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Experimental evaluation of combined humidifier-dehumidifier desalination with thermoelectric module for simultaneous use of heating and cooling

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A R T I C L E I N F O

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Thermoelectric cooling system
Gain output ratio

A B S T R A C T

The objective of this study was to assess the performance of a Humidifier-Dehumidifier (HDH) desalination system paired with thermoelectric cooling, in order to achieve effective water desalination. The system employed the thermoelectric module's heating and cooling capabilities to warm the water entering the HDH system and remove moisture from the humid air. An investigation was conducted to examine the impact of varying sea water mass flow rate (SWMFR) and air mass flow rate (AMFR) on the performance characteristics of the system. These metrics include gain output ratio (GOR), coefficient of performance (COP), fresh water generation, and dehumidifier efficiency. The data collected clearly demonstrated that the performance of the system was significantly influenced by the WMFR and AMFR. The ideal values for the amount of fresh water produced, COP, GOR, and dehumidifier efficiency were determined to be 140 gs per hour, 0.93, 0.7 and, 52.5 %, respectively. The experimental assessment showcased the capability of the integrated HDH desalination with thermoelectric cooling system as a highly efficient and economically viable approach for desalination, particularly in regions with limited water resources.

Introduction

Water is a vital necessity for human life and the advancement of society and industry. Nevertheless, water resources are dwindling at a fast pace because of gradually increasing urbanization, industrial pollution, human population, natural disasters and improper agricultural policies [1,2]. Desalination of seawater is a sustainable solution to satisfy the water demand of individuals in case of water scarcity [3]. It is a process that can convert saline water into freshwater, making it a valuable resource for drinking, irrigation, industry, and other purposes. Desalination can help reduce water scarcity and promote sustainable development in areas with limited water resources [4]. Therefore, it is essential to explore and implement desalination technologies to ensure a sufficient and sustainable supply of freshwater for present and future generations [5–7].

The Humidification-Dehumidification (HDH) process is a leading small-scale water desalination technique that has been the focus of many recent studies [8,9]. This is due to its ability to utilize low-temperature energy sources [10] such as geothermal [11], sola and waste energy [12], as well as its simplicity and low installation and operational costs. Additionally, these systems operate at atmospheric pressure, requiring minimal mechanical energy, typically only fans and circulation pumps. As a result, their operation, construction and design are relatively easy and straightforward. The technical systems in developing countries are good for making these types of systems for households. Furthermore, the modular nature of HDH systems allows for increased capacity by adding additional collectors and HDH cycles [13,14].

Furqan et al. [15] studied the combination of an HDH desalination plant with a med desalination plant. Dehghan et al. [16] introduced a hybrid model of HDH with a Vapor Compression Refrigeration (VCR) cycle. In this model, the freshwater produced by the HDH process was cooled by a VCR evaporator and then sprayed back into the dehumidifier (DHF). When the humid air comes into contact with the cold freshwater particles, its humidity is distilled and additional freshwater is produced. The heat from the VCR condenser was utilized to heat the seawater before spraying it into the humidifier (HUF), improving the overall efficiency of the system. In an experimental study conducted by Dai and Zhang [17], they investigated the impact of air mass flow rate (AMFR), seawater mass flow rate (SWMFR) and seawater temperature on the

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Nomenclature

P	Electricity power (kW)
$\dot{m}$	Mass flow rate (kg/s)
Cp	Specific heat (kJ/kg K)
$\dot{Q}$	Heat transfer rate (kW)
RH	Relative humidity (%)
ω	Absolute humidity (kg water/kg air)
η	Efficiency (%)
h	Enthalpy (kJ/kg K)
T	Temperature (°C)
Subscript	
fwp	Fresh Water Production
EL	Electricity
a	Air
w	Water
Dh	Dehumidifier
H	Humidifier
L	Lost
i	Inlet
o	Outlet

productivity of an HDH system. Their findings revealed that these parameters have a high impact on the system's efficiency. Furthermore, they identified the optimal speed of the blower that corresponds to an optimal AMFR, which can improve the productivity and system's efficiency. This study provides valuable insights into the design and operation of HDH systems, which can help enhance their performance and ensure their sustainability. Siddiqui et al. [18] introduced a HDH desalination that operates at various pressures. They observed that the HDH operating at a HUF pressure of 50 kPa achieved a maximum GOR of 8.2, while the their HDH operating at a pressure ratio of 1.33 achieved 90 % effectiveness. These findings demonstrate the potential for HDH systems to operate efficiently at different pressure levels, which can enhance their performance and expand their range of applications. Elbassoussi et al. [19] conducted a recent study on a novel hybrid desalination that combines an AD (adsorption desalination) system with an HDH. The study showed that the hybrid desalination can produce around 22 Liter/h water at a cost of 1.15 cents/liter. Additionally, the COP and GOR values of the system were found to be 0.46 and 2.62, respectively. Furthermore, there has been recent research into coupling HDH systems with absorption heat pumps. This research aims to investigate the potential benefits of combining these two technologies to enhance the efficiency of water desalination and improve the overall sustainability of the process. Qasem et al. [20] proposed a combination of an absorption refrigeration system with HDH solar desalination and conducted an experimental investigation. They showed that the system's efficiency can be improved by optimizing the MFR and temperature of the air. These results indicate that such a combination has the potential to enhance the performance of both technologies and improve the overall efficiency of desalination processes. This research provides valuable insights into the operation and design of hybrid systems for water desalination, which can help address the growing demand for fresh water in environmentally sustainable ways. Patel et al. [21] conducted an experimental evaluation of the combination of HDH solar desalination and thermoelectric cooling modules. Their results demonstrated that this combination can increase the system's efficiency and reduce the cost of producing fresh water. This research suggests that the integration of thermoelectric cooling modules with HDH solar desalination has the potential to enhance the performance and sustainability of desalination processes, which can help address the growing demand for fresh water in an environmentally friendly and cost-effective manner.

Thermoelectric coolers (TECs), or Peltier devices, are electronic devices utilized to cool or heat items. They function by utilizing the Peltier effect, which entails the movement of heat from one side to the other when an electric current is applied to the device. The functioning principle of TECs is based on the phenomenon that occurs when an electric current flows through two ceramic blocks. In this process, one block experiences a decrease in temperature while the other block undergoes an increase in temperature. This effect can be reversed by applying an opposite electric charge [22]. Simply said, when an electric current flows through the device, one block becomes cold while the other becomes warmer. This occurs because of the phenomenon known as electric polarization counter-joule and/or the thermoelectric effect. TECs find use in electronic products, particularly in processes that need low sensitivity, such as sensors, medical equipment, compact processing units, and laptops. Additionally, they find applications in diverse sectors such as automotive, aerospace, and military. TEC technology has made significant progress in terms of enhanced performance, heightened efficiency, extended lifespan, and decreased expenses. Moreover, employing more effective and high-performing materials in the fabrication of TEC components and adopting novel techniques in the design and production of these devices might further enhance their performance.

The TECs in various applications, such as dehumidification, FWP, and solar desalination, has been investigated in several studies. Vian et al. [23] conducted a study to optimize TECs, condensed SWMFR, the COP value and fan supply voltage. Their findings suggest that TECs have high potential in dehumidification systems. In a separate study, Milani et al. [24] explored the possibility of producing fresh water from atmospheric moisture using a dehumidification system that utilizes TECs. They developed an algorithm to determine the required energy, cost, and amount of FWP based on the system's psychrometric parameters.

Esfahani et al. [25] examined a solar desalination with a TEC. Their results indicated that productivity increases with ambient temperature and solar intensity, while wind speed has an adverse effect. Rahbar and Esfahani [26] studied a solar desalination that utilized a TEC and a heat pipe. The TEC was responsible for the condensation process, while the heat pipe removed heat from the hot side of the TEC. The study highlighted the potential of TECs in solar desalination systems.

Several researchers worldwide have explored the combination of HDH desalination systems with refrigeration systems, but the integration of these desalination with thermoelectric cooling modules has received little attention. This study introduces a model of a hybrid system that combines these technologies, and an example of the system is also constructed. In this model, the heat generated by the thermoelectric module is utilized to heat water, while the cooling produced is utilized for dehumidifying the air. The sample system, located in Saudi Arabia, was experimentally evaluated, and the process of the test and its results are reported. In the results section, the impact of the of SWMFR and AMFR entering the system on the system's performance characteristics is investigated. The study demonstrates the potential of combining HDH with thermoelectric cooling modules and presents a novel approach for utilizing waste heat from the cooling process for heating water. Further studies can explore the use of alternative materials and designs for improving the performance and efficiency of this hybrid system.

Experimental model

Desalination is an essential process to produce fresh water in many arid and semi-arid regions. Among various desalination techniques, the HDH process has gained significant attention due to its low energy consumption and simplicity. However, the low efficiency of these systems remains a significant challenge, and researchers are exploring various solutions to improve their performance.

The present investigation presents a new hybrid HDH system that integrates a thermoelectric module to enhance the efficiency of the process. The system consists of a HUF, DEH, blower, pump, and water heating system. The seawater is introduced into the water heating system and subsequently heated by the thermoelectric module, which harnesses waste heat to elevate the temperature of the water. Subsequently, the heated saltwater is directed into the HUF, where it is atomized and introduced into the chamber. Concurrently, the blower pulls in the surrounding air and brings it into touch with the heated seawater, leading to the generation of humid air. Subsequently, the humid air is channeled towards the DEH, where it encounters the frigid surface of the TEC module. As the air with high moisture content comes into contact with the low temperature surface, it undergoes condensation, resulting in the formation of pure water. The potable water is accumulated in a reservoir, while the air that has been stripped of moisture is discharged into the surroundings. Fig. 1 displays a diagram of the model that was built. The system components' specifications are presented in Table 1.

The hybrid system offers a promising approach for achieving efficient and sustainable desalination, utilizing waste heat from the thermoelectric module. The system's design is simple, and it requires minimal maintenance and low energy consumption, making it ideal for portable applications. The system's performance characteristics are investigated by evaluating the impact of several parameters such as AMFR and SWMFR on the system's efficiency and output. The system's design has significant potential for future development and optimization, leading to improved performance and broader practical applications.

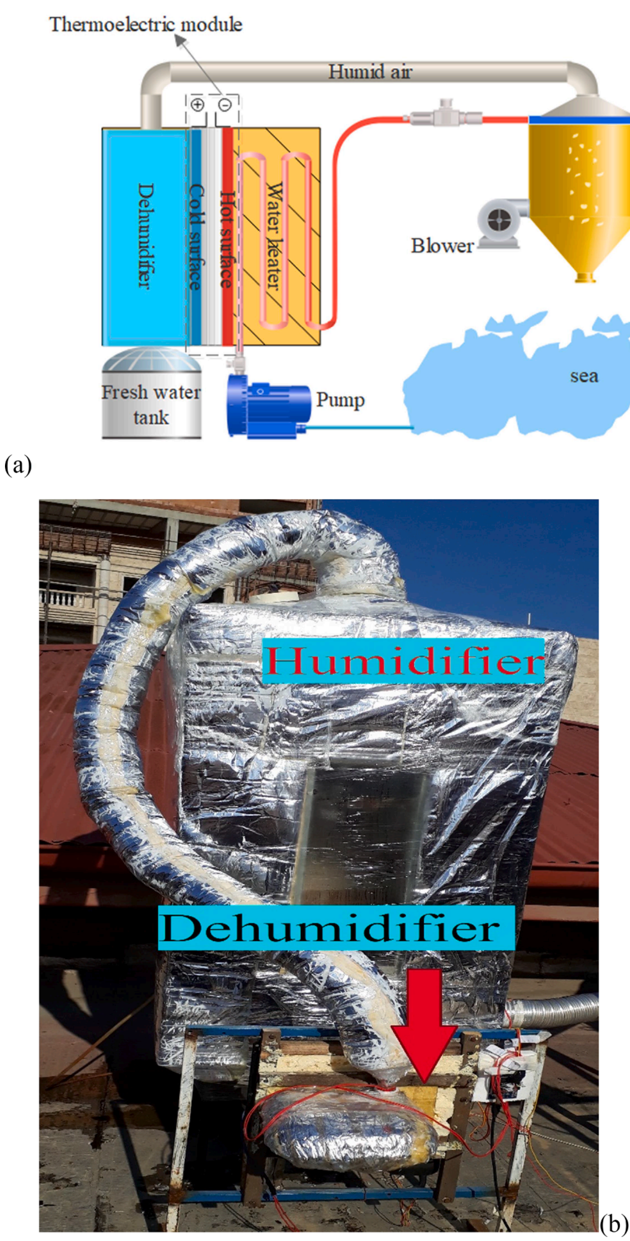

Fig. 1. (a) Schematic of the experimental model, (b) real picture of system.

Table 1
Specifications of System Components.

Components	Specifications
Humidifier	A rectangular cube with dimensions of 500 mm × 200 mm × 300 mm, Plexiglas body material
Dehumidifier	A rectangular cube with dimensions of 40 mm × 40 mm × 30 mm, Plexiglas body material
Thermoelectric	Voltage: 12 V V max(V): 15.4 V I max(A): 10A Q max(W): 154 W Dimensions: 40 mm × 40 mm × 3.2 mm
Pump	Power equal to 30 W, maximum pressure 135 psi
Blower	Power equal to 15 W

Measuring equipment

To accurately measure the performance characteristics of the constructed hybrid HDH desalination system, several sensors are installed to measure thermodynamic characteristics and mass flow. A temperature sensor is installed at the entrance and exit of each equipment to measure temperature changes accurately. Additionally, a Humidity Sensor is installed at the outlet and inlet of the DEH and inside the environment to measure humidity levels. The speed of the air entering the system is measured by an anemometer to ensure the desired flow rate is maintained. The SWMFR is measured by a flow meter sensor to calculate the amount of water passing through the system. The data obtained from the sensors during the test process is transferred to the Arduino board. This board is equipped with an ATMEGA32 microcontroller, which analyzes the signals received from the sensors and displays the results on the laptop monitor screen. Before starting the test process, each equipment in the system is calibrated to ensure accurate data acquisition. The use of sensors and a data acquisition system allows for accurate measurement and analysis of the system's performance characteristics. This information can be utilized to optimize the system's design and operation, leading to improved performance and efficiency. The details of the measuring equipment are presented in Table 2.

The specifications of these measuring equipment ensure that accurate and reliable measurements are obtained during the test process. These measurements are crucial in evaluating the performance characteristics of the hybrid HDH desalination system and optimizing its design and operation.

Experimental test process

The experimental test process aimed to assess the efficiency of the HDH system combined with a TEC module. The model used

Table 2
The details of the measuring equipment.

Equipment	Type	Measured Quantity	**Measuring Range**
Temperature sensor	PT100	Temperature	**−50 to + 150 °C**
Humidity Sensor	SHTC1	Relative Humidity	**0 to 100 %**
Anemometer	LUTRON LM-8102	Air velocity	**0.2 to 20 m/s**
Flow meter sensor	YF-S201	Flow rate	**0.3 to 6 L/min**

thermoelectric heating for seawater heating and thermoelectric cooling for dehumidification in the DEH. The main target of the experiment was to specify the optimal mode of operation for the system. The experiment was conducted in Jeddah, one of the warmest cities in Arabia, under controlled laboratory conditions. In all experiments, the ambient temperature (inlet air to the HUF) was considered constant at 21 °C. The AMFR varied during the experiment, with values of 0.004, 0.0055, 0.0070, and 0.0085 kg/s. The SWMFR was also varied during the experiment, with flow rates of 0.009, 0.010, 0.013, and 0.015 kg/s.

During the experiment, the heat produced by the thermoelectric module was used for water heating. We used a device called a heat exchanger to move heat from the thermoelectric module to the seawater. The heated water was then directed to the HUF and sprayed inside. The air and heated water were mixed together in the humidifying chamber, resulting in the production of humid air, which exited from the upper side of the HUF and flowed to the DEH.

The AMFR and SWMFR were the two main variables of the experiment. The experiment was carried out with a constant SWMFR, while the AMFR was changed. The system was set at different AMFRs of 0.004, 0.0055, 0.0070, and 0.0085 kg/s for each setting of the SWMFRs. The system took 30 min to reach stable conditions at each flow rate setting, and then 1 h was spent performing each test. During this 1 h period, the relative humidity and temperature of the ambient air, incoming and outgoing air from the DEH, and water temperature measurements were recorded. The amount of fresh water produced by the graduated containers was also measured and recorded at the end of the 1 h test.

The SWMFR was measured using a water flow meter, while the AMFR was measured and adjusted by an anemometer. The values of the parameters that remained constant during the experiment are stated in Table 3.

Table 3
Constant Parameters in the Experimental Test.

Parameter	Value
Laboratory ambient temperature	21 °C
Humidifier inlet air temperature	21 °C
Seawater temperature	21 °C
Humidifier spray nozzle diameter	0.5 mm
Pump power	30 W
Blower power	15 W

Uncertainty analysis

Uncertainty analysis was performed to ensure the accuracy and reliability of the experimental results according to the method of Kempers et al. [27]. The analysis evaluated the uncertainty associated with the measurement of key parameters, including temperature, humidity, air velocity, and SWMFR. The results of the analysis indicate that the uncertainty associated with the measurement of humidity is 1.5 %, while the uncertainty associated with the measurement of temperature is 4.5 %. Additionally, the uncertainty associated with the measurement of air velocity and SWMFR is 4.76 % and 1.23 %, respectively.

The analysis of the uncertainty budget provides valuable insights into the sources of error and their impact on the measurement results [28]. However, the results of the analysis demonstrate that the measurement uncertainties are relatively small, indicating that the results are highly reliable. Based on the analysis of the uncertainty budget, it can be concluded that the experimental results have a high level of accuracy, and can be trusted with a confidence level of over 95 %. The results of the uncertainty analysis can be used to improve the experimental procedures, optimize the measurement methods, and enhance the overall quality of the study.

Performance parameters

In the current study, to assess the constructed system, the impact of SWMFR and FMFR entering the system on the performance parameters of the system such as GOR, COP, FWP and DEH efficiency were investigated. To calculate these parameters, the variables measured during the experiment were used. Each of these performance parameters are calculated as follows.

The amount of heat that the thermoelectric provides to the seawater at the hot side is expressed as:

$$\dot{Q}_H = \dot{m}_w \times C_{p_w} \times \left(T_{w,i,H} - T_{sw}\right) \tag{1}$$

The air temperature that leaving the humidifier is equal to the temperature of the air entering the dehumidifier. The rationale for this is that humid air flows via a fully insulated conduit.

$$T_{w,o,H} = T_{w,i,Dh}$$

The AMFR is a constant value throughout the cycle.

$$\dot{m}_{a,i,H} = \dot{m}_{a,o,H} = \dot{m}_{a,i,Dh} = \dot{m}_{a,o,Dh} = \dot{m}_a$$

The amount of cooling that the thermoelectric provides to the humid air in the dehumidifier is expressed as:

$$\dot{Q}_L = \dot{m}_a \times \left(h_{a,i,Dh} - h_{a,o,Dh}\right) - \dot{m}_{fwp} \times h_{fwp} \tag{2}$$

The COP value of the system is calculated according to Eq. (3):

$$COP = \frac{\dot{Q}_L}{\dot{Q}_H - \dot{Q}_L} \tag{3}$$

The GOR value of the system is calculated according to Eq. (4):

$$GOR = \frac{\dot{m}_{fwp} \times h_{fg}}{P_{EL}} \tag{4}$$

The efficiency of the dehumidification process (η_{Dh}) is obtained as a ratio between the absolute humidity changes before and after the dehumidification process to the changes when the outlet air is saturated at a temperature equal to the temperature of the Thermoelectric cold surface [33].

$$\eta_{Dh} = \frac{\left(\omega_{i,Dh} - \omega_{o,Dh}\right)}{\left(\omega_{i,Dh} - \omega_{o,Dh,s}\right)} \tag{5}$$

$\omega_{o,Dh,\,s}$ is the absolute humidity, when the air coming out of the DEH is at a temperature equal to the temperature of the DEH surface and in a saturated state.

Results and discussion

The performance of the HDH desalination system with a thermoelectric module was influenced by variations in the SWMFR and AMFR. This section presents the evaluation of how these factors affect the performance characteristics of the system, including GOR, COP, fresh water output, and DEH efficiency. During this process, water was heated by harnessing the heat generated by the thermoelectric module. Fig. 2 demonstrates that there is an inverse relationship between the SWMFR and the heat transfer from the thermoelectric module to the water. This relationship follows a parabolic pattern. This phenomenon can be explained by the fact that as the rate of flow increases, the velocity of water flow also increases, leading to a decrease in the potential for heat exchange. Hence, in order to enhance the heating efficiency of water and raise its temperature, it is imperative to adhere to a specific upper limit for the flow rate.

The heated water is directed towards the HUF and inside distributed by means of spraying. The HUF introduces the surrounding air into its system, where it becomes moistened as it comes into touch with the hot water spray. The higher temperature of the water facilitates the process

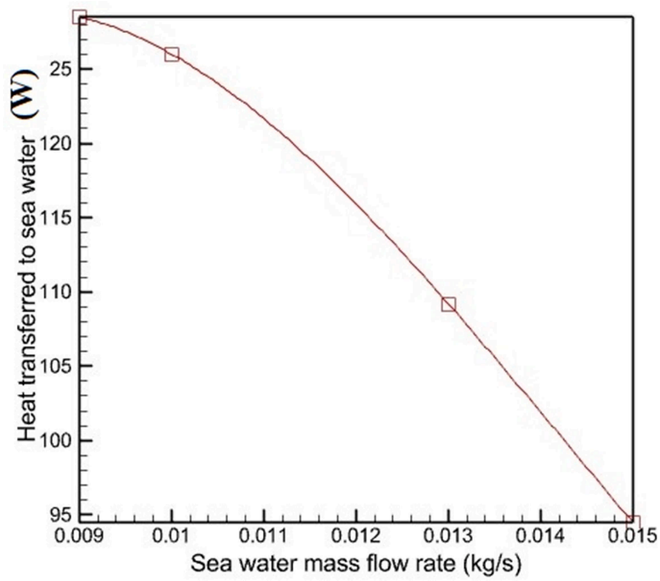

Fig. 2. The impact of SWMFR on the heat input to it.

of augmenting humidity. Fig. 3 illustrates that enhancing the AMFR has no impact on the temperature of the seawater as it enters and exits the HUF. The water temperature stays completely unaltered by the AMFR. However, it was observed that the temperature of the water entering the HUF decreases as the SWMFR increases. This behavior can be explained by the inverse correlation between the SWMFR and the amount of heat that is transferred to it. On the other hand, when the flow rate increases, the thermoelectric module needs to distribute the heat it produces to a larger volume of water. Therefore, with an increase in the SWMFR, the temperature of the water entering the HUF (i.e., the water that comes out of the water heating system) decreases. Fig. 3 illustrates a direct correlation between the decrease in the temperature of the water entering the HUF and the corresponding decrease in the temperature of the water departing the HUF. The decrease in temperature occurs due to the dissipation of heat from the water in the HUF chamber, which is used to warm and add moisture to the air entering the HUF. The humid air produced in this region is transported to the DEH chamber through a conduit in order to remove moisture and produce drinkable water.

As mentioned before, the HUF produces humid air that enters the DEH chamber. Based on the data presented in Fig. 4, it can be deduced that the temperature of the air entering and exiting the DEH decreases in a linear fashion, with a minimal gradient, as the AMFR increases. When the AMFR increases, the velocity of air particles correspondingly increases. This leads to a reduction in the likelihood of heat transfer. As a result, the water sprayed in the HUF must transfer heat to a greater volume of air per unit of time. As a result, the air temperature decreases at the point where the HUF unit ends and the DEH unit begins.

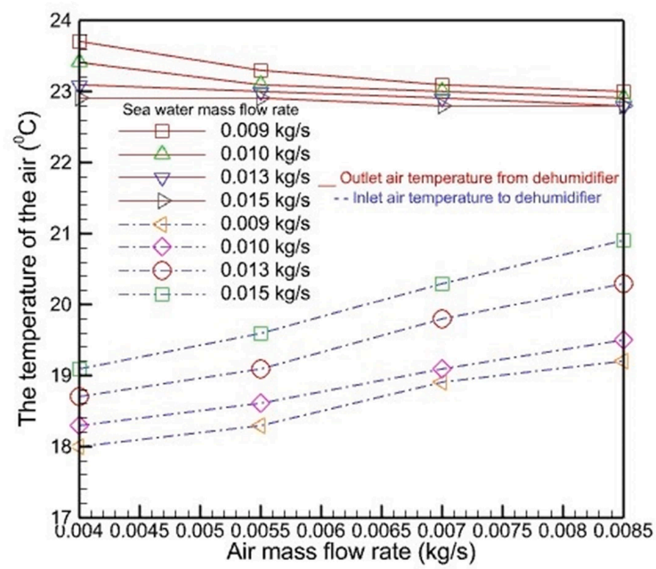

Fig. 4. Inlet and outlet air temperature of the DEH unit at different MFRs.

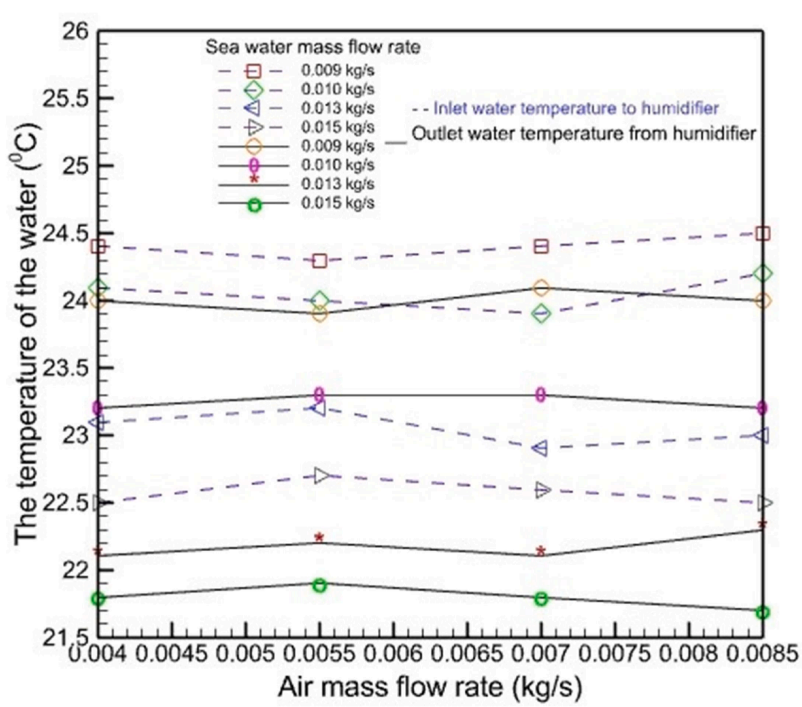

Fig. 3. The impact of SWMFR on water temperature.

Observations revealed that the temperature of the entering air to the DEH consistently decreased as the SWMFR increased in all test circumstances. The association between the rise in SWMFR and the decrease in the temperature of the water entering the HUF can account for this phenomenon.

The study also examined the influence of SWMFR and AMFR on the temperature of the air that is discharged from the DEH. Fig. 4 demonstrates that the thermoelectric cold surface must dissipate heat to a greater amount of air over a given time period, resulting in a reduction in temperature difference.

The COP value of the system was calculated using the Eq. (3) and the impact of increasing the flow of water entering the system on its COP is shown in Fig. 5. It can be observed that with the increase in SWMFR, the COP value decreases in all test cases. This decrease in COP occurs at lower AMFRs with a lower slope, and as the AMFR entering the system increases, the decrease in COP with the increase in SWMFR becomes more significant. Therefore, in order to maintain the COP of the system, it is not possible to increase the flow rate of water and air beyond a certain limit. To explain the decrease in COP with increasing SWMFR, it can be said that as the SWMFR increases, the heat transferred from the thermoelectric module decreases (as shown in Fig. 2). Consequently, the amount of cooling produced by this module is also reduced, resulting in a decrease in the COP value of the system.

According to Fig. 6, the COP of the system increases with the increase in AMFR. Moreover, it is observed that at high SWMFRs, the increase in COP with increasing AMFR is less significant, while at low SWMFRs, the increase in COP with increasing AMFR is more pronounced.

The highest COP value of 0.93 is obtained at the AMFR of 0.0085 kg/s and the SWMFR of0.009 kg/s. Therefore, to achieve a good COP, it is necessary to reduce the SWMFR as much as possible and increase the AMFR.

In the experimental study, the impact of SWMFR and AMFR on the amount of FWP was also investigated. The trend of FWP similar to the COP trend with a good approximation. This can be explained by the fact that both cooling and heating produced by the thermoelectric modules are utilized in the system. As the COP value increases, both the heating of water in the cycle and the production of cooling increases. Finally, with the increase in production cooling, more moisture is distilled from the air, leading to an increase in the amount of FWP.

According to Fig. 7, it was observed that with the increase in SWMFR, the amount of FWP decreases in all test cases. This is because as

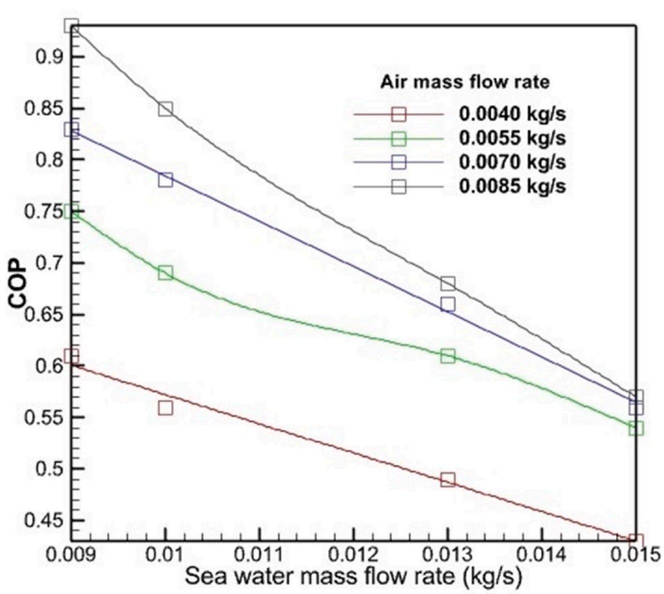

Fig. 5. COP system in different SWMFRs.

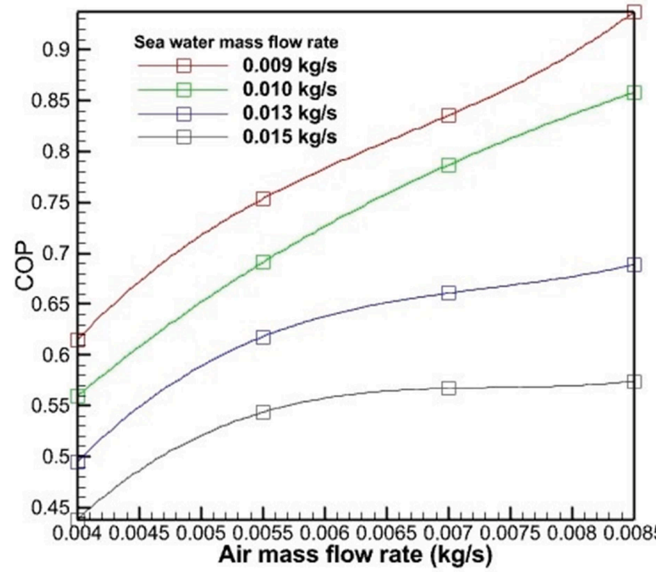

Fig. 6. COP system in different AMFRs.

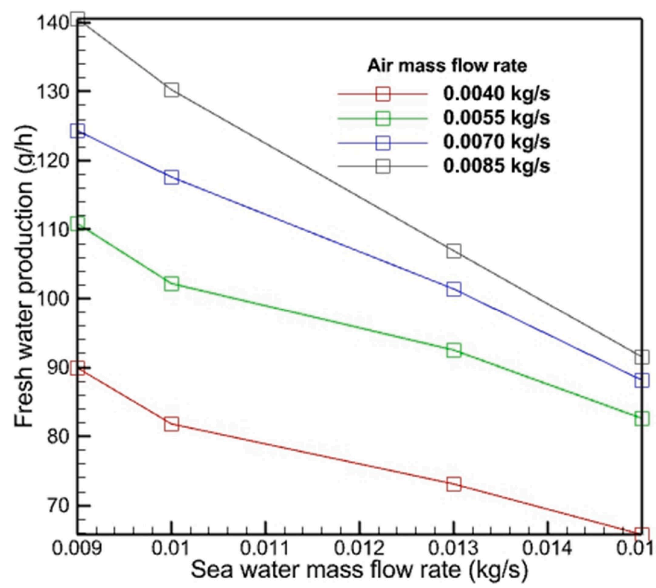

Fig. 7. The MFR of fresh water produced in different SWMFRs.

the SWMFR increases, the amount of water heating as well as the temperature of the water entering the HUF chamber decreases. Therefore, it is not possible to humidify the air optimally, and as a result, the air with lower humidity and temperature enters the DEH chamber, leading to a decrease in the amount of FWP.

On the other hand, according to Fig. 8, it was observed that with the increase in AMFR, the amount of FWP increases in all test cases. The obtained results may be explained by this fact that as the AMFR increases, more moisture enters the DEH chamber per unit of time, leading to an increased conversion of moisture into fresh water. Overall, the SWMFR and AMFR are the important variables that affect the amount of FWP in the system. The SWMFR should be optimized to balance the trade-off between FWP rate and system efficiency, while the AMFR should be increased to improve the amount of FWP. However, it should be mentioned that the optimal values of these variables depend on the specific design and operating parameters of the system, and they should be determined through experimentation and optimization.

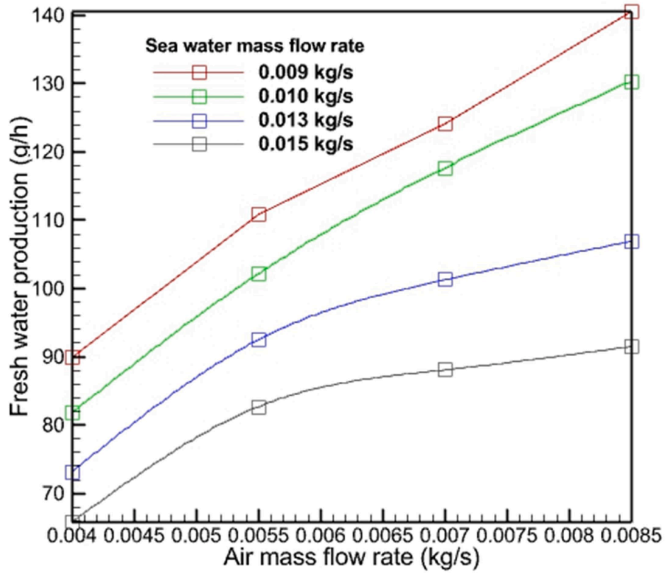

Fig. 8. The MFR of fresh water produced in different AMFRs.

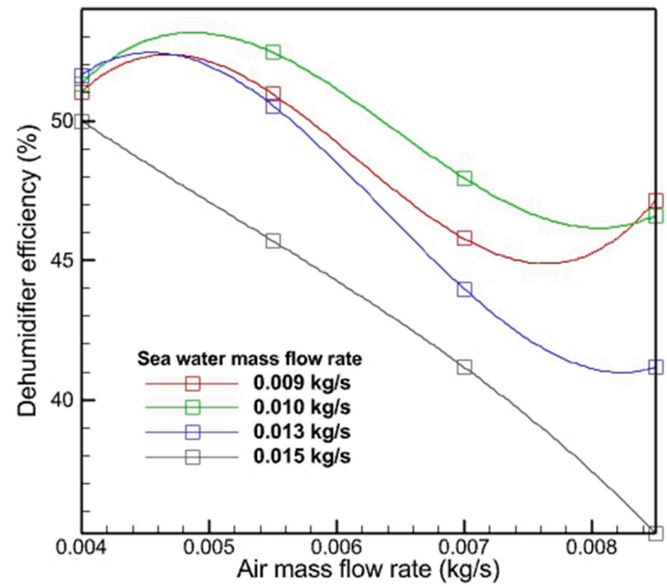

Fig. 10. DEH efficiency in different AMFRs.

The experimental investigation studied the dehumidification efficiency, which is a crucial performance parameter of the HDH desalination with thermoelectric module. Fig. 9 demonstrates a consistent drop in DEH efficiency across all test conditions when the SWMFR increases. This decline is less pronounced at low AMFRs, but becomes more pronounced at high AMFRs. This relationship can be elucidated by the fact that as the SWMFR grows, the COP of the system falls, as depicted in Fig. 5. A reduction in COP is anticipated to hinder the dehumidification process, leading to a decline in the efficiency of the DEH.

Conversely, Fig. 10 indicates a general trend of decreasing DEH efficiency as the AMFR entering the DEH increases. The pattern can be modeled by a cubic function. At high SWMFRs, as the AMFR increases, the efficiency of the DEH initially rises, then declines, and then rises again with further increases in AMFR. The observed outcomes can be attributed to the phenomenon that, as the AMFR increases, although more moisture enters the DEH per unit of time, the velocity of air particles also increases, resulting in a reduced chance for dehumidification.

Fig. 10 demonstrates that the highest DEH efficiency achieved was 52.5 % when the AMFR was 0.0055 kg/s and the SWMFR was 0.01 kg/s. Hence, in order to maximize the effectiveness of the DEH, it is imperative to optimize the AMFR and the SWMFR of the system. The DEH efficiency is a crucial factor that directly impacts the entire performance of the system. A high DEH efficiency results in increased moisture extraction from the air, leading to a higher rate of FWP and improved system performance. Hence, it is crucial to enhance the design and operational variables of the system in order to get maximum efficiency of the DEH, while simultaneously upholding other significant performance criteria like COP and FWP rate.

The study also examined the GOR value, which is a significant metric. Fig. 11 demonstrates a significant decrease in the GOR value as the SWMFR increases. This phenomenon is observed at lower AMFRs with a more gradual incline. The reason behind this pattern is that as the SWMFR grows, there is a corresponding decrease in water output, leading to a decrease in the COP value of the system, as previously mentioned. As the COP value lowers, the cooling output of the system

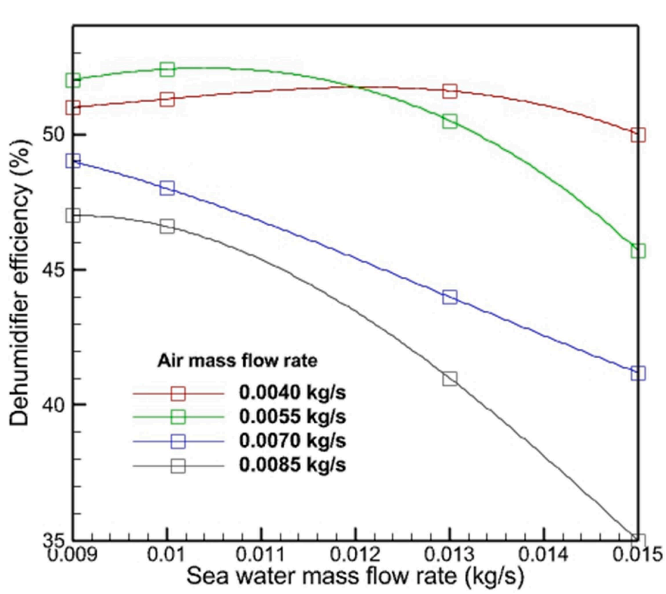

Fig. 9. DEH efficiency in different SWMFRs.

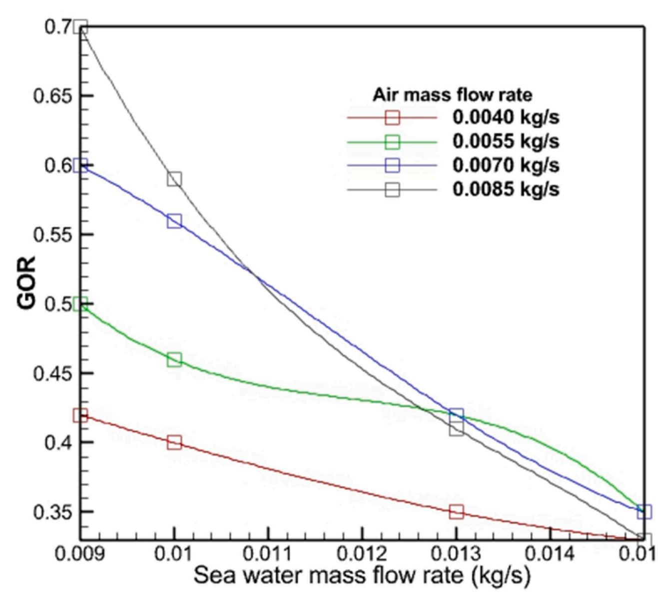

Fig. 11. The impact of SWMFR on GOR.

similarly reduces, resulting in a decrease in the GOR value.

Conversely, Fig. 12 examined the impact of increasing AMFR on the GOR value. At high SWMFRs, namely at 0.015 kg/s, it was noted that the GOR value remains nearly constant as the AMFR increases. Nevertheless, when the SWMFR is lower, namely at 0.009 kg/s, the GOR value rises as the AMFR grows. This pattern tends to become more linear as the SWMFR drops. This phenomenon can be attributed to the positive correlation between the AMFR, FWP, COP, and GOR. As the AMFR grows, there is a corresponding increase in both FWP and COP, resulting in an overall increase in the GOR value.

Overall, the GOR value is an important parameter that represents the efficiency of the system in converting energy input into fresh water output. A higher GOR value indicates a more efficient system, and it is important to optimize the system's design and operating parameters to achieve the highest GOR value possible. The SWMFR and AMFR are two important variables that affect the GOR value, and they should be optimized to achieve the highest GOR value possible while maintaining other important performance parameters such as COP, FWP rate, and DEH efficiency.

It is worth noting that the optimal values of these variables depend on the specific design and operating parameters of the system, and they should be determined through experimentation and optimization. Additionally, the quality of the sea water used in the system also plays an important role in its performance, and proper pre-treatment of the sea water is necessary to ensure optimal performance and longevity of the system. In summary, the GOR value is an important parameter that should be considered when designing and operating a HDH desalination with thermoelectric module for desalination. The SWMFR and AMFR are two important variables that affect the GOR value, and they should be optimized to achieve the highest GOR value possible while maintaining other important performance parameters.

A comparison has been made between the results of this study and the results of other researchers (Table 4). In general, water production in desalination plants of other studies is much higher than this study. The reason can be stated that the cooling capacity produced by the thermoelectric module for dehumidification is small and as a result produces less water.

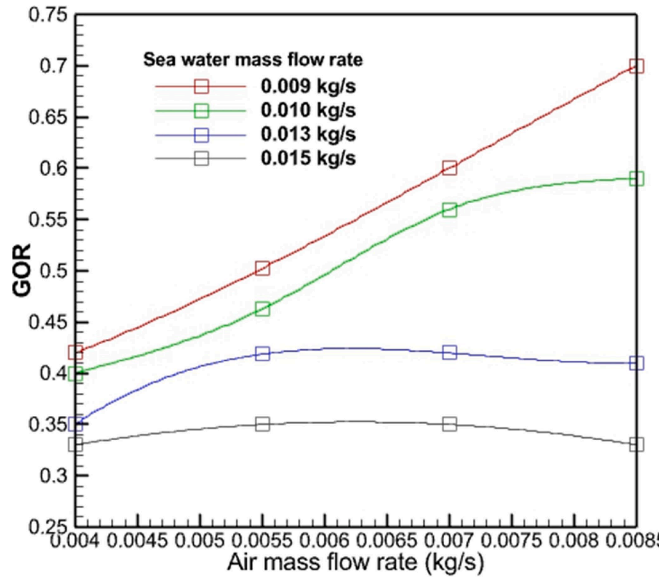

Fig. 12. The impact of AMFR on GOR.

Table 4
Comparison of the results of this study with other studies.

Ref.	Year	Solar	Use cooling system	Produced fresh water (L/h)	GOR
Santosh, R., et al. [29]	2020	No	Yes	4.7	1.27
Chen, Qian, et al. [30]	2020	No	Yes	140	2.4
Alsehli, et al. [31]	2021	Yes	No	0.05–1.8	0.03–1
Tangellapalli, et al. [32]	2023	No	Yes	5	–
Lai, et al. [33]	2023	No	Yes	148	3
This study	2023	No	Yes	0.14	0.7

Conclusion

In summary, the experimental evaluation of the combined HDH desalination with thermoelectric cooling system showed that the performance characteristics of the system are strongly influenced by the SWMFR and AMFR. The increase in SWMFR leads to a decrease in FWP, COP, GOR, and DEH efficiency, while increasing the AMFR leads to an increase in FWP, COP, and GOR, but a decrease in DEH efficiency.

The optimal values for the produced fresh water, COP, GOR, and DEH efficiency were found to be 140 gs per hour, 0.93, 52.5 %, and 0.7, respectively. It was also observed that at lower SWMFRs, the GOR value increases with the increase in AMFR, and this trend becomes more intense as the SWMFR decreases. Therefore, it is recommended to reduce the flow of water entering the system to the extent that all the water sprayed in the HUF chamber is used to humidify the air to the saturation level. Additionally, by reducing SWMFR, the temperature of the water can be increased to a greater extent by thermoelectric heating, and more heat can be introduced into the HUF.

Overall, the results of the current study prove the potential of the combined HDH desalination with thermoelectric cooling system as an efficient and cost-effective method for desalination, especially in areas with limited access to fresh water. The system offers the advantage of using waste heat to enhance the efficiency of the process, and it has the potential to be optimized further by adjusting the SWMFR and AMFR. Further research and development in this area could lead to the implementation of this technology on a larger scale and contribute to addressing the global water scarcity problem.

CRediT authorship contribution statement

Kairat A. Kuterbekov: Formal analysis, Investigation, Resources, Visualization, Writing – original draft, Funding acquisition. **Asset M. Kabyshev:** Formal analysis, Investigation, Software, Validation, Funding acquisition. **Kenzhebatyr Zh. Bekmyrza:** Conceptualization, Data curation, Investigation, Methodology, Funding acquisition. **Marzhan M. Kubenova:** Data curation, Investigation, Software, Validation. **Amirhossein Aghajani.A:** Conceptualization, Formal analysis, Software, Writing – original draft, Writing – review & editing.

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.

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