is clearly presented in Fig. 11. In order to summarize the findings Table 6 presents a comparison of COP and average cooling power.

4. Conclusions

An improved water management system for the DIEC device is proposed. The authors evaluated non-porous heat exchanger with intermittent water supply. Constant water supply was compared to three spray time cycles (30 s, 60 s, and 90 s) with 420 s of non-spraying period. Three inlet air velocities were investigated (1.6 m/s, 2.0 m/s, and 2.5 m/s). The experiment resulted in the following outcomes.

1. The intermittent water supply for the non-porous heat exchanger does not worsen the performance of the device. In addition, the electric energy consumption is reduced.
2. The intermittent water supply has increased the COP and cooling capacity of the examined device. The highest COP values occurred during the shortest operating time of the water pumps, compared to constant spraying. The 30 s spraying cycle and 420 s idle corresponded to COP in a range of 50–107. On the contrary, the constant operation of the water pump system corresponded to COP around 20.
3. The 30-s spray cycle enhances cooling capacity especially at lower dry channel air velocities, demonstrating the effectiveness of optimized water management. There is an increase in every case when intermittent water spraying is implemented compared to constant water spraying.
4. The proposed improvement can be applied to any DIEC device without interference with the device itself. Only the water system needs to be modified.
5. The proposed improvement for the DIEC device can help provide sustainable cooling based on natural refrigerants (R-718 and R-729).

The study has certain limitations. As a preliminary study it evaluates only a specific device with heat exchanger of specific material. Also more parameters (both ambient air and spraying intervals and water flow) could be evaluated. However, as the results of the study are promising, it gives an opportunity to investigate those in future. Nevertheless, the study gives an alternative path to increase energy-efficiency of DIEC devices by implementing new water management idea. It provides an opportunity to support built

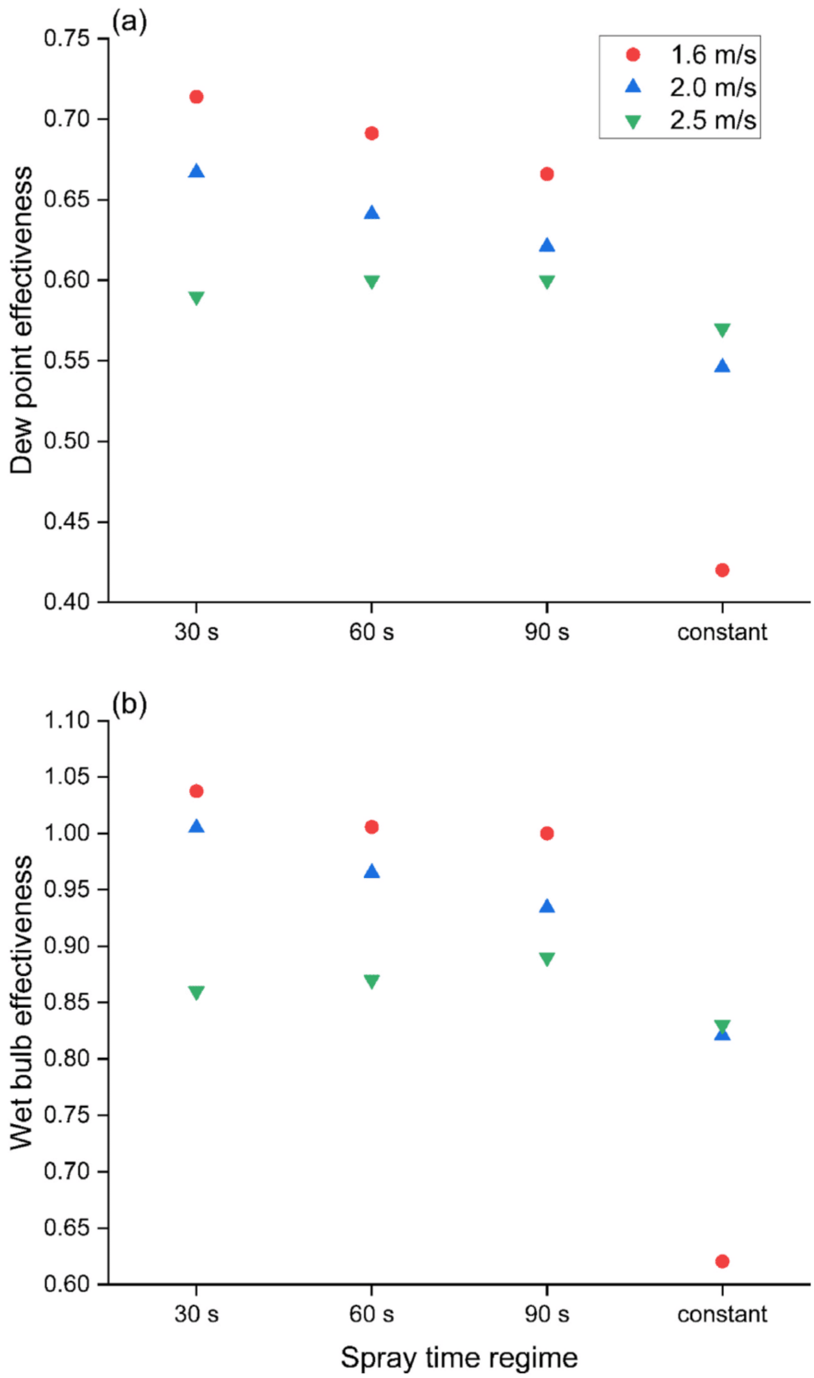


Fig. 9. Dew point (a) and wet bulb effectiveness (b) for constant and intermittent spraying for dry channel air velocity 1.6, 2.0, 2.5 m/s.

environment with sustainable and efficient cooling device, which is crucial in extremally developing building sector under climate changing conditions.

CRediT authorship contribution statement

Łukasz Stefaniak: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Juliusz Walaszczyk:** Writing – review & editing, Writing – original draft, Methodology,

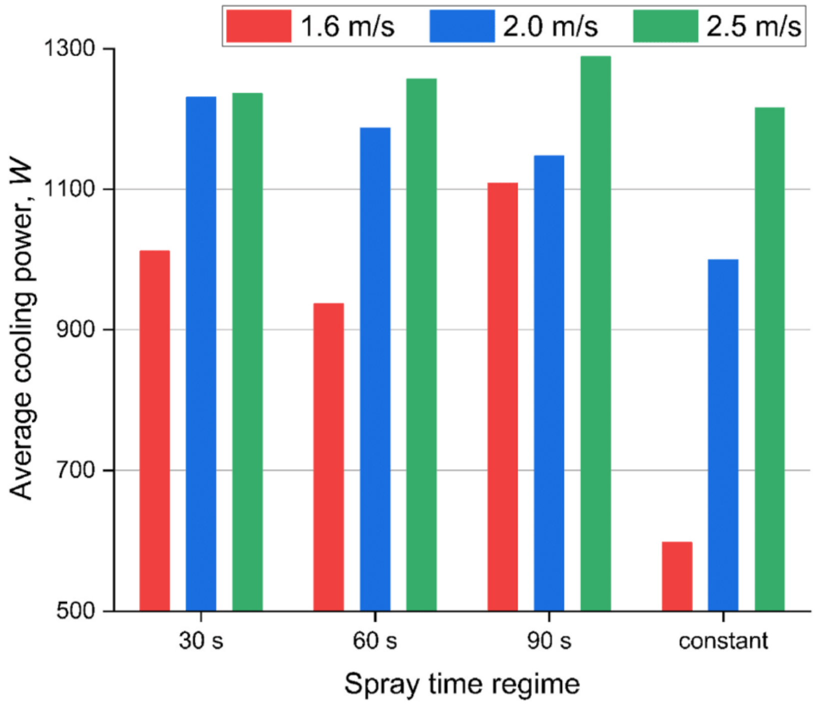


Fig. 10. Average cooling power for constant and intermittent spraying for dry channel air velocity 1.6, 2.0, 2.5 m/s.

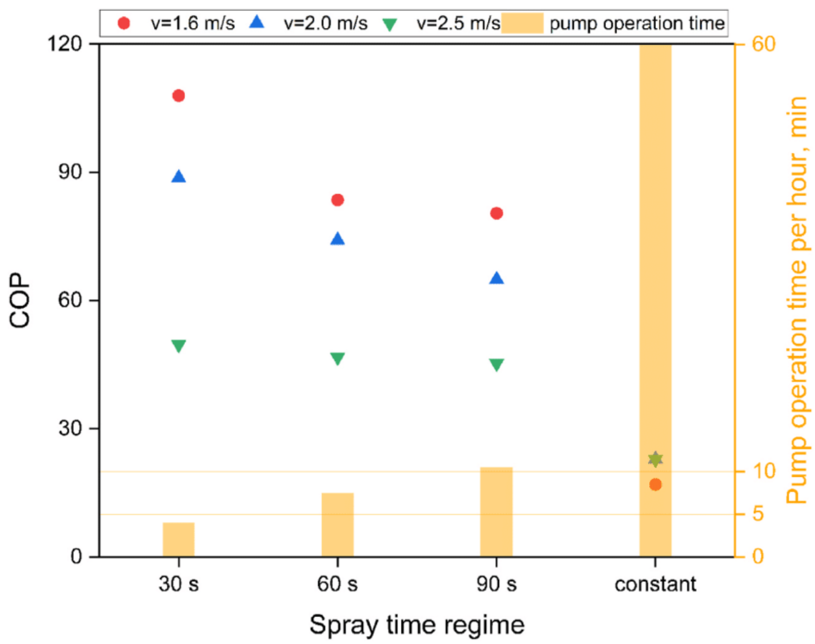


Fig. 11. COP and the pump operation time per hour for dry channel air velocity 1.6, 2.0, 2.5 m/s.

Table 6
COP and average cooling power summary.

Spraying time interval	Inlet air velocity, *m/s*					
	1.6		2.0		2.5	
	COP, -	Cooling power, *W*	COP, -	Cooling power, *W*	COP, -	Cooling power, *W*
30s	107.9	1012	88.7	1231	49.7	1236
60s	83.5	937	74.1	1187	46.7	1257
90s	80.4	1108	64.9	1147	45.3	1289
constant	17.0	598	22.9	999	22.8	1215

Investigation, Formal analysis, Data curation, Conceptualization. **Jan Danielewicz:** Writing – review & editing, Supervision. **Krzysztof Rajski:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Keeping cool in a hotter world is using more energy, making efficiency more important than ever – analysis - IEA, Available online, https://www.iea.org/commentaries/keeping-cool-in-a-hotter-world-is-using-more-energy-making-efficiency-more-important-than-ever. (Accessed 24 February 2024).
[2] Cooling - IEA available online. https://www.iea.org/energy-system/buildings/space-cooling. (Accessed 24 February 2024).
[3] M.W. Shahzad, M. Burhan, D. Ybyraiymkul, S.J. Oh, K.C. Ng, An improved indirect evaporative cooler experimental investigation, Appl. Energy 256 (2019) 113934, https://doi.org/10.1016/J.APENERGY.2019.113934.
[4] S. Szczęśniak, Ł. Stefaniak, Global warming potential of new gaseous refrigerants used in chillers in HVAC systems, Energies 15 (2022), https://doi.org/10.3390/en15165999.
[5] R.O. Fagbenle, O.M. Amoo, S. Aliu, A. Falana, Applications of Heat, Mass and Fluid Boundary Layers, Elsevier, 2020. ISBN 9780128179499.
[6] R.J. Tripathi, D. Kumar, Performance assessment of solar-driven indirect evaporative cooling with a novel wet channel: an experimental study, J. Build. Eng. 78 (2023) 107674, https://doi.org/10.1016/J.JOBE.2023.107674.
[7] R.J. Tripathi, D. Kumar, H. Caliskan, H. Hong, Exergo-enviro-economic analyses of solar energy based novel air cooling system, Appl. Therm. Eng. 257 (2024) 124389, https://doi.org/10.1016/J.APPLTHERMALENG.2024.124389.
[8] R.J. Tripathi, D. Kumar, Prediction and optimization of wet bulb efficiency in solar energy-based novel evaporative cooling system: response surface method approach, J. Therm. Sci. Eng. Appl. 16 (2024), https://doi.org/10.1115/1.4066692/1206713.
[9] R.J. Tripathi, D. Kumar, A holistic approach for solar-driven HVAC evaporative cooling system: comparative study of dry and wet channel, J. Build. Eng. 83 (2024) 108465, https://doi.org/10.1016/J.JOBE.2024.108465.
[10] Ł. Stefaniak, S. Szczęśniak, J. Walaszczyk, K. Rajski, K. Piekarska, J. Danielewicz, Challenges and future directions in evaporative cooling: balancing sustainable cooling with microbial safety, Build. Environ. 267 (2025) 112292, https://doi.org/10.1016/J.BUILDENV.2024.112292.
[11] H. Sadighi Dizaji, E.J. Hu, L. Chen, A comprehensive review of the maisotsenko-cycle based air conditioning systems, Energy 156 (2018) 725–749, https://doi.org/10.1016/j.energy.2018.05.086.
[12] M. Kalsia, A. Sharma, R. Kaushik, R.S. Dondapati, Evaporative cooling technologies: conceptual review study, Evergreen 10 (2023) 421–429, https://doi.org/10.5109/6781102.
[13] E. Sofia, N. Putra, Evaporative Cooling Innovations - A Review, 2020 020036.
[14] Y. Yang, G. Cui, C.Q. Lan, Developments in evaporative cooling and enhanced evaporative cooling - a review, Renew. Sustain. Energy Rev. 113 (2019) 109230, https://doi.org/10.1016/j.rser.2019.06.037.
[15] A.H.H. Ali, Passive cooling of water at night in uninsulated open tank in hot arid areas, Energy Convers. Manag. 48 (2007) 93–100, https://doi.org/10.1016/j.enconman.2006.05.012.
[16] S.H. Hammadi, Tempering of water storage tank temperature in hot climates regions using earth water heat exchanger, Therm. Sci. Eng. Prog. 6 (2018) 157–163, https://doi.org/10.1016/j.tsep.2018.03.009.
[17] J. Lee, D.-Y. Lee, Experimental study of a counter flow regenerative evaporative cooler with finned channels, Int. J. Heat Mass Tran. 65 (2013) 173–179, https://doi.org/10.1016/j.ijheatmasstransfer.2013.05.069.
[18] C. Wray, H. Akbari, The effects of roof reflectance on air temperatures surrounding a rooftop condensing unit, Energy Build. 40 (2008) 11–28, https://doi.org/10.1016/j.enbuild.2007.01.005.
[19] A. Green, L. Ledo Gomis, R. Paolini, S. Haddad, G. Kokogiannakis, P. Cooper, Z. Ma, B. Kosasih, M. Santamouris, Above-roof air temperature effects on HVAC and cool roof performance: experiments and development of a predictive model, Energy Build. 222 (2020) 110071, https://doi.org/10.1016/j.enbuild.2020.110071.
[20] A.R. Al-Badri, A.A.Y. Al-Waaly, The influence of chilled water on the performance of direct evaporative cooling, Energy Build. 155 (2017) 143–150, https://doi.org/10.1016/j.enbuild.2017.09.021.
[21] J.L.B. Fernandes, T. Yanagi Junior, G.B. de Moura, A. de O. Ribeiro, Pre-cooling water applied to porous plates of evaporative cooling systems, Ciência Rural. 52 (2022), https://doi.org/10.1590/0103-8478cr20201015.
[22] S. De Antonellis, C.M. Joppolo, P. Liberati, S. Milani, L. Molinaroli, Experimental analysis of a cross flow indirect evaporative cooling system, Energy Build. 121 (2016) 130–138, https://doi.org/10.1016/J.ENBUILD.2016.03.076.
[23] E. Sofia, N. Putra, E.A. Kosasih, Development of indirect evaporative cooler based on a finned heat pipe with a natural-fiber cooling pad, Heliyon 8 (2022) e12508, https://doi.org/10.1016/j.heliyon.2022.e12508.
[24] M. Grzegorzek, K. Wartalska, B. Kaźmierczak, Review of water treatment methods with a focus on energy consumption, Int. Commun. Heat Mass Tran. 143 (2023) 106674, https://doi.org/10.1016/J.ICHEATMASSTRANSFER.2023.106674.

[25] P. Xu, X. Ma, X. Zhao, K. Fancey, Experimental investigation of a super performance dew point air cooler, Appl. Energy 203 (2017) 761–777, https://doi.org/10.1016/j.apenergy.2017.06.095.

[26] T. Sun, X. Huang, Y. Chen, H. Zhang, Experimental investigation of water spraying in an indirect evaporative cooler from nozzle type and spray strategy perspectives, Energy Build. 214 (2020) 109871, https://doi.org/10.1016/J.ENBUILD.2020.109871.

[27] W. Shi, Y. Min, X. Ma, Y. Chen, H. Yang, Performance evaluation of a novel plate-type porous indirect evaporative cooling system: an experimental study, J. Build. Eng. 48 (2022) 103898, https://doi.org/10.1016/J.JOBE.2021.103898.

[28] W. Shi, Y. Min, X. Ma, Y. Chen, H. Yang, Dynamic performance evaluation of porous indirect evaporative cooling system with intermittent spraying strategies, Appl. Energy 311 (2022) 118598, https://doi.org/10.1016/J.APENERGY.2022.118598.

[29] Ł. Stefaniak, K. Rajski, J. Danielewicz, Przegląd zastosowania nanopłynów oraz materiałów porowatych w pośrednim chłodzeniu wyparnym, CIEPŁOWNICTWO, OGRZEWNICTWO, WENTYLACJA 1 (2023) 35–42, https://doi.org/10.15199/9.2023.12.5.

[30] X. Zhao, Porous materials for direct and indirect evaporative cooling in buildings, in: Materials for Energy Efficiency and Thermal Comfort in Buildings, Elsevier, 2010, pp. 399–426.

[31] A. Hasan, Indirect evaporative cooling of air to a sub-wet bulb temperature, Appl. Therm. Eng. 30 (2010) 2460–2468, https://doi.org/10.1016/j.applthermaleng.2010.06.017.

[32] B. Riangvilaikul, S. Kumar, An experimental study of a novel dew point evaporative cooling system, Energy Build. 42 (2010) 637–644, https://doi.org/10.1016/j.enbuild.2009.10.034.

[33] B. Riangvilaikul, S. Kumar, Numerical study of a novel dew point evaporative cooling system, Energy Build. 42 (2010) 2241–2250, https://doi.org/10.1016/j.enbuild.2010.07.020.

[34] F. Bruno, On-site experimental testing of a novel dew point evaporative cooler, Energy Build. 43 (2011) 3475–3483, https://doi.org/10.1016/j.enbuild.2011.09.013.

[35] C. Zhan, Z. Duan, X. Zhao, S. Smith, H. Jin, S. Riffat, Comparative study of the performance of the M-cycle counter-flow and cross-flow heat exchangers for indirect evaporative cooling – paving the path toward sustainable cooling of buildings, Energy 36 (2011) 6790–6805, https://doi.org/10.1016/J.ENERGY.2011.10.019.

[36] M. Jradi, S. Riffat, Experimental and numerical investigation of a dew-point cooling system for thermal comfort in buildings, Appl. Energy 132 (2014) 524–535, https://doi.org/10.1016/j.apenergy.2014.07.040.

[37] A.E. Kabeel, M. Abdelgaied, Numerical and experimental investigation of a novel configuration of indirect evaporative cooler with internal baffles, Energy Convers. Manag. 126 (2016) 526–536, https://doi.org/10.1016/j.enconman.2016.08.028.

[38] P. Xu, X. Ma, T.M.O. Diallo, X. Zhao, K. Fancey, D. Li, H. Chen, Numerical investigation of the energy performance of a guideless irregular heat and mass exchanger with corrugated heat transfer surface for dew point cooling, Energy 109 (2016) 803–817, https://doi.org/10.1016/j.energy.2016.05.062.

[39] Z. Duan, X. Zhao, J. Li, Design, fabrication and performance evaluation of a compact regenerative evaporative cooler: towards low energy cooling for buildings, Energy 140 (2017) 506–519, https://doi.org/10.1016/j.energy.2017.08.110.

[40] X. Cui, W. Tian, X. Yang, Q. Kong, Y. Chai, L. Jin, Experimental study on a cross-flow regenerative indirect evaporative cooling system, Energy Proc. 152 (2018) 395–400, https://doi.org/10.1016/j.egypro.2018.09.163.

[41] Y. Wang, X. Huang, L. Li, Comparative study of the cross-flow heat and mass exchangers for indirect evaporative cooling using numerical methods, Energies 11 (2018) 3374, https://doi.org/10.3390/en11123374.

[42] R. Boukhanouf, O. Amer, H. Ibrahim, J. Calautit, Design and performance analysis of a regenerative evaporative cooler for cooling of buildings in arid climates, Build. Environ. 142 (2018) 1–10, https://doi.org/10.1016/j.buildenv.2018.06.004.

[43] A. Alharbi, A. Almaneea, R. Boukhanouf, Integrated hollow porous ceramic cuboids-finned heat pipes evaporative cooling system: numerical modelling and experimental validation, Energy Build. 196 (2019) 61–70, https://doi.org/10.1016/j.enbuild.2019.05.012.

[44] Y. Liu, Y.G. Akhlaghi, X. Zhao, J. Li, Experimental and numerical investigation of a high-efficiency dew-point evaporative cooler, Energy Build. 197 (2019) 120–130, https://doi.org/10.1016/j.enbuild.2019.05.038.

[45] K. Rajski, J. Danielewicz, E. Brychcy, Performance evaluation of a gravity-assisted heat pipe-based indirect evaporative cooler, Energies 13 (2020) 200, https://doi.org/10.3390/en13010200.

[46] J. Chu, W. Xu, Y. Fu, H. Huo, Experimental research on the cooling performance of a new regenerative dew point indirect evaporative cooler, J. Build. Eng. 43 (2021) 102921, https://doi.org/10.1016/j.jobe.2021.102921.

[47] S.H. Elahi, S.D. Farhani, Increasing evaporative cooler efficiency by controlling water pump run and off times, Int. Commun. Heat Mass Tran. 127 (2021) 105525, https://doi.org/10.1016/J.ICHEATMASSTRANSFER.2021.105525.

[48] Y. Chen, H. Yan, Y. Min, Visualized study of wetting enhancement and thermal performance of fiber-coated indirect evaporative cooler, Appl. Therm. Eng. 221 (2023) 119904, https://doi.org/10.1016/j.applthermaleng.2022.119904.

[49] Y. Chen, H. Yan, Y. Pan, Wetting and evaporative performance analysis of wet channels in indirect evaporative cooler with hydrophilic nano-coating, Appl. Therm. Eng. 229 (2023) 120622, https://doi.org/10.1016/J.APPLTHERMALENG.2023.120622.

[50] Y. Chen, L. Liu, H. Yan, Q. Tao, Y. Fan, Study of a nano-coated hydrophilic polymer for indirect evaporative cooler from wetting, thermal and corrosion resistance performance, Appl. Therm. Eng. 257 (2024) 124180, https://doi.org/10.1016/J.APPLTHERMALENG.2024.124180.

[51] I. Khan, W. Khalid, H.M. Ali, M. Sajid, Z. Ali, M. Ali, An experimental investigation on the novel hybrid indirect direct evaporative cooling system, Int. Commun. Heat Mass Tran. 155 (2024) 107503, https://doi.org/10.1016/J.ICHEATMASSTRANSFER.2024.107503.

[52] Y. You, G. Wang, B. Yang, C. Guo, Y. Ma, B. Cheng, Study on heat transfer characteristics of indirect evaporative cooling system based on secondary side hydrophilic, Energy Build. 257 (2022) 111704, https://doi.org/10.1016/J.ENBUILD.2021.111704.

[53] X. Zhao, S. Liu, S.B. Riffat, Comparative study of heat and mass exchanging materials for indirect evaporative cooling systems, Build. Environ. 43 (2008) 1902–1911, https://doi.org/10.1016/j.buildenv.2007.11.009.

[54] F. Wang, T. Sun, X. Huang, Y. Chen, H. Yang, Experimental research on a novel porous ceramic tube type indirect evaporative cooler, Appl. Therm. Eng. 125 (2017) 1191–1199, https://doi.org/10.1016/J.APPLTHERMALENG.2017.07.111.

[55] Y. Min, Y. Chen, H. Yang, C. Guo, Characteristics of primary air condensation in indirect evaporative cooler: theoretical analysis and visualized validation, Build. Environ. 174 (2020) 106783, https://doi.org/10.1016/J.BUILDENV.2020.106783.

[56] H.M.U. Raza, M. Sultan, M. Bahrami, A.A. Khan, Experimental investigation of evaporative cooling systems for agricultural storage and livestock air-conditioning in Pakistan, Build. Simulat. 14 (2021) 617–631, https://doi.org/10.1007/s12273-020-0678-2.

[57] Y. Zhou, T. Zhang, F. Wang, Y. Yu, Performance analysis of a novel thermoelectric assisted indirect evaporative cooling system, Energy 162 (2018) 299–308, https://doi.org/10.1016/J.ENERGY.2018.08.013.

[58] S. Szczęśniak, Ł. Stefaniak, P. Kanaś, M. Małyszko, W. Jaskóła, K.O. Brzeźniak, Potrzebie zmian parametrów obliczeniowych powietrza zewnętrznego Na przykładzie miasta wrocław, CIEPŁOWNICTWO, OGRZEWNICTWO, WENTYLACJA 1 (2023) 13–20, https://doi.org/10.15199/9.2023.4.2.

[59] S. Szczęśniak, M. Karpuk, Ł. Stefaniak, A. Grabka, W. Michalak, W. Jaskóła, M. Maciewicz, Obowiązujące normy Na tle rzeczywistych wartości temperatury powietrza zewnętrznego w polsce, CIEPŁOWNICTWO, OGRZEWNICTWO, WENTYLACJA 1 (2024) 22–31, https://doi.org/10.15199/9.2024.4.4.

[60] BIPM Evaluation of Measurement Data — Guide to the Expression of Uncertainty in Measurement, 2010.

[61] S. Saha, J. Khan, T. Farouk, Numerical study of evaporation assisted hybrid cooling for thermal powerplant application, Appl. Therm. Eng. 166 (2020) 114677, https://doi.org/10.1016/J.APPLTHERMALENG.2019.114677.

[62] C. Sheng, A.G. Agwu Nnanna, Empirical correlation of cooling efficiency and transport phenomena of direct evaporative cooler, Appl. Therm. Eng. 40 (2012) 48–55, https://doi.org/10.1016/J.APPLTHERMALENG.2012.01.052.

[63] B. Zhou, J. Lv, M. Zhu, L. Wang, S. Li, E. Hu, Experiment for the performance of a thin membrane inclined automatic wicking dew-point evaporative cooling device based on simulation results, Energy Build. 308 (2024) 114021, https://doi.org/10.1016/J.ENBUILD.2024.114021.

[64] Z. Duan, C. Zhan, X. Zhang, M. Mustafa, X. Zhao, B. Alimohammadisagvand, A. Hasan, Indirect evaporative cooling: past, present and future potentials, Renew. Sustain. Energy Rev. 16 (2012) 6823–6850, https://doi.org/10.1016/j.rser.2012.07.007.
[65] C. Zhan, X. Zhao, S. Smith, S.B. Riffat, Numerical study of a M-cycle cross-flow heat exchanger for indirect evaporative cooling, Build. Environ. 46 (2011) 657–668, https://doi.org/10.1016/j.buildenv.2010.09.011.
[66] X. Zhao, J.M. Li, S.B. Riffat, Numerical study of a novel counter-flow heat and mass exchanger for dew point evaporative cooling, Appl. Therm. Eng. 28 (2008) 1942–1951, https://doi.org/10.1016/j.applthermaleng.2007.12.006.
[67] S.P. Fisenko, A.A. Brin, A.I. Petruchik, Evaporative cooling of water in a mechanical draft cooling tower, Int. J. Heat Mass Tran. 47 (2004) 165–177, https://doi.org/10.1016/S0017-9310(03)00409-5.
[68] S.P. Fisenko, A.I. Petruchik, A.D. Solodukhin, Evaporative cooling of water in a natural draft cooling tower, Int. J. Heat Mass Tran. 45 (2002) 4683–4694, https://doi.org/10.1016/S0017-9310(02)00158-8.

III Summary

7. General conclusions

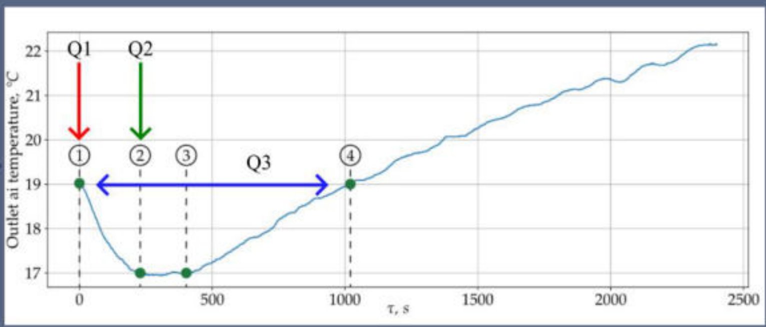
The thesis has been proved by the research presented in the articles. Doctoral dissertation presents both theoretical and practical knowledge, ability to plan and carry out experiments, and to present the results in both national and international journals. To sum up the presented work, summary part has been divided into: final conclusions, and future research directions.

7.1. Graphical conclusions

Results

Operation after water spraying shut off

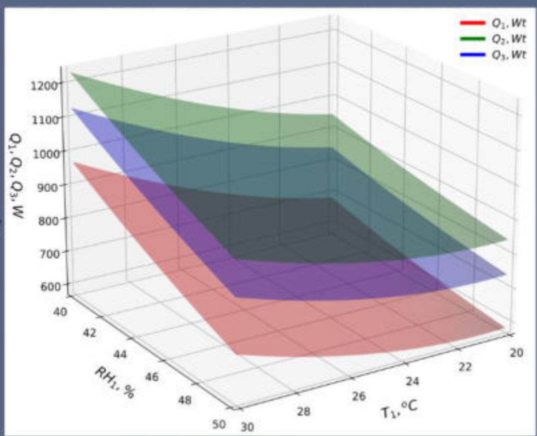
The outlet air temperature after water spraying shut off is shown in a chart below. It can be described by four points:



1. Water system stop
2. Lowest outlet air temperature achieved
3. Outlet air temperature starts to increase
4. Outlet air temperature is equal temperature in point 1

Markings Q1, Q2, and Q3 are presented with respect to the figure below in section Cooling capacity

Cooling capacity



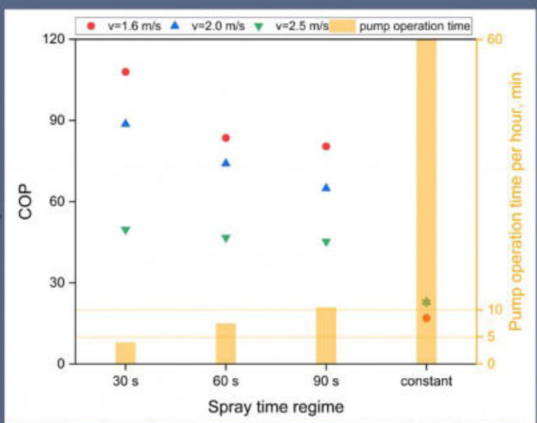
Possible improvement in cooling capacity is presented in the figure on the left.

Red surface represents the cooling capacity for point 1, which is under constant spraying.

Green surface represents the cooling capacity for point 2, where the lowest outlet temperature is obtained.

Blue surface represents the average cooling capacity between point 1 and 4, which is the time of outlet air temperature drop after water system shut off.

Coefficient Of Performance (COP) and pump operation time



The performance effect of intermittent water spraying is presented in the figure on the left.

Yellow bars represent the time of pump operation in an hour that depends on spray time regime.

Points represent COP values for three air velocities in DIECs' dry channel (red 1.6 m/s, blue 2.0 m/s, and green 2.5 m/s).

The inverse correlation between pump operation time and COP is visible. Due to reduced energy consumption for pumping and simultaneous increase in cooling capacity, the improvement in COP is visible.

7.2. Final conclusions

1. Intermittent water spraying in non-porous indirect evaporative coolers (IECs) significantly enhances cooling capacity, achieving 25–64% higher performance compared to constant spraying, particularly under moderate outdoor conditions (20–30°C, 40–50% RH).
2. Non-porous heat exchangers exhibit reduced microbial contamination risks (e.g., *Legionella pneumophila*, fungi) compared to porous materials. Therefore, using intermittent water spraying in non-porous DIEC can reduce the microbial risk when compared to porous DIEC.
3. Optimizing water spray intervals (e.g., 30–90 seconds active, 420 seconds inactive) in dew-point IECs (DIECs) improves energy efficiency, achieving COP values of 50–107 versus 20 for constant spraying, while maintaining or exceeding cooling performance.
4. Post-spray drying phases (4–6 minutes) in non-porous systems temporarily enhance cooling capacity due to reduced thermal inertia, offering a window for energy-efficient operation without compromising humidity control.

7.3. Future research direction

Future research should prioritize advancing material science to develop non-porous heat exchanger surfaces with enhanced wettability, corrosion resistance, and antimicrobial properties, reducing reliance on porous substrates. Innovations in intermittent spray algorithms, informed by real-time climate data and machine learning, could optimize water-use efficiency and cooling performance across diverse environments.

Now, when intermittent water spraying in non-porous DIEC is proved to be possible, wider range of ambient air parameters should be investigated to see to what extent this could be used worldwide.

Eventually, integrating renewable energy sources (e.g., solar-driven pumps) with DIEC systems warrants exploration to further reduce operational carbon footprints. Also combining hybrid systems of DIEC with desiccant dehumidification or vapor compression could extend applicability to humid climates while maintaining energy efficiency.

8. References

1. Miranda, N.D.; Lizana, J.; Sparrow, S.N.; Zachau-Walker, M.; Watson, P.A.G.; Wallom, D.C.H.; Khosla, R.; McCulloch, M. Change in Cooling Degree Days with Global Mean Temperature Rise Increasing from 1.5 °C to 2.0 °C. *Nat Sustain* **2023**, 1–5, doi:10.1038/s41893-023-01155-z.
2. Palme, M. The Possible Shift between Heating and Cooling Demand of Buildings under Climate Change Conditions: Are Some Mitigation Policies Wrongly Understood? *Mediterranean Green Buildings and Renewable Energy: Selected Papers from the World Renewable Energy Network's Med Green Forum* **2017**, 417–422, doi:10.1007/978-3-319-30746-6_30/TABLES/3.
3. Khosla, R.; Miranda, N.D.; Trotter, P.A.; Mazzone, A.; Renaldi, R.; McElroy, C.; Cohen, F.; Jani, A.; Perera-Salazar, R.; McCulloch, M. Cooling for Sustainable Development. *Nat Sustain* **2020**, *4*, 201–208, doi:10.1038/s41893-020-00627-w.
4. IEA *The Future of Colling*; Paris, 2018;
5. Szczęśniak, S.; Stefaniak, Ł. Global Warming Potential of New Gaseous Refrigerants Used in Chillers in HVAC Systems. *Energies (Basel)* **2022**, *15*, doi:10.3390/en15165999.
6. Frequently Asked Questions (FAQ) Available online: https://www.ashrae.org/technical-resources/frequently-asked-questions-faq? (accessed on 20 May 2025).
7. ASHRAE Terminology - Terminology.Presentation Available online: https://terminology.ashrae.org/?submit=Search&term=comfort&utm (accessed on 20 May 2025).
8. Pełech, A. *Wentylacja i Klimatyzacja. Podstawy.*; Oficyna Wydawnicza Politechniki Wrocławskiej: Wrocław, 2013;
9. Mohammed, R.H.; El-Morsi, M.; Abdelaziz, O. Indirect Evaporative Cooling for Buildings: A Comprehensive Patents Review. *Journal of Building Engineering* **2022**, *50*, 104158, doi:10.1016/J.JOBE.2022.104158.
10. Kalsia, M.; Sharma, A.; Kaushik, R.; Dondapati, R.S. Evaporative Cooling Technologies: Conceptual Review Study. *Evergreen* **2023**, *10*, 421–429, doi:10.5109/6781102.
11. Hussain, I.; Bibi, F.; Bhat, S.A.; Sajjad, U.; Sultan, M.; Ali, H.M.; Azam, W.; Kaushal, S.K.; Hussain, S.; Yan, W.M. Evaluating the Parameters Affecting the Direct and Indirect Evaporative Cooling Systems. *Eng Anal Bound Elem* **2022**, *145*, 211–223, doi:10.1016/J.ENGANABOUND.2022.09.016.
12. Haile, M.G.; Garay-Martinez, R.; Macarulla, A.M. Review of Evaporative Cooling Systems for Buildings in Hot and Dry Climates. *Buildings 2024, Vol. 14, Page 3504* **2024**, *14*, 3504, doi:10.3390/BUILDINGS14113504.
13. Yang, H.; Shi, W.; Chen, Y.; Min, Y. Research Development of Indirect Evaporative Cooling Technology: An Updated Review. *Renewable and Sustainable Energy Reviews* **2021**, *145*, 111082, doi:10.1016/J.RSER.2021.111082.
14. Ndukaife, T.A.; Nnanna, A.G.A. Optimization of Water Consumption in Hybrid Evaporative Cooling Air Conditioning Systems for Data Center Cooling Applications. *Heat Transfer Engineering* **2019**, *40*, 559–573, doi:10.1080/01457632.2018.1436418.

15. Yan, M.; He, S.; Gao, M.; Xu, M.; Miao, J.; Huang, X.; Hooman, K. Comparative Study on the Cooling Performance of Evaporative Cooling Systems Using Seawater and Freshwater. *International Journal of Refrigeration* **2021**, *121*, 23–32, doi:10.1016/J.IJREFRIG.2020.10.003.

16. Stefaniak, Ł.; Szczęśniak, S.; Walaszczyk, J.; Rajski, K.; Piekarska, K.; Danielewicz, J. Challenges and Future Directions in Evaporative Cooling: Balancing Sustainable Cooling with Microbial Safety. *Build Environ* **2025**, *267*, 112292, doi:10.1016/J.BUILDENV.2024.112292.

17. Xu, P.; Ma, X.; Zhao, X.; Fancey, K. Experimental Investigation of a Super Performance Dew Point Air Cooler. *Appl Energy* **2017**, *203*, 761–777, doi:10.1016/j.apenergy.2017.06.095.

18. Wang, F.; Sun, T.; Huang, X.; Chen, Y.; Yang, H. Experimental Research on a Novel Porous Ceramic Tube Type Indirect Evaporative Cooler. *Appl Therm Eng* **2017**, *125*, 1191–1199, doi:10.1016/J.APPLTHERMALENG.2017.07.111.

19. Sun, T.; Huang, X.; Chen, Y.; Zhang, H. Experimental Investigation of Water Spraying in an Indirect Evaporative Cooler from Nozzle Type and Spray Strategy Perspectives. *Energy Build* **2020**, *214*, 109871, doi:10.1016/J.ENBUILD.2020.109871.

20. Elahi, S.H.; Farhani, S.D. Increasing Evaporative Cooler Efficiency by Controlling Water Pump Run and off Times. *International Communications in Heat and Mass Transfer* **2021**, *127*, 105525, doi:10.1016/J.ICHEATMASSTRANSFER.2021.105525.

21. Chen, Y.; Huang, X.; Sun, T.; Chu, J. Experimental Study of Plant Fiber-Polymer Composite for Indirect Evaporative Cooler Application. *Appl Therm Eng* **2021**, *199*, 117543, doi:10.1016/J.APPLTHERMALENG.2021.117543.

22. Shi, W.; Min, Y.; Ma, X.; Chen, Y.; Yang, H. Dynamic Performance Evaluation of Porous Indirect Evaporative Cooling System with Intermittent Spraying Strategies. *Appl Energy* **2022**, *311*, 118598, doi:10.1016/J.APENERGY.2022.118598.

23. Shi, W.; Min, Y.; Ma, X.; Chen, Y.; Yang, H. Performance Evaluation of a Novel Plate-Type Porous Indirect Evaporative Cooling System: An Experimental Study. *Journal of Building Engineering* **2022**, *48*, 103898, doi:10.1016/J.JOBE.2021.103898.

24. Shi, W.; Yang, H.; Ma, X.; Liu, X. A Novel Indirect Evaporative Cooler with Porous Media under Dual Spraying Modes: A Comparative Analysis from Energy, Exergy, and Environmental Perspectives. *Journal of Building Engineering* **2023**, *76*, 106874, doi:10.1016/J.JOBE.2023.106874.

25. Chen, Y.; Yan, H.; Min, Y. Visualized Study of Wetting Enhancement and Thermal Performance of Fiber-Coated Indirect Evaporative Cooler. *Appl Therm Eng* **2023**, *221*, 119904, doi:10.1016/j.applthermaleng.2022.119904.

26. Chen, Y.; Yan, H.; Pan, Y. Wetting and Evaporative Performance Analysis of Wet Channels in Indirect Evaporative Cooler with Hydrophilic Nano-Coating. *Appl Therm Eng* **2023**, *229*, 120622, doi:10.1016/J.APPLTHERMALENG.2023.120622.

27. Jin, Q.; Yu, Y.; Zhang, J. Numerical and Experimental Study on Intermittent Spray Cooling for Plate-Fin Heat Exchanger. *Appl Therm Eng* **2023**, *234*, 121328, doi:10.1016/J.APPLTHERMALENG.2023.121328.

28. Chen, Y.; Liu, L.; Yan, H.; Tao, Q.; Fan, Y. Study of a Nano-Coated Hydrophilic Polymer for Indirect Evaporative Cooler from Wetting, Thermal and Corrosion Resistance Performance. *Appl Therm Eng* **2024**, *257*, 124180, doi:10.1016/J.APPLTHERMALENG.2024.124180.

29. Khan, I.; Khalid, W.; Ali, H.M.; Sajid, M.; Ali, Z.; Ali, M. An Experimental Investigation on the Novel Hybrid Indirect Direct Evaporative Cooling System. *International Communications in Heat and Mass Transfer* **2024**, *155*, 107503, doi:10.1016/J.ICHEATMASSTRANSFER.2024.107503.

30. Shim, J.; Ki, S.; Seo, D.; Moon, B.; Bang, S.; Nam, Y. Intermittent Spray Cooling on Rationally-Designed Hierarchical Surfaces for Enhanced Evaporative Heat Transfer Performance. *International Communications in Heat and Mass Transfer* **2024**, *153*, 107354, doi:10.1016/J.ICHEATMASSTRANSFER.2024.107354.

31. Stefaniak, Ł.; Grabka, A.; Walaszczyk, J.; Rajski, K.; Danielewicz, J.; Jaskóła, W.; Wochniak, M.; Zyta, W.˙ Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review. *Energies 2025, Vol. 18, Page 2296* **2025**, *18*, 2296, doi:10.3390/EN18092296.

32. Stefaniak, Ł.; Walaszczyk, J.; Danielewicz, J.; Rajski, K. Experimental Performance Analysis of Non-Porous Indirect Evaporative Coolers under Intermittent Water Spraying Conditions. *Journal of Building Engineering* **2025**, *105*, 112585, doi:10.1016/J.JOBE.2025.112585.

Wrocław 4.06.2025

Jan Danielewicz

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

jan.danielewicz@pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:

1) Ł. Stefaniak, K. Rajski, J. Danielewicz. „Przegląd zastosowania nanopłynów oraz materiałów porowatych w pośrednim chłodzeniu wyparnym". In: Ciepłownictwo, Ogrzewnictwo, Wentylacja 2023, vol. 54, no. 12, p. 33-40, DOI: 10.15199/9.2023.12.5

my participation consisted of: writing – review and editing, supervision;

2) Ł. Stefaniak, S. Szczęśniak, J. Walaszczyk, K. Rajski, K. Piekarska, J. Danielewicz. „Challenges and future directions in evaporative cooling: balancing sustainable cooling with microbial safety". In: Building and Environment 2025, vol. 267, Pt. A, art. 112292, p. 1-12, DOI: 10.1016/j.buildenv.2024.112292

my participation consisted of: formal analysis, writing – review and editing, supervision;

3) Ł. Stefaniak, A. Grabka, J. Walaszczyk, K. Rajski, J. Danielewicz, W. Jaskóła, M. Wochniak, W. Żyta. „Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review" In: Energies 2025, vol. 18, no. 9, art. 2296, p. 1-24., DOI: 10.3390/en18092296

my participation consisted of: conceptualization, writing – review and editing, supervision;

4) Ł. Stefaniak, J. Walaszczyk, M. Karpuk, K. Rajski, J. Danielewicz. „*The possibility of intermittent water spray implementation in a non-porous indirect evaporative cooler*". In: *Energies* 2025, vol. 18, no. 4, art. 882, DOI: 10.3390/en18040882

my participation consisted of: conceptualization, writing – review and editing, supervision;

5) Ł. Stefaniak, J. Walaszczyk, J. Danielewicz, K. Rajski. „Experimental performance analysis of non-porous indirect evaporative coolers under intermittent water spraying conditions". In: Journal of Building Engineering 2025, vol. 105, art. 112585, p. 1-16, DOI: 10.1016/j.jobe.2025.112585

my participation consisted of: writing – review and editing, supervision.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Wrocław, 12.06.2025r.

Krzysztof Rajski

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

krzysztof.rajski@pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:

1) Ł. Stefaniak, K. Rajski, J. Danielewicz. „Przegląd zastosowania nanopłynów oraz materiałów porowatych w pośrednim chłodzeniu wyparnym". In: Ciepłownictwo, Ogrzewnictwo, Wentylacja 2023, vol. 54, no. 12, p. 33-40, DOI: 10.15199/9.2023.12.5

my participation consisted of: conteptualization, writing – original draft preparation, writing – review and editing, supervision;

2) Ł. Stefaniak, A. Grabka, J. Walaszczyk, K. Rajski, J. Danielewicz, W. Jaskóła, M. Wochniak, W. Żyta. „Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review" In: Energies 2025, vol. 18, no. 9, art. 2296, p. 1-24., DOI: 10.3390/en18092296

my participation consisted of: conceptualization, writing – original draft preparation, writing – review and editing, supervision;

3) Ł. Stefaniak, S. Szczęśniak, J. Walaszczyk, K. Rajski, K. Piekarska, J. Danielewicz. „Challenges and future directions in evaporative cooling: balancing sustainable cooling with microbial safety". In: Building and Environment 2025, vol. 267, Pt. A, art. 112292, p. 1-12, DOI: 10.1016/j.buildenv.2024.112292

my participation consisted of: formal analysis, writing – review and editing, supervision;

4) Ł. Stefaniak, J. Walaszczyk, M. Karpuk, K. Rajski, J. Danielewicz. „The possibility of intermittent water spray implementation in a non-porous indirect evaporative cooler". In: Energies 2025, vol. 18, no. 4, art. 882, DOI: 10.3390/en18040882

my participation consisted of: resources, writing – review and editing, supervision;

5) Ł. Stefaniak, J. Walaszczyk, J. Danielewicz, K. Rajski. „Experimental performance analysis of non-porous indirect evaporative coolers under intermittent water spraying conditions". In: Journal of Building Engineering 2025, vol. 105, art. 112585, p. 1-16, DOI: 10.1016/j.jobe.2025.112585

my participation consisted of: conteptualization, methodology, resources, writing – original draft preparation, writing – review and editing, supervision.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Krzysztof Rajski

Wrocław 02.06.2025

Juliusz Walaszczyk

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

juliusz.walaszczyk@pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:

1) Ł. Stefaniak, A. Grabka, J. Walaszczyk, K. Rajski, J. Danielewicz, W. Jaskóła, M. Wochniak, W. Żyta. „Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review" In: Energies 2025, vol. 18, no. 9, art. 2296, p. 1-24., DOI: 10.3390/en18092296

my participation consisted of: conceptualization, investigation, writing – original draft preparation, writing – review and editing;

2) Ł. Stefaniak, S. Szczęśniak, J. Walaszczyk, K. Rajski, K. Piekarska, J. Danielewicz. „Challenges and future directions in evaporative cooling: balancing sustainable cooling with microbial safety". In: Building and Environment 2025, vol. 267, Pt. A, art. 112292, p. 1-12, DOI: 10.1016/j.buildenv.2024.112292

my participation consisted of: formal analysis, investigation, resources, writing – original draft preparation, writing – review and editing;

3) Ł. Stefaniak, J. Walaszczyk, M. Karpuk, K. Rajski, J. Danielewicz. *„The possibility of intermittent water spray implementation in a non-porous indirect evaporative cooler"*. In: *Energies* 2025, vol. 18, no. 4, art. 882, DOI: 10.3390/en18040882

my participation consisted of: conceptualization, methodology, formal analysis, data curation, writing – original draft preparation, writing – review and editing, visualization;

4) Ł. Stefaniak, J. Walaszczyk, J. Danielewicz, K. Rajski. „experimental performance analysis of non-porous indirect evaporative coolers under intermittent water spraying conditions". In: Journal of Building Engineering 2025, vol. 105, art. 112585, p. 1-16, DOI: 10.1016/j.jobe.2025.112585

my participation consisted of: conceptualization, methodology, formal analysis, data curation, investigation, writing – original draft preparation, writing – review and editing.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Juliusz Walaszczyk

Wrocław 03.06.2025r.

Wiktoria Jaskóła

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

266342@student.pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:

1) Ł. Stefaniak, A. Grabka, J. Walaszczyk, K. Rajski, J. Danielewicz, W. Jaskóła, M. Wochniak, W. Żyta. „Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review" In: Energies 2025, vol. 18, no. 9, art. 2296, p. 1-24., DOI: 10.3390/en18092296

my participation consisted of: writing—original draft preparation.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Wiktoria Jaskóła

Wrocław 2.06.2025

Sylwia Szczęśniak

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

sylwia.szczesniak@pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:
1) S. Szczęśniak and Ł. Stefaniak. "Global Warming Potential of New Gaseous Refrigerants Used in Chillers in HVAC Systems". In: Energies 2022, vol. 15, no. 16, art. 5999, p. 1-20., DOI: 10.3390/en15165999

my participation consisted of: conceptualization, methodology, validation, formal analysis, investigation, resources, writing – original draft preparation, writing – review and editing, visualization;

2) Ł. Stefaniak, S. Szczęśniak, J. Walaszczyk, K. Rajski, K. Piekarska, J. Danielewicz. „Challenges and future directions in evaporative cooling: balancing sustainable cooling with microbial safety". In: Building and Environment 2025, vol. 267, Pt. A, art. 112292, p. 1-12, DOI: 10.1016/j.buildenv.2024.112292

my participation consisted of: conceptualization, methodology, formal analysis, investigation, resources, writing – original draft preparation, writing – review and editing, visualization.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Sylwia Szczęśniak
....

Wrocław 05.06.2025r.

Agnieszka Grabka

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

agnieszka.grabka@pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:

1) Ł. Stefaniak, A. Grabka, J. Walaszczyk, K. Rajski, J. Danielewicz, W. Jaskóła, M. Wochniak, W. Żyta. „Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review" In: Energies 2025, vol. 18, no. 9, art. 2296, p. 1-24., DOI: 10.3390/en18092296

my participation consisted of: conceptualization, investigation, writing – original draft preparation, writing – review and editing, visualisation.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Grabka
....

Wrocław 03.06.2025r.

Katarzyna Piekarska

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

katarzyna.piekarska@pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:

1) Ł. Stefaniak, S. Szczęśniak, J. Walaszczyk, K. Rajski, K. Piekarska, J. Danielewicz. „Challenges and future directions in evaporative cooling: balancing sustainable cooling with microbial safety". In: Building and Environment 2025, vol. 267, Pt. A, art. 112292, p. 1-12, DOI: 10.1016/j.buildenv.2024.112292

my participation consisted of: formal analysis, writing – review and editing, supervision.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Piekarska
....

Wrocław 1.06.2025

Michał Karpuk

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

michal.karpuk@pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:

1) Ł. Stefaniak, J. Walaszczyk, M. Karpuk, K. Rajski, J. Danielewicz. „The possibility of intermittent water spray implementation in a non-porous indirect evaporative cooler". In: Energies 2025, vol. 18, no. 4, art. 882, DOI: 10.3390/en18040882

my participation consisted of: methodology, formal analysis, software, validation, data curation, writing – original draft preparation, writing – review and editing, visualisation.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Michał Karpuk
....

Wrocław 3.06.2025r.

Maja Wochniak

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

281603@student.pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:

1) Ł. Stefaniak, A. Grabka, J. Walaszczyk, K. Rajski, J. Danielewicz, W. Jaskóła, M. Wochniak, W. Żyta. „Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review" In: Energies 2025, vol. 18, no. 9, art. 2296, p. 1-24., DOI: 10.3390/en18092296

my participation consisted of: writing—original draft preparation.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Maja Wochniak
....

Wrocław 02.06.2025r.

Weronika Żyta

ul. Wybrzeże Wyspiańskiego 27
50-370 Wrocław

281589@student.pwr.edu.pl

Politechnika Wrocławska
Wydział Inżynierii Środowiska

DECLARATION

I declare my contribution in following papers:

1) Ł. Stefaniak, A. Grabka, J. Walaszczyk, K. Rajski, J. Danielewicz, W. Jaskóła, M. Wochniak, W. Żyta. „Enhancing Dewpoint Indirect Evaporative Cooling with Intermittent Water Spraying and Advanced Materials: A Review" In: Energies 2025, vol. 18, no. 9, art. 2296, p. 1-24., DOI: 10.3390/en18092296

my participation consisted of: writing—original draft preparation.

I consent to the submission of the above-mentioned work by MSc Eng. Łukasz Stefaniak as part of a doctoral dissertation in the form of a thematically coherent collection of scientific articles published in scientific journals.

I declare that an independent and separable part of the above-mentioned work demonstrates the individual contribution of MSc Eng. Łukasz Stefaniak in developing the concept, performing the experimental part, developing and interpreting the results of this work.

Weronika Żyta
....

List of figures