Derna University Journal of Applied Sciences
Vol. 2, Issue 1, 2025
ISSN: 3079-0719 (Online) | DOI: https://doi.org/10.58987/2kpnea60

Solar Desalination Using Humidification-Dehumidification Method Under the Climate Condition of Tobruk City

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Received: May 15, 2025; **Accepted**: June 09, 2025

الملخص—تم تصميم وبناء ودراسة وحدة تحليه مياه تعمل بالطاقة الشمسية باستخدام نظام الترطيب وإزالة الرطوبة (HDH) من خلال التحكم في معدل تدفق كتلة الهواء. أجريت الدراسة عند ثلاث معدلات مختلفة لتدفق كتلة الهواء: 0.00276 كجم/ثانية، و0.02022 كجم/ثانية، و0.02682 كجم/ثانية. تشمل المكونات الرئيسية لنظام تحليه المياه سخان هواء/ماء شمسي مزدوج الزجاج ومرطب (مبخر) ومزيل رطوبة (مكثف) ومضخة دوران ومروحة وخزان تخزين. يتم تسخين كل من الهواء والماء المالح (أو قليل الملوحة) في سخان هواء/ماء شمسي واحد مدمج. أظهرت نتائج البحث أن التغيرات في معدل تدفق كتلة الهواء لها تأثير مباشر على إنتاج المياه العذبة، حيث تؤدي معدلات تدفق الهواء الأعلى إلى زيادة إنتاج المياه من النظام. وكانت أقصى إنتاجية لهذا النظام في 6 أكتوبر، حيث تم إنتاج 570 ملي لتر من المياه العذبة يوميًا بمعدل تدفق كتلة هوائية يبلغ 0.02682 كجم / ثانية.

الكلمات المفتاحية—تحليه المياه بالطاقة الشمسية؛ الترطيب؛ إزالة الترطيب؛ الطاقة المتجددة

Abstract—A solar water desalination system based on the humidification and dehumidification (HDH) process was designed, built, and tested by varying the air mass flow rate. The study explored three different air flow rates: 0.00276 kg/s, 0.02022 kg/s, and 0.02682 kg/s. The system included a combined solar air/water heater with double glass, a humidifier (evaporator), a dehumidifier (condenser), a circulation pump, a fan, and a storage tank. Both the air and brackish or low-salinity water were heated simultaneously in the combined solar air/water heater. The results indicated that increasing the air mass flow rate significantly improved freshwater production, suggesting that higher air flow rates yield greater water output. The system reached its peak productivity of 570 mL/day on October 6 at an air mass flow rate of 0.02682 kg/s.

Keywords—Solar desalination; Humidification; Dehumidification; Renewable energy

1. Introduction

Water and energy are crucial topics on the global environmental and development agenda, as both play a significant role in the economic progress of any region. Currently, water scarcity is a pressing issue in many countries. In many regions around the globe, contamination of seas, oceans, lakes, rivers, and groundwater has greatly impacted the availability of clean freshwater. This has led to the increased use of purification methods to treat saline water. Many governments are striving to provide drinking water to their populations, but in numerous areas, the demand for water surpasses the available supply [1]. The cost of water treatment varies based on the availability of resources and a country's ability to offer affordable solutions for desalinating salty water. This presents one of the main challenges in producing fresh water. With the rapid increase in population, water resources are diminishing significantly. In arid and semi-arid regions, particularly in countries in the Middle East, addressing future water scarcity remains a critical issue. It is a growing concern in nations that face challenges related to limited water resources [2]. Desalination is becoming a widely regarded solution to address the increasing need for water in certain areas facing shortages of drinkable water. Harnessing solar power for water desalination is considered more cost-effective compared to other purification methods [3]. The earth's water resources are distributed as 3% fresh water and 97% salty water. Factors such as population growth, uneven distribution of water sources, and climate change have contributed to the decline in fresh water availability globally. These challenges highlight the importance of exploring alternative methods for obtaining fresh water. Water purification is widely regarded in many regions as an effective and economical solution for producing drinking water [4].

Renewable energy and purification plants are two distinct technologies that can be effectively combined in various ways. Purification systems can operate using renewable energy sources, renewable energy sources like wind and solar power are ideal for powering systems in regions lacking access to an electricity grid. Renewable energy sources such as wind and solar power can drive these systems. However, a challenge of using renewable energy is the high initial cost and the need for large spaces. Despite this, renewable energy technologies offer significant advantages. For instance, solar energy is a promising option for water desalination, providing a reliable method for producing potable water. In some regions, especially those experiencing increased freshwater demand due to tourism or other factors, solar-powered purification systems can offer self-sufficiency, particularly during summer when solar radiation is abundant. In developing countries facing water scarcity, utilizing renewable energy for purification and desalination presents an effective solution to reduce dependency on traditional energy supplies and meet growing water demands [5]. The primary goal of solar desalination units is to purify and remove salt from water using solar energy. These systems are categorized based on their technical design into direct and indirect collection systems. Direct systems integrate all components into a single unit, whereas indirect systems are made up of separate sub-systems. Some solar desalination units are combined with conventional purification techniques and have been applied in different regions, especially in the Middle East, often as experimental or demonstration projects. However, these systems tend to have high initial and maintenance costs. In some Arab countries that facing potable water shortages, where nearly 95% of their water needs are met through seawater desalination and they possess abundant oil resources, there is potential to shift towards using renewable energy like solar power, especially given the high levels of solar radiation throughout the year [6]. Therefore, the objective of this study was to design a solar water desalination system based on humidification-dehumidification process and to investigate the effect of air mass flow rate on freshwater productivity.

2. Experimental Procedure

2.1 Apparatus

A pilot evaporation and condensation system was developed and constructed to collect research data. As illustrated in the schematic diagram in Fig. 1, the system comprises a solar air/water collector, an evaporator, a condenser, a pump, a fan, piping, and instruments designed to measure temperature, humidity, and solar radiation. The components of the system will be briefly described in the subsequent subsections.

The experiments spanned a seven-day period from October 4, 2024, to October 10, 2024, and were conducted under Tobruk city's prevailing climatic conditions (latitude 32.05 N, longitude 23.57 E). Data collection was carried out daily between 12:00 PM and 4:00 PM to coincide with peak solar radiation hours. The study focused on two primary parameters: the temperature difference between the air exiting the collector and water/air at the humidifier outlet, and the air mass flow rate.

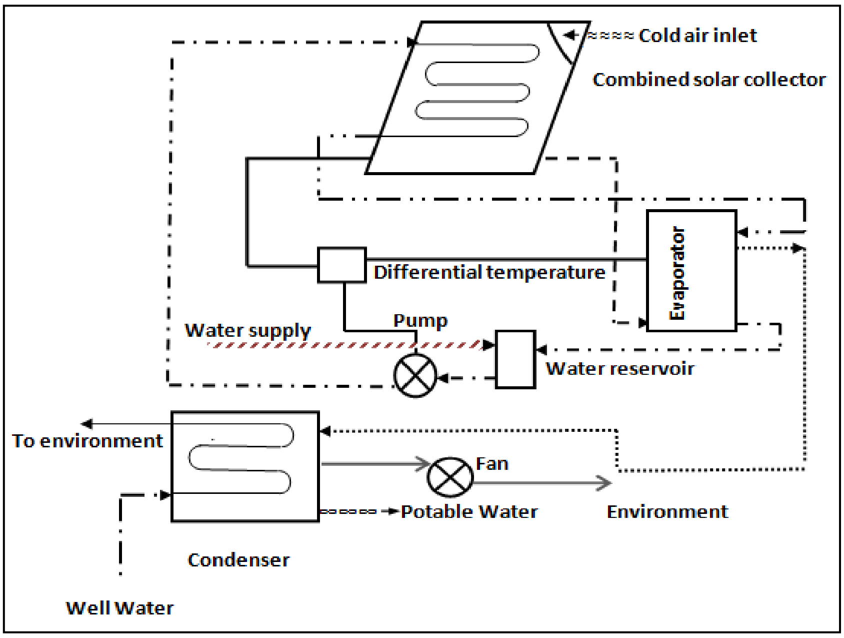

Figure 1. Schematic diagram of solar desalination unit used in this study.

2.1.1 Double Pass Solar Air and Water Heater Collector

The dual-pass solar air and water heater collector is constructed with a 0.4 cm thick galvanized iron box, measuring 150 cm in length, 100 cm in width, and 10 cm in height. Its interior is painted black to enhance heat absorption, while the bottom is externally insulated with 2 cm thick polystyrene. The collector uses two 0.4 cm thick ordinary window panes as glazing, forming a secondary air channel with a 3 cm gap between them. A quarter-circle opening with a 15 cm radius is made in the lower pane to allow airflow between the first pane and the collector's bottom. Inside, a 30-meter-long copper pipe with a 10 mm diameter is installed for water heating, bent into a U-shape and positioned 2.5 cm below the first pane. Air enters the collector through an opening between the cone and the lower pane, then flows into the second passage via the quarter-circle opening, where it interacts with the copper pipes carrying water.

2.1.2 Evaporator

The evaporation section of the experiment is designed with a metal box constructed from 4 mm galvanized steel sheets, measuring 45 cm in length, 45 cm in width, and 60 cm in height. Inside, sixteen glass trays are positioned parallel to each other, each fitted with at least sixteen small cloth chips on the back to promote evaporation. Thermocouples are installed at the center of the trays to monitor temperature. A liquid distributor at the top supplies hot water from a combined solar air/water heater collector to the trays, and the drained water is recirculated back to the collector. Air enters the humidifier and interacts with the water in the trays, which are enhanced with cloth chips to improve heat and mass transfer. As water flows downward, air moves across the trays in a cross-flow pattern, evaporating upon contact with the wetted surfaces. This process aims to increase the water vapor content in the air. The higher air and water temperatures provide better results [7].

2.1.3 Condenser

Two air conditioning condensers were utilized as stills within the isolated dehumidifier section. Each condenser includes tubes with an inlet and outlet for water circulation. The dehumidifier's metal box measures 150 cm in length, 50 cm in width, and 50 cm in height, and is constructed from 4 mm thick galvanized steel. As cooling water flows through the tubes of the dehumidifier, the condensed water collects in a pipe connected to the condensate collector. The water temperature varied during operation. The system's performance is primarily influenced by the condenser's efficiency and the cooling water's temperature. Figure 2 provides a depiction of the evaporative and condensate purification system.

Figure 2. Photo of evaporative and condensate purification system.

3. Results and Discussion

This study conducted a comprehensive investigation into the interaction between solar radiation, ambient temperature, ambient relative humidity, and the temperatures of air and water at both the inlet and outlet of a humidifier, alongside the relative humidity at these points, in relation to the production of potable water. The research utilized the MacSolar device, an advanced solar-powered instrument designed for precise measurement of solar radiation intensity while simultaneously monitoring temperature and humidity levels. The use of this solar-powered device ensured both accuracy in data collection and sustainability in its operation.

The research highlighted the predictable daily pattern of solar radiation, which increased during the morning, peaked around noon, and gradually declined toward sunset. The intensity of solar radiation was found to have a direct impact on freshwater production, with additional factors such as ambient air temperature and the temperature of cooling water also playing significant roles in influencing productivity. The study primarily focused on the evaporation process, paying particular attention to how variations in air mass flow rate affected the efficiency of water production.

Experimental results revealed a clear and positive correlation between airflow rate and freshwater output as indicated in Fig. 3. For instance, an initial airflow rate of 0.00276 kg/s resulted in the production of 430 ml of freshwater. When the airflow rate was increased to 0.02022 kg/s, freshwater output rose to 510 ml, even under less favorable weather conditions characterized by cloud cover and reduced humidity. Further increasing the airflow rate to 0.02682 kg/s yielded 570 ml of freshwater. These findings underscored the significant role airflow rate plays in enhancing water production efficiency. Moreover, the consistency of results across varying weather conditions validated the reliability of this relationship, suggesting that optimizing airflow rates could be a key factor in improving system performance.

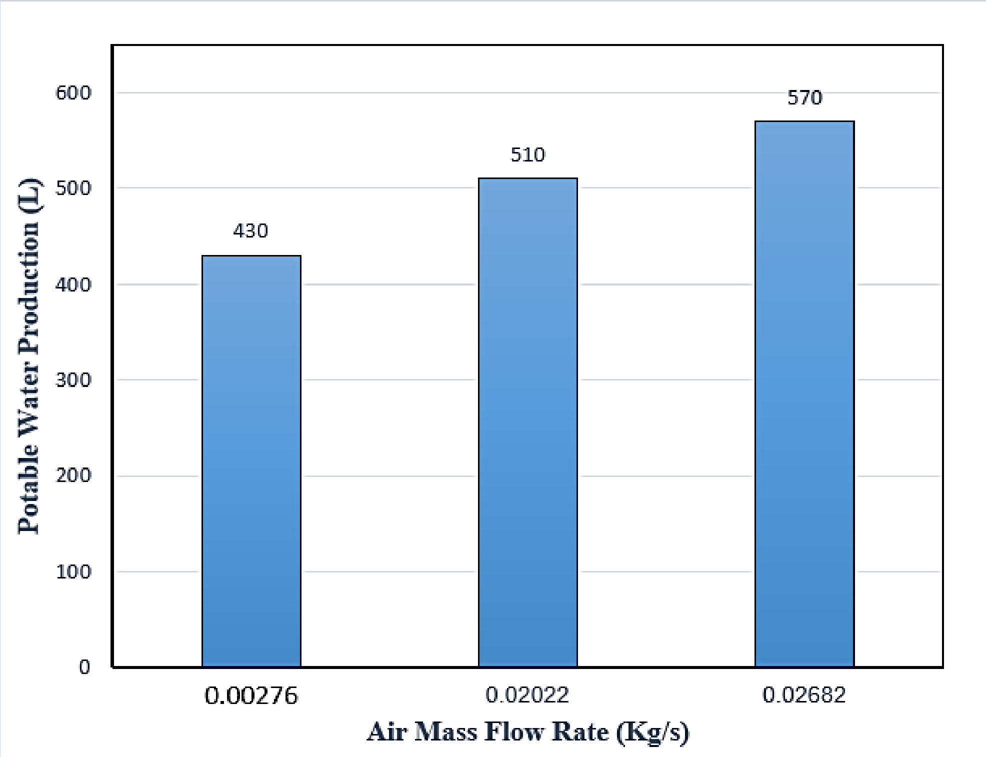

Figure 3. Fresh water production versus air mass flow rate.

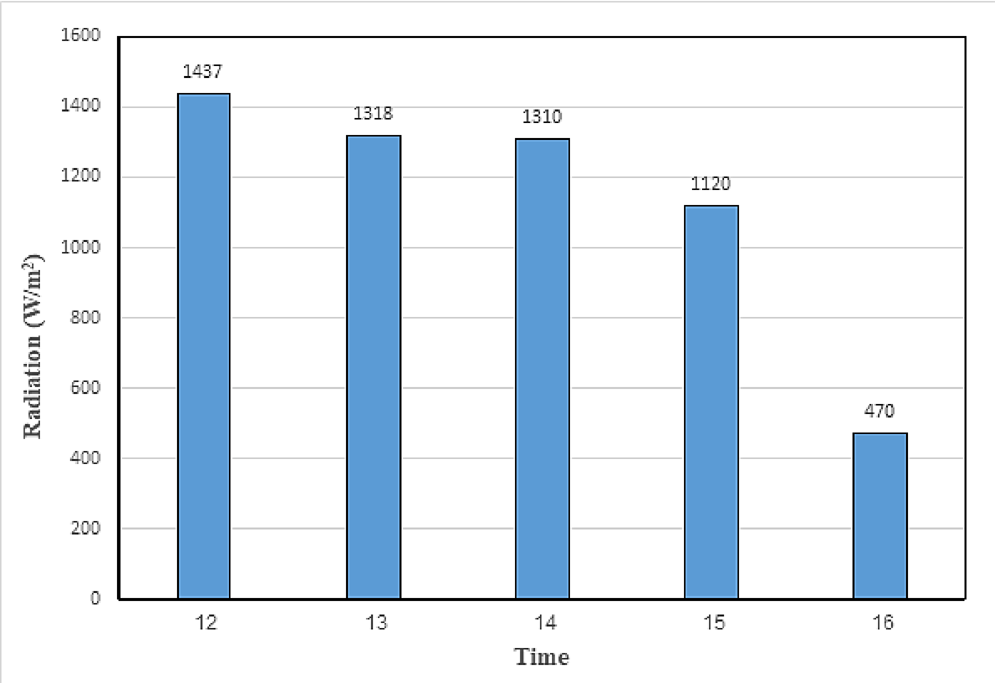

Figure 4. The total solar irradiance at air mass flow rate of 0.00276 kg/s.

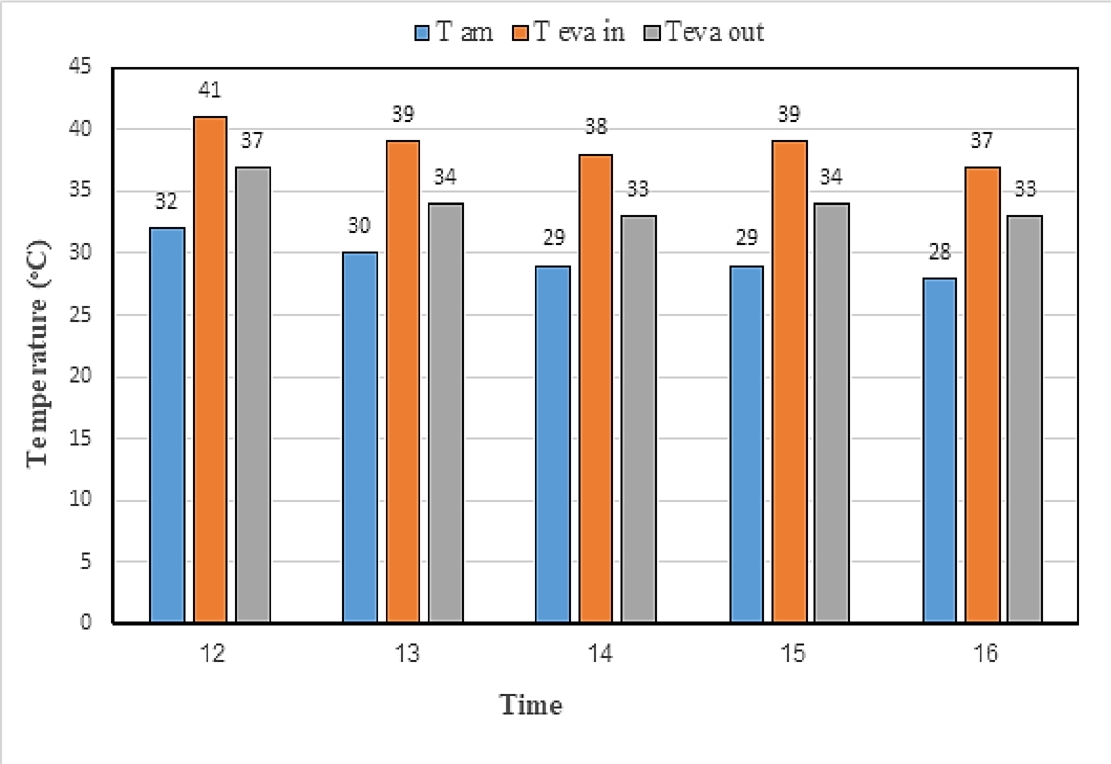

Figure 5. The temperature variation at air mass flow rate of 0.00276 kg/s, T_{am} is ambient temperature, $T_{eva\ in}$ and $T_{eva\ out}$ are temperatures at both the inlet and outlet of a humidifier.

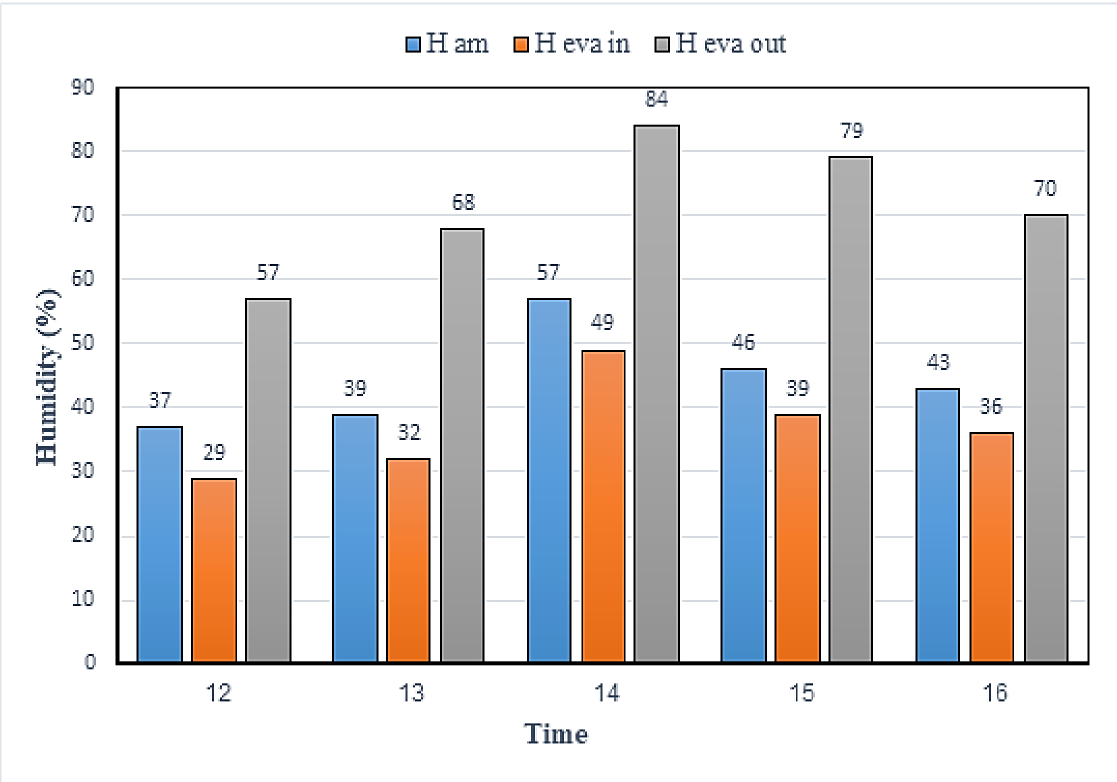

Figure 6. The humidity variation at air mass flow rate of 0.00276 kg/s, H_{am} is relative humidity, $H_{eva\ in}$ and $H_{eva\ out}$ are relative humidity at both the inlet and outlet of a humidifier.

For mass air flow equal to 0.00276 kg/s, the solar radiation rate, the atmospheric air temperatures alongside the temperature variations observed at the evaporator's inlet and outlet, and the relative humidity of atmospheric air are presented in Fig. 4, Fig. 5, and Fig. 6 respectively. These data were recorded utilizing a MacSolar system. It is observed that the solar radiation rate reaches its peak at midday and gradually decreases during the evening hours. All of these results have direct effect on the potable water production.

The mass airflow rate was adjusted to 0.02022 kg/s, and the experiment was repeated, resulting in a notable increase in system productivity from 430 mL/day to 510 mL/day. Interestingly, this improvement occurred despite the higher average solar radiation observed during the previous day's experiment, underscoring the significant impact of the mass airflow rate on system performance.

Fig.7, Fig. 8, and Fig. 9 provide a detailed representation of the variations in solar irradiance, ambient temperature, relative humidity, as well as the humidifier inlet and outlet temperatures and humidity at the adjusted air mass flow rate. The results clearly indicated that air mass flow rate plays a critical role in enhancing system productivity, surpassing the influence of solar irradiance in this case.

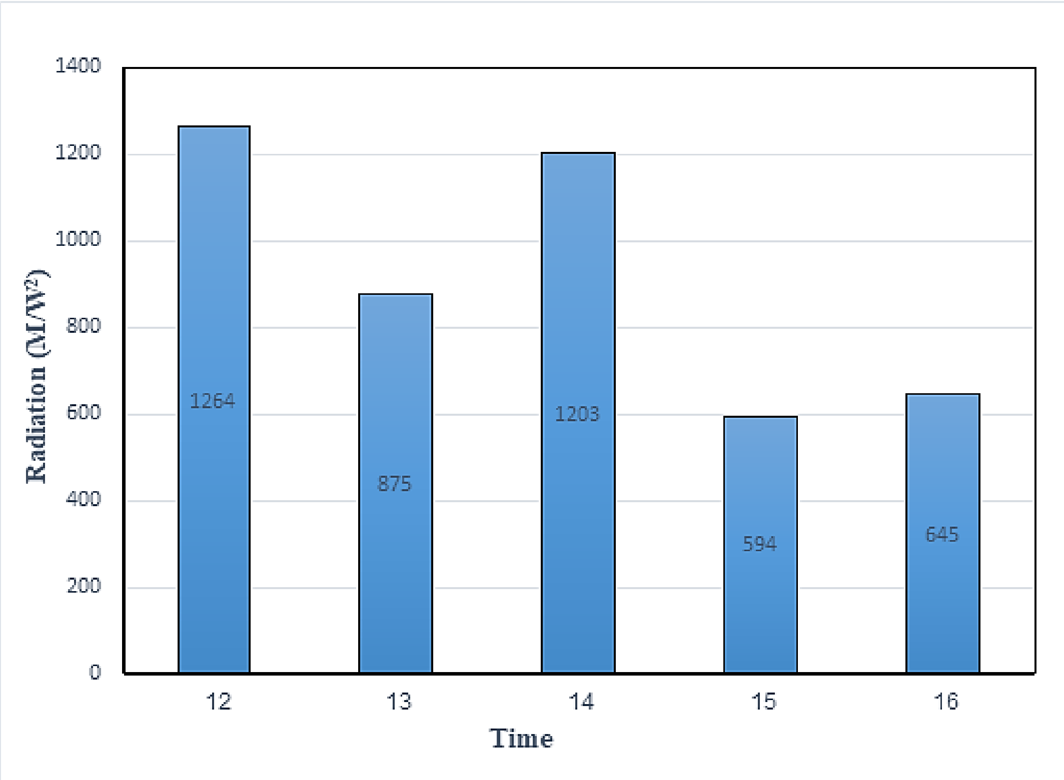

Figure 7. The total solar irradiance at air mass flow rate of 0.02022 kg/s.

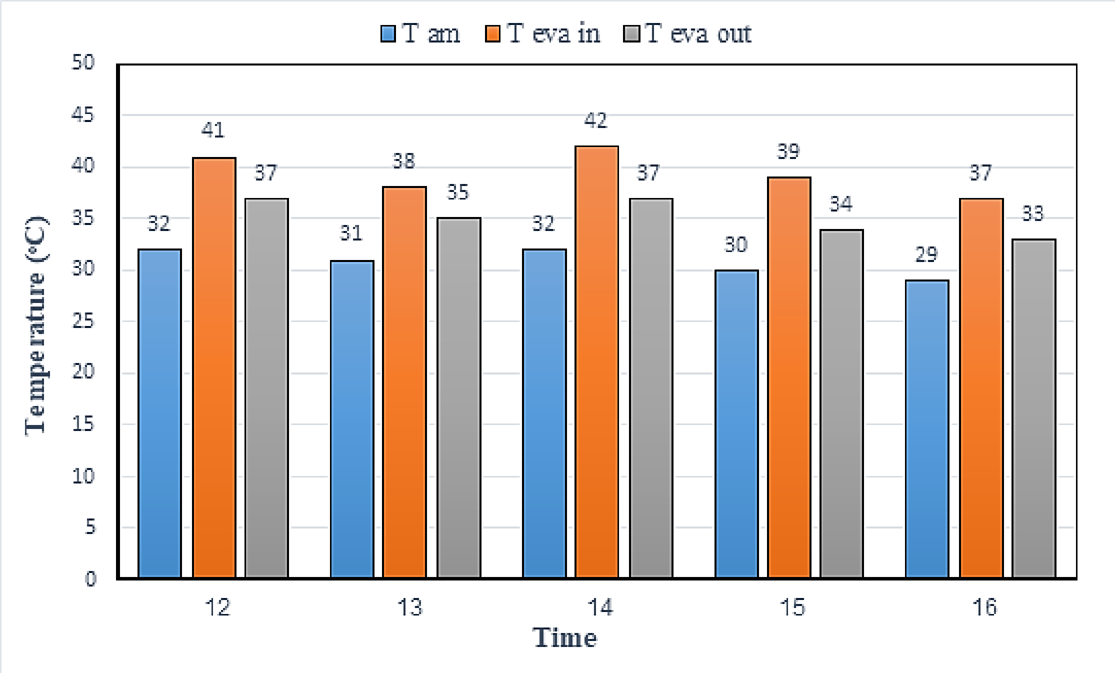

Figure 8. The temperature variation at air mass flow rate of 0.02022 kg/s, T_{am} is ambient temperature, $T_{eva\ in}$ and $T_{eva\ out}$ are temperatures at both the inlet and outlet of a humidifier.

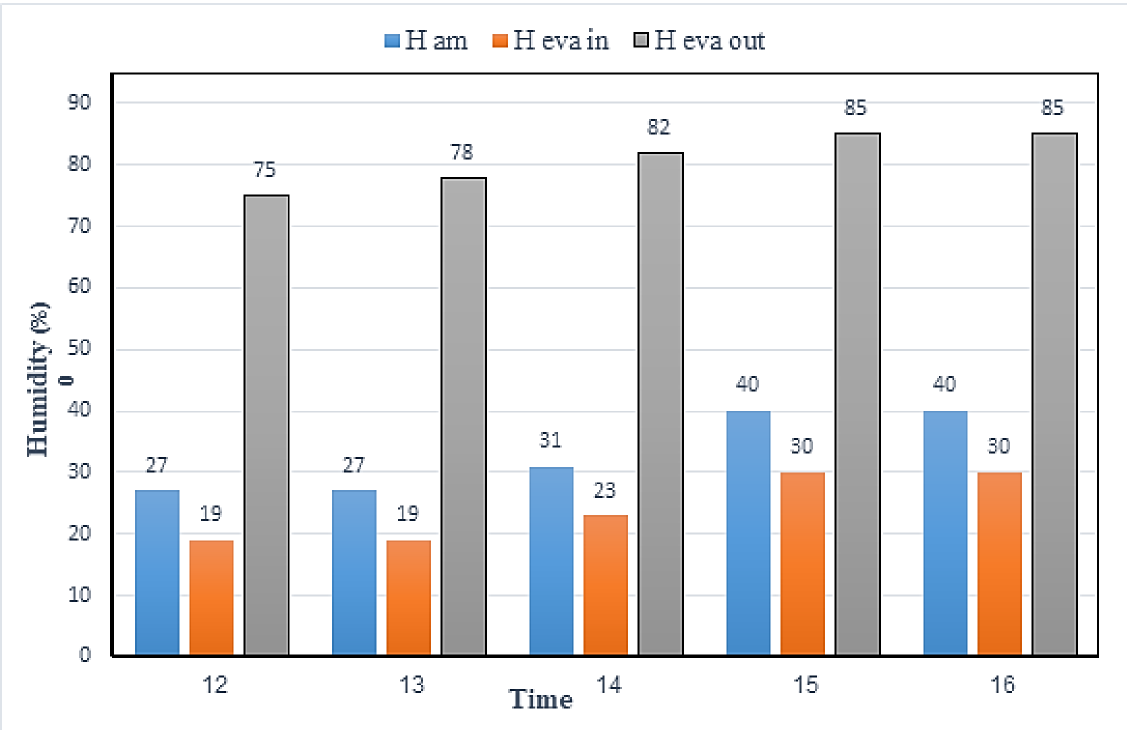

Figure 9. The relative humidity variation at air mass flow rate of 0.02022 kg/s, H_{am} is relative humidity, $H_{eva\ in}$ and $H_{eva\ out}$ are relative humidity at both the inlet and outlet of a humidifier.

As previously stated, increasing the mass airflow rate to a certain level enhances the water production. For instance, raising the mass airflow rate from 0.02022 kg/s to 0.02682 kg/s resulted in an increase in the drinking water production rate, which rose from 510 milliliters per day to 570 milliliters per day. The various variables that measured at mass flow rate of 0.02682 kg/s are presented in Fig. 10, Fig. 11, and Fig. 12. This indicates that temperature differences did not significantly affect production, whereas the mass airflow rate is a key factor in improving system efficiency. Fig. 9 illustrates solar radiation throughout the day, Fig. 10 shows the temperature differences, and Fig. 11 highlights the variations in relative humidity.

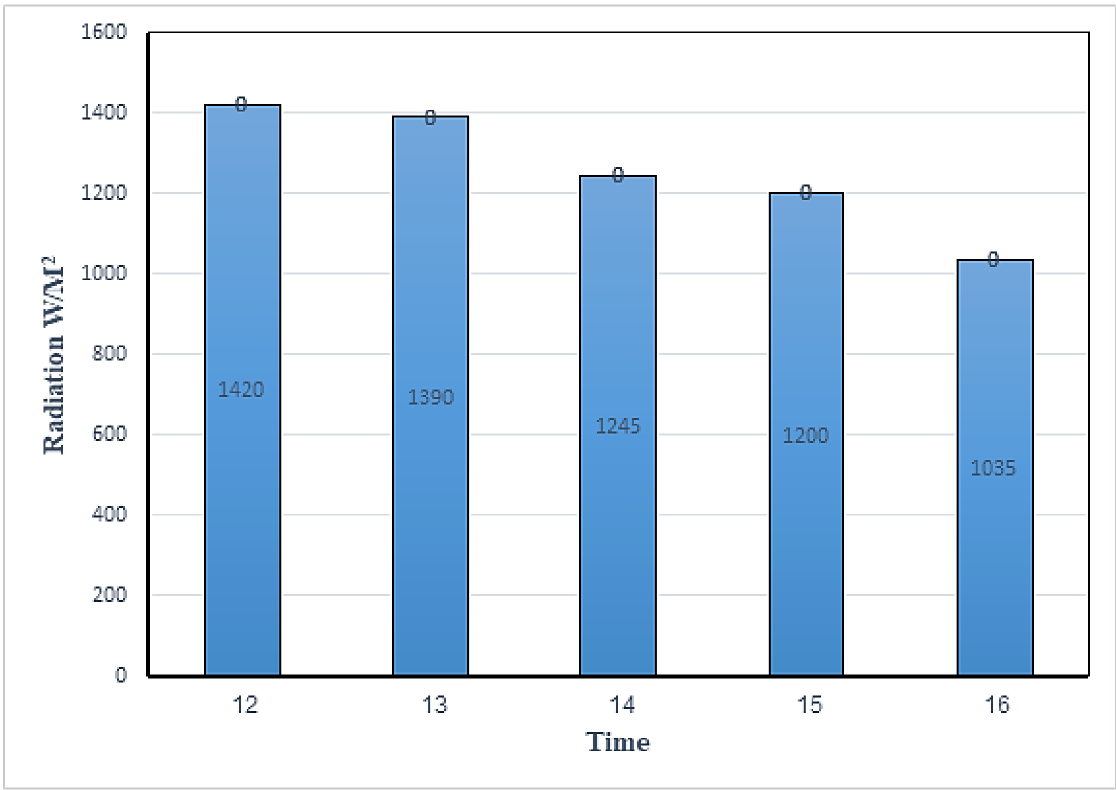

Figure 10. The total solar irradiance at air mass flow rate of 0.02682 kg/s.

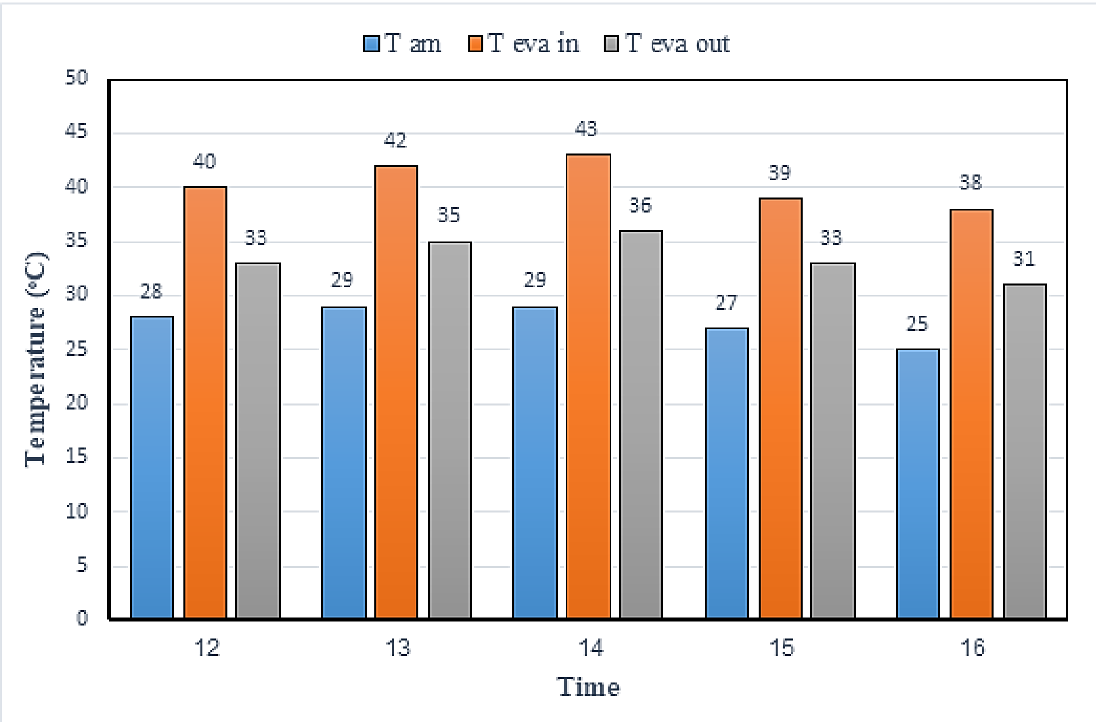

Figure 11. The temperature variation at air mass flow rate of 0.02682 kg/s, T_{am} is ambient temperature, $T_{eva\ in}$ and $T_{eva\ out}$ are temperatures at both the inlet and outlet of a humidifier.

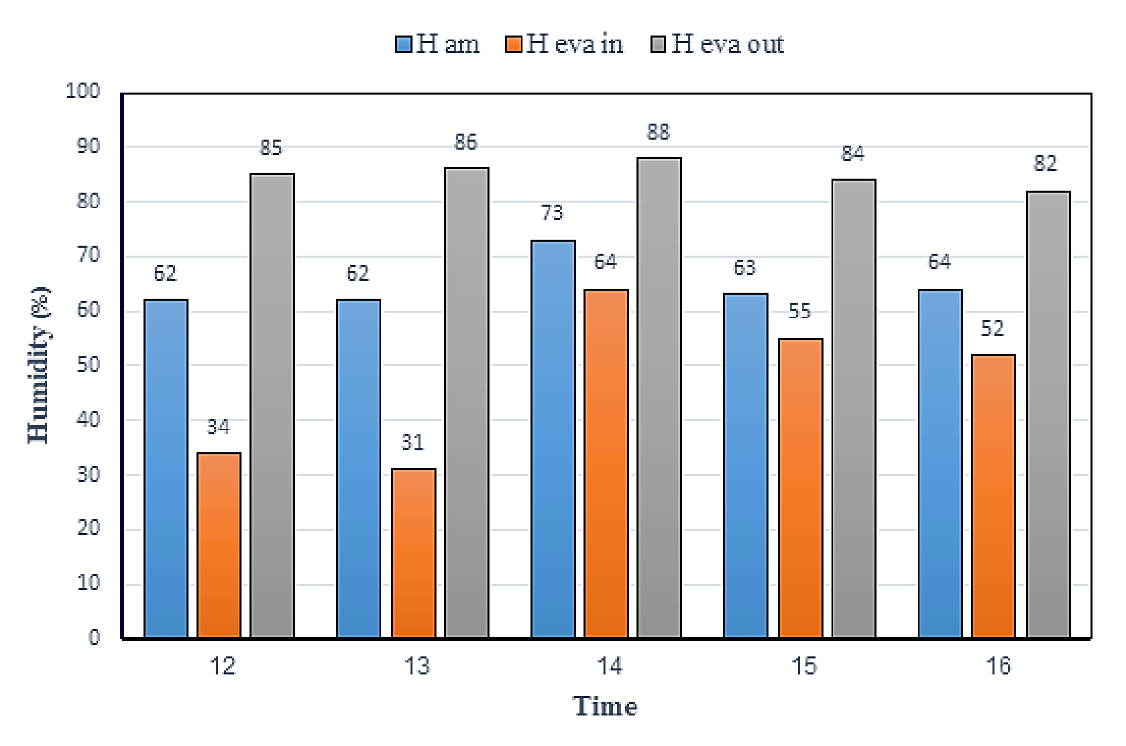

Figure 12. The relative humidity variation at air mass flow rate of 0.02682 kg/s, H_{am} is relative humidity, $H_{eva\ in}$ and $H_{eva\ out}$ are relative humidity at both the inlet and outlet of a humidifier

The experimental results reveal a notable positive relationship between the increase in airflow mass flow rate and the improvement in freshwater production within the system. As illustrated in Fig. 3, the data clearly indicate the significant influence of varying airflow mass flow rates on water production during the experiment. This finding suggests that optimizing airflow is a critical factor in enhancing the system's freshwater output. By carefully adjusting and controlling airflow, the efficiency and performance of the system can be improved, leading to a higher yield of freshwater. This emphasizes the role of effective airflow management as an essential aspect in the design and operation of freshwater generation systems, contributing to more sustainable and efficient water production technologies.

Furthermore, the findings were compared with existing studies in the scientific literature. It was noted that increasing the size of the humidification (evaporation) chamber, improving the insulation of system components, and extending the length of the pipes within the solar collector can enhance the system's ability to produce fresh water. Additionally, the mass flow rate emerges as a critical factor, while the size and insulation of system components play a significant role in influencing overall performance.

4. Conclusions

The research highlights an innovative approach to desalination, utilizing the humidification-dehumidification method under the climatic conditions of Tobruk, East Libya. The study identifies the air mass flow rate as a critical factor influencing the efficiency of the desalination process. By optimizing this parameter, the system demonstrated peak productivity on October 6th, achieving an output of 570ml/day with an air mass flow rate of 0.02682 kg/s. These findings underscore the potential for developing sustainable desalination technologies tailored to arid and coastal regions, addressing water scarcity challenges and enhancing water security in such areas. By establishing a clear relationship between airflow rate and freshwater output, this study lays a foundation for future investigations aimed at further improving the efficiency and scalability of such systems. Additionally, it highlights the importance of continued exploration into optimizing system parameters to maximize their potential for addressing global water scarcity challenges sustainably.

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