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Furqan Haider Mohammed Ali
MSc
Technical Engineering College Kirkuk
Northern Technical University
36001, Kirkuk, Iraq
https://orcid.org/0009-0004-5491-3224

Zahraa Haider Mohammed Ali
MSc
Kirkuk Polytechnic College
Northern Technical University
36001, Kirkuk, Iraq
https://orcid.org/0009-0007-7034-5230

Mustafa Naozad Taifor
MSc
Renewable Energy Research Centre
Northern Technical University
36001, Kirkuk, Iraq
https://orcid.org/0000-0001-7146-1160

Hussein Hayder Mohammed Ali*
PhD
Technical Engineering College Kirkuk
Northern Technical University
36001, Kirkuk, Iraq
https://orcid.org/0000-0003-4264-400X

Experimental study of some parameters to enhance efficiency of evaporative cooler: Technical notes

Abstract. As an alternative to conventional vapour-compression air conditioning systems, which significantly increase peak electrical demand and energy consumption, this study investigates methods to enhance the performance and energy efficiency of evaporative cooling systems. A hybrid dual cooling configuration integrating a vapour-compression refrigeration unit with an evaporative cooler was experimentally developed and evaluated. The study focused on key modifications, including the replacement of conventional wood dust pads with padding cartoon material, the use of an auxiliary submersible pump to increase water circulation, and the combined operation of both pad materials. The experimental results demonstrated a substantial improvement in system performance due to these modifications. In particular, the hybrid system operating with a combined wood dust and padding cartoon medium achieved the highest cooling efficiency of 89%, indicating a significant enhancement in heat and mass transfer processes. The integration of increased water flow further contributed to improved wettability of the pads and more effective evaporative cooling. In terms of energy performance, the hybrid system exhibited an energy efficiency ratio (EER) of 8.3, which is markedly higher than that of the standalone vapour-compression system (EER = 1.95). Additionally, the independent evaporative cooling system achieved a maximum EER of 14.8 with a cooling efficiency of 71%, confirming its superior energy-saving potential

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*Corresponding author

under suitable operating conditions. The results also revealed that optimising pad material characteristics and water distribution plays a critical role in enhancing cooling efficiency while minimising energy input. These findings confirmed that the integration of evaporative cooling with conventional systems, along with appropriate material selection and hydraulic enhancement, can significantly reduce overall energy consumption while maintaining satisfactory thermal comfort levels. From a practical perspective, the proposed hybrid cooling system is a cost-effective, energy-efficient, and sustainable solution for hot, dry climates, utilising low-cost local materials and simple modifications to reduce energy demand and emissions while improving and guiding future cooling technologies

Keywords: hybrid air conditioning; thermodynamic analysis; wood dust; cardboard padding; energy efficiency

INTRODUCTION

The growing global demand for cooling, driven by rising ambient temperatures and urbanisation, has led to a significant increase in energy consumption associated with conventional air-conditioning systems. Vapour-compression refrigeration, while widely used, imposes substantial electrical loads and contributes to greenhouse gas emissions, making it increasingly unsustainable in the context of current energy and environmental challenges. In 2026, the need for alternative cooling strategies was particularly urgent in hot and dry regions, where efficient and low-energy solutions can directly alleviate pressure on power infrastructure. From a theoretical perspective, improving evaporative cooling performance through enhanced heat and mass transfer mechanisms offers a promising pathway to increase system efficiency. Practically, hybridising evaporative and vapour-compression systems provides an opportunity to balance thermal comfort with reduced energy use. Therefore, investigating optimised materials and system configurations for hybrid cooling systems is essential for advancing sustainable and cost-effective air-conditioning technologies.

A comparison of recent studies highlights both methodological and technological advancements in evaporative cooling systems. M.J. Romero-Lara *et al*. (2023) focused on developing a simplified method for calculating the seasonal energy efficiency ratio (SEER) of regenerative indirect evaporative coolers, demonstrating reliable prediction accuracy with minimal deviation from detailed simulation models. In contrast, the review by R.A. Hasan *et al*. (2025) provided a broader perspective, emphasising recent innovations such as desiccant-assisted and hybrid cooling systems, and identifying key challenges like humidity sensitivity and maintenance requirements. Meanwhile, S. Rasheed *et al*. (2025a) presented a detailed experimental and numerical investigation into material selection and airflow configurations, showing that high-wettability materials and optimised flow patterns significantly enhance cooling performance and thermal effectiveness. A.H. Salman *et al*. (2024) investigated the performance of a multistage evaporative cooling system designed to enhance cooling efficiency under extreme climatic conditions such as those in Iraq. The study highlighted that conventional evaporative media typically achieve efficiencies between 80% and 90%, though performance can vary widely depending on system design. To address these limitations, a multistage configuration incorporating successive water-air heat exchanger stages was developed to pre-cool the incoming air before direct evaporative cooling. The results indicated that this approach significantly improves thermal performance, reducing outlet dry-bulb temperature by approximately 50% and lowering specific humidity by about 80%. Furthermore, the system demonstrated clear advantages over conventional vapour-compression systems, including reduced energy consumption, lower environmental impact, and cost-effectiveness. A.F. Santos *et al*. (2021) improved the evaluation of evaporative cooler energy efficiency. They developed a COP index for this type of system using parameters that were easier to simulate. Their results showed COP values of 45.58 and 25.77 for two different simulated evaporative cooling units, compared with 6.29 for a conventional vapour-compression refrigeration system.

The purpose of this study was to experimentally enhance the performance and energy efficiency of an evaporative cooling system through structural modifications and hybrid integration with a vapour-compression refrigeration unit. To achieve this, the study investigated the effect of increasing water circulation by incorporating an additional submersible pump on overall cooling performance. It also evaluated the influence of different cooling pad materials, including wood dust, cardboard padding, and their combination, on heat and mass transfer characteristics. Furthermore, the study analysed the impact of key operating parameters such as airflow rate, water flow rate, and ambient air conditions on cooling effectiveness, and energy efficiency ratio (EER), with the goal of identifying the optimal operating configuration for improved system performance.

MATERIALS AND METHODS

The experimental measurements were conducted using a set of calibrated instruments to ensure accurate monitoring of thermal and operating parameters. Air temperature at the inlet and outlet of the evaporative cooler was measured using digital thermocouples (Type K) connected to a multi-channel data logger (e.g., model TM-747DU), with an accuracy of ±0.5°C. To account for high-humidity conditions, shielded temperature probes were employed to minimise measurement drift. Relative humidity of both ambient air and supply air was determined using a digital hygrometer (e.g., Testo 608-H1 or equivalent), with an accuracy of

±3% RH, and cross-validated using a sling psychrometer to improve reliability under varying moisture conditions. All sensors were calibrated prior to testing using standard reference conditions to reduce systematic error.

Measurement points were carefully defined to ensure consistency. The inlet air temperature and humidity were recorded at the external air intake of the system, while outlet conditions were measured directly at the discharge duct of the evaporative cooler. Additional measurements were taken within the test space (working area) to assess the cooling effect on the surrounding environment. Experiments were conducted under controlled conditions during midday hours (11:00 am to 1:00 pm) to ensure relatively stable ambient temperature and solar load.

Airflow rate was measured using an anemometer (e.g., hot-wire type, accuracy ±0.1 m/s) installed at the air outlet, and volumetric flow rate was calculated based on duct cross-sectional area, as shown in Figure 1. Water flow rate was monitored using a calibrated rotameter (range 0-3,000 l/hr, accuracy ±2%), allowing precise adjustment of circulation rates. Electrical power consumption of the system components, including pumps and compressor, was measured using a digital power meter (accuracy ±1%), enabling calculation of the EER.

Figure 1. Types of evaporative cooler system pads
Note: a – evaporative cooler system; b – wood dust; c – cardboard padding; d – wood dust and cardboard padding
Source: developed by the authors

In addition to the measurement instrumentation, the experimental rig specifications and operating ranges were carefully defined. The evaporative air cooler was powered by a 1/3 HP (249 W) electric motor operating at 220 V and 50 Hz with a rotational speed of 1,425 RPM. The system was tested under three airflow rates of 0.566, 0.797, and 1.132 m^3/s. Water circulation was provided by two submersible pumps (40 W each), and the water flow rate was varied between 700 and 2,800 l/hr to evaluate its influence on cooling performance. The cooler body dimensions were 73 × 73 × 87 cm, while the outlet duct measured 34.5 × 21 × 19.5 cm. Furthermore, the hybrid cooling configuration incorporated a vapour-compression refrigeration unit equipped with a hermetic reciprocating compressor (1/3 HP, 280 W) using R600a refrigerant. The condenser fan power was 16 W, and the condenser dimensions were 35 × 26 × 3.5 cm. These system parameters were essential in defining the operational envelope of the experiments and ensuring reproducibility of results. To ensure data reliability, each experiment was repeated at least three times under identical operating conditions, and the average values were reported. Measurement uncertainty was estimated based on instrument accuracy and propagated through calculations, resulting in an overall uncertainty of approximately ±3 - 5% for efficiency and EER values. The repeatability of the results was confirmed by observing minimal deviation between repeated trials.

The performance of the evaporative cooling system was evaluated using fundamental heat and mass transfer relationships, which describe the thermodynamic behaviour of air-water interaction during the cooling process. The cooling efficiency (η) represents the ability of the system to reduce the dry-bulb temperature of the incoming air relative to the maximum possible cooling, defined by the wet-bulb temperature. It is expressed as the ratio of the actual temperature drop to the theoretical maximum temperature drop:

$$\eta = \frac{(T_1 - T_{\prime 2})}{(T_1 - T_2)} \times 100\%, \qquad (1)$$

where T_1 – dry-bulb's temperature of air at entering (outdoor air temperature) in (°C); $T_{\prime 2}$: dry-bulb's temperature of air at the exit (supply air temperature) in (°C); T_2 – wet-bulb's temperature of air at entering (outdoor air temperature) in (°C). Then the cooling capacity (Q_c) was calculated as:

$$Qc = Qa \times \rho \times Cp \times (T_1 - T_2), \qquad (2)$$

where Q_a – air flow rate in (m^3/s), Cp – specific air at constant pressure in (kJ/kg.K), ρ – air density (kg/ m^3), T_1 – air temperature at the inlet (°C), T_2 – air temperature at the outlet (°C). The EER can be calculated from the following equation:

$$EER = \frac{Q_c}{P_E}, \qquad (3)$$

where P_E – electrical power consumed in kW. Figure 2 represents the evaporative cooling process on a psychrometric chart, illustrating how air properties change during cooling and humidification. The horizontal axis (DBT) denotes the dry-bulb temperature, while the vertical axis indicates the specific humidity (humidity ratio). The curved boundary on the left corresponds to the saturation line (100% relative humidity), where air becomes fully saturated.

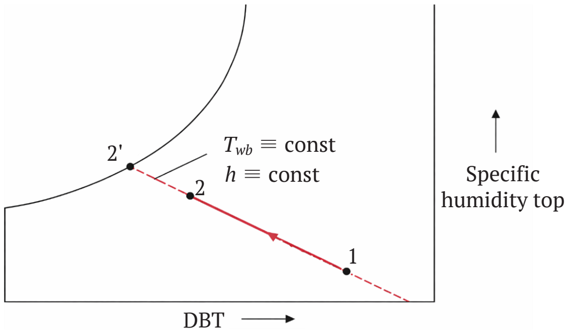

Figure 2. Demonstrates the evaporative cooler process

Source: developed by the authors

Point 1 represents the initial state of the incoming air, characterised by high dry-bulb temperature and low humidity (hot and dry conditions). As the air passes through the evaporative cooling system, it undergoes a transformation along the red line toward point 2. This process involves simultaneous cooling and humidification, where water evaporates into the air, reducing its temperature while increasing its moisture content. The key feature of this process is that it occurs approximately along a constant wet-bulb temperature ($T_{wb} \equiv$ const.) and constant enthalpy ($h \equiv$ const.) line, as indicated in the Figure 2. This reflects the thermodynamic principle that evaporative cooling is an adiabatic process, where the sensible heat of the air is converted into latent heat for water evaporation without external heat exchange. Point 2 represents the actual outlet air condition of the evaporative cooler. However, the process ideally could continue further toward point 2′, which lies closer to the saturation curve. This point represents the maximum achievable cooling limit, where the air approaches saturation and its temperature approaches the wet-bulb temperature. The dashed extension of the line indicates the ideal path, while the solid red line shows the real process, which deviates due to system inefficiencies such as incomplete evaporation, non-uniform wetting, and heat losses.

A simplified statistical assessment was performed to support the reliability of the experimental results. Based on the estimated overall measurement uncertainty (±3 - 5%), the standard deviation of the measured parameters was approximated, and the coefficient of variation was found to be within 4%, indicating good repeatability of the experiments. The maximum cooling efficiency of 89% under hybrid mode (P1&P2&C) falls within an uncertainty range of 85.4-92.6%, confirming the stability of the observed performance improvement. Similarly, the calculated EER values for different operating modes show limited dispersion, supporting the validity of the comparative analysis. Although this estimation provides an initial indication of data consistency, more rigorous statistical analysis based on extensive datasets is recommended for future work.

RESULTS AND DISCUSSION

The effect of the outside air temperature on actual energy consumed per ton of refrigeration is shown in Figure 3a. The results noted that the relationship is inverse with the stability of the airflow rate. These results showed that the increase in the air temperature leads to an increase in the cooling effect. While the energy consumed remains constant at the constant air flow rate, according to equation 3, the energy consumed per tonne of refrigeration is low. The test conditions were at airflow (0.566, 0.797, and 1.132 m^3/sec), where the best airflow was selected (1.132 m^3/sec) at water flow (1,400 l/hr). In this paper, three different types of packing were used in testing (wood dust, cardboard padding, wood dust and cardboard padding) shown in Figure 3b. It clears a relationship between efficiency and dry air inlet temperature, with airflow of 1.132 m^3/s and water flow of 1,400 l/hr. The results showed that the increase of temperature of dry air inlet and lower relative humidity leads to a higher ability of the air stream to contain water vapour. In Figure 3b the mode (wood dust and cardboard padding) indicates that at an ambient temperature of 45°C, the better cooling efficiency was about 84.4%, and a temperature reduction was 65.6%. Figure 5 also indicates in mode (wood dust and cardboard padding) that increasing the ambient air temperature from 25°C to 45°C leads to an increase in the cooling efficiency from 70 to 84.4% and a reduction in the temperature from 58 to 65.6% respectively.

Figure 3c shows that the relationship adjusts the flow rate of circulating water in the system. As the amount of water sprayed in the humidified channels increases, the temperature of the air in the dry channels will continue to decrease to a certain extent. This decrease will be accompanied by an increase in the latent heat gain of the air as it passes through the humidified channels. This result is conditioned by a large amount of sprayed water, where the increase in the enthalpy of water vapour is higher than the decrease in the temperature of dry air of the wet connection. The moisture content of the air will rise after leaving the evaporative cooling system. It leads to an increase in the enthalpy of the ambient air and thus causes a decrease in cooling efficiency. Therefore, high rates of water quantities do not meet the requirement of a good and appropriate design for the cooling system used. The small amount of water requires a small pump to rotate water during the system operation. The result showed that in this case, the consuming electrical energy spent in the system was lower than in other cases, which means a more beneficial case from an economic standpoint. Ultimately, it increased the performance coefficient of the system. This feature is considered one of the benefits of the cooling system concerned with this research. Figure 3c showed that the amount of water flowed at the low rates until it reached a value of 2,100 l/hr, but continuing to increase the water flow above this amount caused a small increase in cooling efficiency sensible where the percentage did not exceed (1%) until it reached the peak value when the amount of water is increased to 2,450 l/hr, then the relationship began to reverse with the flow of water until it reached a maximum value of water flow 2,800 l/hr. On this basis, it can be considered the amount of 2,100 l/hr is the practical and appropriate value for the water flow rate in this case.

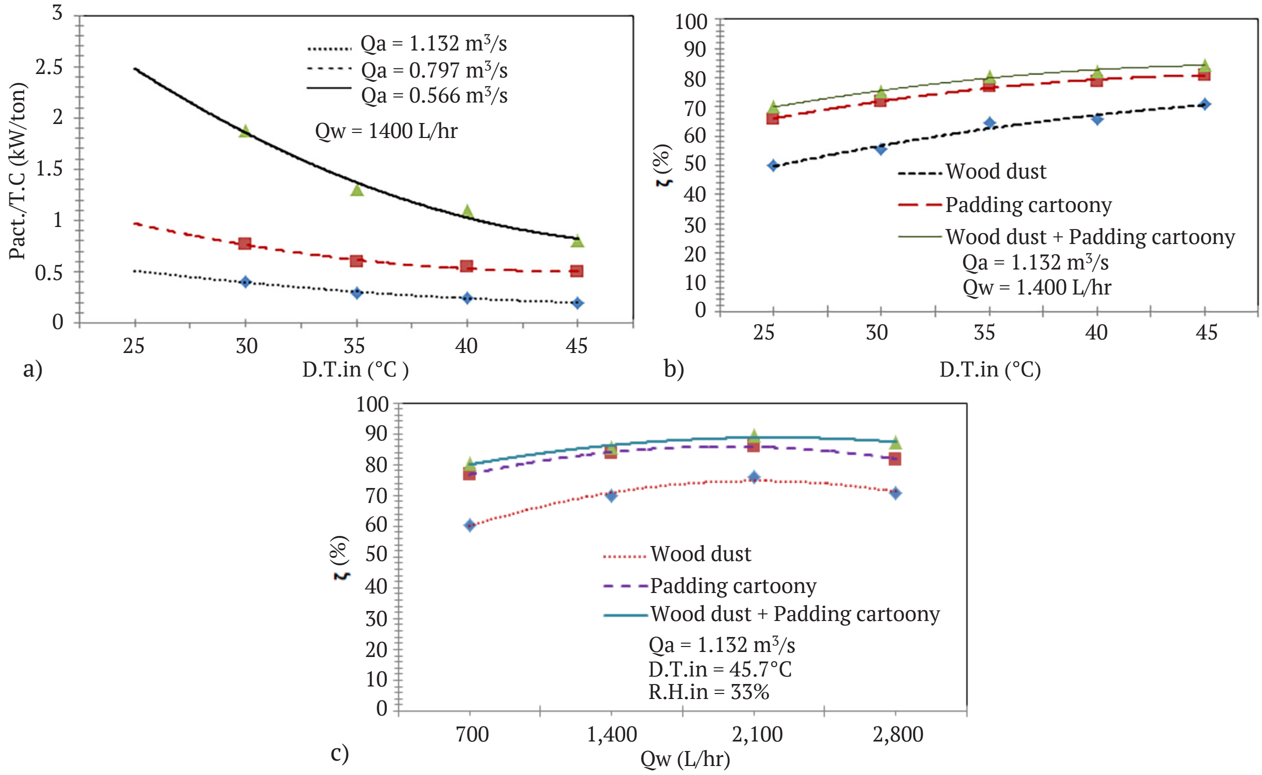

Figure 3. Influence of outdoor climatic and operating parameters on energy consumption and evaporative cooling efficiency

Note: a – effect of the temperature of the dry bulb outside air on real energy consumed per tonne of cooling; b – effect of the temperature of the dry bulb outside air on evaporative cooler efficiency; c – effect of the water mass flow-rate on evaporative cooler efficiency

Source: developed by the authors

Figure 4a showed the relation between the variation between the dry bulb inlet and outlet with time for varied paddings (wood dust, cardboard padding, and wood dust and cardboard padding). The results demonstrated that the temperature of the water and the air leaving the cooler was relatively decreased when using the second submersible pump, and the addition of the compression refrigeration cycle to the refrigerant reduced the air temperature of the coolant space. The use of a second submersible pump with the compression refrigeration cycle together led to a decrease in the space temperature. For mode (P1&P2&C), the comparison between Figure 4b, 4c showed that the reduction in the ambient air temperature is (9.7%), the reason for this reduction in temperature is conditioned by the delay in the passage of ambient air in the cardboard padding channels, and the occurrence of vortices of the incoming air, which leads to good contact of the incoming air with water droplets. The reduction ratio of the ambient air temperature may reach (16.3%) as Figure 5c compared with Figure 4a for mode (P1&P2&C). This reduction was because the padding channel contained (wood dust and cardboard padding) together.

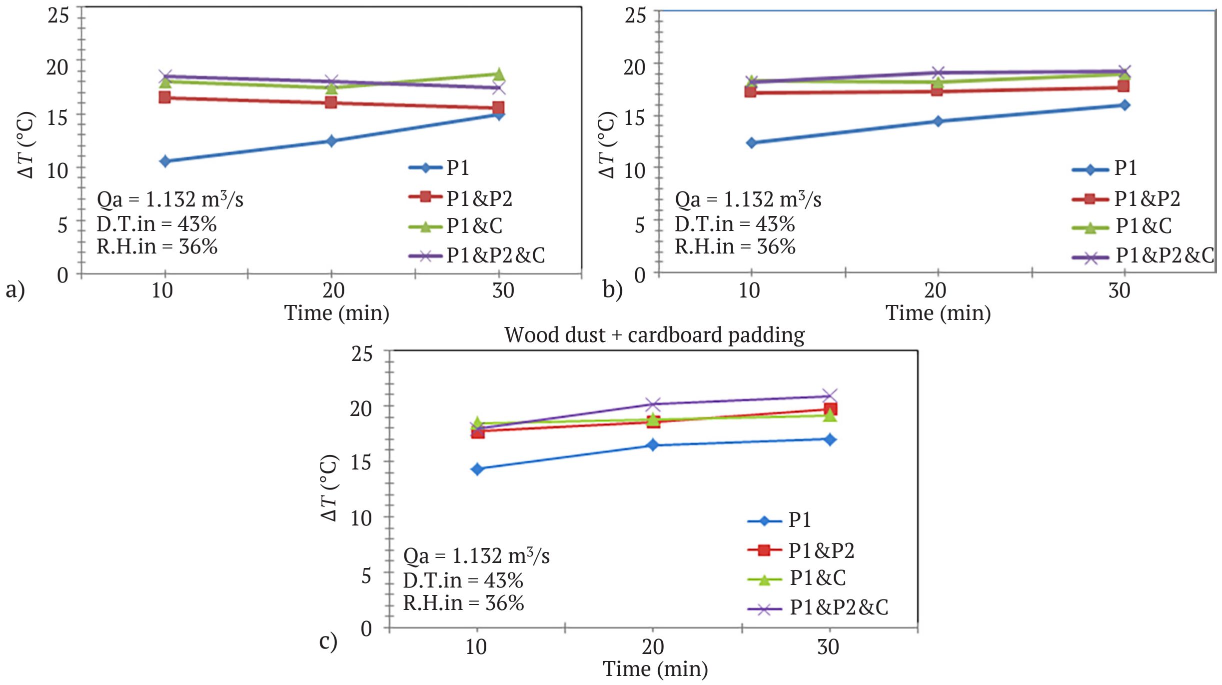

Figure 4. Time-dependent variation of dry-bulb temperature drop across evaporative pad materials (wood dust, cardboard, and their combination)

Note: a – relation between difference dry bulb inlet and outlet with time for wood dust paddings; b – relation between difference dry bulb inlet and outlet with time for cardboard padding; c – relation between difference dry bulb inlet and outlet with time for (wood dust and cardboard) paddings

Source: developed by the authors

Figure 5a, 5b shows the effect of the change in the padding types on the system on the evaporative cooler efficiency simultaneously. This change has been studied for three paddings (wood dust, cardboard padding, and wood dust and cardboard padding) with constant parameters air quantity (1.132 m^3/s), inlet dry bulb temperature at (47°C), and inlet relative humidity (27%). These Figures 5a, 5b show that the relationship is related directly to the constant air flow rate, whereby the increase in time increases efficiency. The reason for this relationship is conditioned by the evaporative quantity of basin water; it was carried out with the stability of the moisture content of the air approximately. In these Figures, there are different modes [only one pump (P1), only two pumps (P1&P2), one pump with refrigeration system (P1&C), and two pumps with refrigeration system (P1&P2&C)]. The temperature of the dry bulb outside air is almost constant during the test. The heat between entry and exit will increase because the susceptibility to heat and mass exchange of air and water increases when using wood dust and cardboard padding together with a constant air flow rate, and thus the efficiency increases. It also appears from Figure 6c that efficiency increases with the modes (P1&P2&C). The results show that maximum efficiency is (89%) at mode (P1&P2&C) with the presence of wood dust and cardboard padding together at the surfaces of the heat exchanger from the side of the humidified channels. Figure 5d depicted the relationship between the EER with the difference between dry bulb inlet and outlet for (wood dust and cardboard) paddings. Figure 6d showed that the EER is higher for evaporate coolers only, and it reaches 15 and decreases with the decrease in the variation between the dry bulb inlet and outlet. In addition, the EER is the lowest possible for (P1&C) mode.

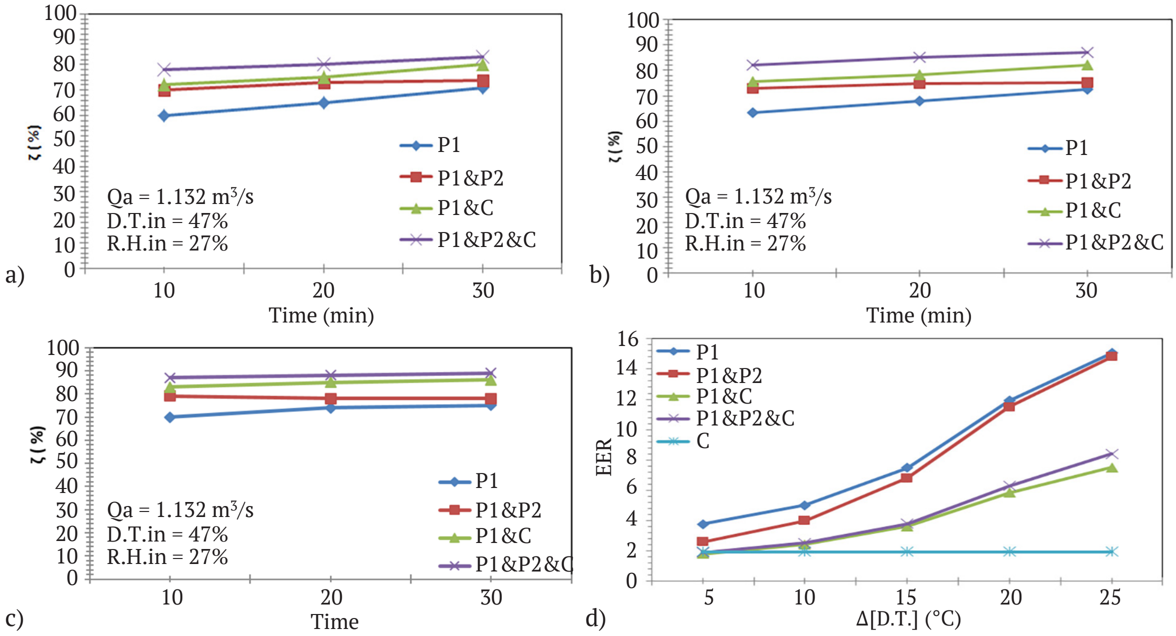

Figure 5. Time-dependent variation of evaporative cooler efficiency and EER for different pad materials (wood dust, cardboard, and their combination)

Note: a – relation between evaporative cooler efficiency with time for wood dust paddings; b – relation between evaporative cooler efficiency with time for (wood dust and cardboard) paddings; c – relation between evaporative cooler efficiency with time for cardboard padding; d – relation between EER with different dry bulb inlet and outlet for (wood dust and cardboard) paddings

Source: developed by the authors

The proposed (P1&P2&C) system is located slightly higher than (P1&C) mode and then from compression refrigeration mode (C). This means that the proposed system consumes less energy than compression cooling for the same cooling effect. Ultimately, the proposed mode (P1&P2&C) gives the best cooling effect when compared with other modes this results coincides with studies by S. Kumar *et al*. (2021), H. Sonawan *et al*. (2022), and S. Rasheed *et al*. (2025b). The analysis revealed that the efficiency and energy performance of the evaporative cooler depend significantly on both the temperature and humidity of the outside air and the design and type of the pad. As the dry-bulb temperature increases, the cooling capacity of the system and the efficiency of evaporation increase, particularly for combined fillers made of wood dust and cardboard. It was also found that optimising water flow is critical, as excessive flow does not improve efficiency but increases energy consumption. The combined configuration provides the highest efficiency and the best cooling performance compared to other operating modes. The results obtained confirm the feasibility of using hybrid systems to improve the energy efficiency of cooling.

CONCLUSIONS

By means of structural and operational changes, this study offered an experimental investigation aimed at improving the performance and energy efficiency of an evaporative cooling system. Under various operating conditions including: variations in airflow rate, water flow rate, and cooling pad materials; a hybrid cooling arrangement including an evaporative cooler with a vapour-compression refrigeration system was created and tested. The findings showed that operating conditions and design elements have a great impact on system performance. The ideal airflow rate was found to be 1.132 m³/s with a related water flow rate of 1,400 l/hr, therefore providing a good compromise between energy use and cooling efficiency. Among the examined pad materials, wood dust and cardboard padding used together showed best thermal performance with a maximum cooling effectiveness of 89% under hybrid operating mode (P1&P2&C). Furthermore, increasing ambient air temperature inside the range under examination improved cooling efficiency as a result of increased evaporation capability. The combination of a second submersible pump and the integration of the refrigeration cycle helped to clearly lower outlet air temperature and generally improve the system. Moreover, the suggested hybrid system showed a much better EER than the traditional compression cooling system, therefore, validating its capacity to lower electricity consumption while keeping excellent cooling performance. The results show throughout that evaporative cooling efficiency may be greatly enhanced by careful selection of pad materials, water flow rate, and system arrangement. Particularly in hot and dry locations, the suggested hybrid system provides a sensible and energy-efficient answer for air conditioning applications.

Further research should focus on optimising padding material structure and composition (including alternative porous and nanostructured media), investigating advanced water distribution techniques to enhance evaporation uniformity, and integrating intelligent control systems for real-time optimisation under varying climatic conditions. In addition, more detailed thermodynamic and economic analyses are required to evaluate long-term performance, water consumption, and system scalability, particularly for large-scale and industrial applications in different climatic regions.

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CONFLICT OF INTEREST

None.

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Фуркан Хайдер Мохамед Алі
Магістр
Технічний інженерний коледж Кіркук
Північний технічний університет
36001, м. Кіркук, Ірак
https://orcid.org/0009-0004-5491-3224

Захраа Хайдер Мохамед Алі
Магістр
Кіркукський політехнічний коледж
Північний технічний університет
36001, м. Кіркук, Ірак
https://orcid.org/0009-0007-7034-5230

Мустафа Наозад Тайфор
Магістр
Центр досліджень відновлювальної енергетики
Північний технічний університет
36001, м. Кіркук, Ірак
https://orcid.org/0000-0001-7146-1160

Хусейн Хайдер Мохамед Алі
Доктор філософії
Технічний інженерний коледж Кіркук
Північний технічний університет
36001, м. Кіркук, Ірак
https://orcid.org/0000-0003-4264-400X

Експериментальне дослідження окремих параметрів підвищення ефективності випарного охолоджувача: технічні нотатки

Анотація. Як альтернатива традиційним системам кондиціонування повітря на основі парокомпресійного циклу, які суттєво збільшують пікове електричне навантаження та енергоспоживання, у цьому дослідженні розглянуто методи підвищення продуктивності та енергоефективності випарних систем охолодження. Було експериментально розроблено та оцінено гібридну дворежимну систему охолодження, що поєднує парокомпресійну холодильну установку з випарним охолоджувачем. Дослідження зосереджено на ключових модифікаціях, зокрема заміні традиційних наповнювачів із деревного пилу на картонний наповнювальний матеріал, використанні допоміжного занурювального насоса для підвищення циркуляції води, а також комбінованій роботі обох типів наповнювачів. Експериментальні результати продемонстрували суттєве покращення роботи системи внаслідок цих змін. Зокрема, гібридна система з комбінованим середовищем із деревного пилу та картонного наповнювача досягла найвищої ефективності охолодження – 89 %, що свідчить про значне покращення процесів тепло- та масообміну. Збільшення витрати води додатково сприяло кращому зволоженню наповнювачів і підвищенню ефективності випарного охолодження. З точки зору енергетичних характеристик, гібридна система продемонструвала коефіцієнт енергоефективності (EER) на рівні 8,3, що значно перевищує показник автономної парокомпресійної системи (EER = 1,95). Окрім того, незалежна випарна система досягла максимального EER 14,8 при ефективності охолодження 71 %, що підтверджує її високий потенціал енергозбереження за відповідних умов експлуатації. Результати також показали, що оптимізація характеристик наповнювачів і розподілу води відіграє ключову роль у підвищенні ефективності охолодження при мінімізації енергоспоживання. Отримані дані підтверджують, що інтеграція випарного охолодження з традиційними системами, разом із належним вибором матеріалів і вдосконаленням гідравлічних параметрів, дозволяє істотно зменшити загальне енергоспоживання, зберігаючи належний рівень теплового комфорту. З практичної точки зору, запропонована гібридна система є економічно вигідним, енергоефективним і сталим рішенням для жарких і сухих кліматичних умов, що передбачає використання доступних місцевих матеріалів і простих модифікацій для зниження енергоспоживання та викидів, а також сприяє розвитку перспективних технологій охолодження

Ключові слова: гібридне кондиціонування повітря; термодинамічний аналіз; деревний пил; картонний наповнювач; енергоефективність