

Experimental Investigation of Humidification-Dehumidification Desalination System

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Abstract

The aim of present study is to investigate an H-DH desalination system experimentally. The system consists of a solar air heater, a humidifier, and a dehumidifier connected with an evaporative cooler. The proposed system is operated in a closed loop configuration, at two airflow rates. The performance metrics are assessed via the examination of energy and economic factors. The solar air heater has the ability to produce hot air with a mean temperature of 100°C, at 150 kg/h of airflow rate. This improved the humidification efficiency, leading to a freshwater production rate of around 22.8 kg/day at a cost of 0.027 \$/kg. It is noticed that the system's performance directly depends upon air flow rate. Furthermore, dehumidifier connected with an evaporative cooler efficiently resolves the problem of fouling that occurs during the condensation of humidified air. The system had an average energy efficacy of 25.39% when the air flow rate was set at 150 kg/h.

Keywords: Dehumidifier, energy, economic, humidifier, renewable energy.

INTRODUCTION

As to a study released by the UN Educational, Scientific, and Cultural Organization, the scarcity of water has caused more fatalities than floods in the last decade (1)-(2). This emphasizes the pressing need to explore sustainable and alternative approaches to provide freshwater on a global scale (3)-(4). The most optimal method for generating water with solar energy in low-to-medium size application seems to be the humidification-dehumidification (H-DH) technique (5)-(6). This approach is reliable due to its flexible and user-friendly operation, straightforward design, and affordable maintenance cost (7)-(8). Various theoretical and experimental analyses have been conducted on different H-DH desalination systems, revealing diverse insights on the system's performance.

The H-DH system obtained 11.14 L/day of productivity by using flat plate solar air heater (SAH) & solar water heater (SWH) as heat source, and salty water for condensing the humidified air (9). The electric heat and reflector (external) helps H-DH setup to achieved 30.3 L/day of productivity at cost of

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0.035 \$/kg (10). The productivity & efficacy of H-DH system were improved by 141% and 20%, respectively by integrating cascade solar still (11). The H-DH system consist of FP-SAH and SWH was tested by (12). The yield, efficacy, and cost were 5.6 kg/m²/day, 32.8%, and 0.03 \$/kg, respectively. The H-DH setup having an electric heater as heat source was able to provide 2.45 L/h of yield at a cost of 0.047 \$/kg (13). The productivity & efficacy of H-DH setup was improved by using an atomizer along with heat pump as condenser (14). The yield, efficacy, and CPL were 7.72 kg/day, 33.84%, and 0.0112 kg/day, respectively. Further, the productivity was increased by minimizing the droplets size inside

the humidifier (15). The system was able to provide 0.85 kg/h of yield. Further, the used low-grade heat in H-DH system achieved 2.1 kg/h of yield (16), whereas recirculate the rejected water in H-DH system achieved 2.73 kg/h of yield (17). Further, a new condenser was utilized to increase the productivity & efficacy of H-DH setup (18), whereas numerical model was developed for hybrid H-DH system to test the performance (19).

It is noticed from the literature that for heating air, FPC and ETC-based SAH are preferred, whereas for heating water, electric heater and ETC-based SWH are preferred. The temperature limit and efficacy of FPC is low, whereas the fabrication of ETC-based SAH is difficult because of addition arrangement for guiding air into solar collector. Also, the accumulation of salts inside ETC, increase the maintenance of SWH (20). Further in literature, salty water is preferred for condensing the humidified air. The use of salty water leads to fouling inside dehumidifier.

The basic goal of desalination unit is to fulfill the freshwater need while reducing the original investment and continuing maintenance costs along with reaching minimum CPL. The current investigation employs an innovative SAH that integrates a double-ends open evacuated tube collector (DEO-ETC). Furthermore, to tackle the problem of fouling in dehumidifiers, ambient air along with evaporative cooler is used. The system's performance is assessed by a its energy efficacy and economic factor.

Materials and methods

Test-ring

The proposed test-ring is installed at NIT Surat, India. The figure 1 present the schematic and pictorial view of the test-ring. The primary assets of proposed test-ring are SAH, humidifier, and dehumidifier. The detailed descriptions of each components are illustrated in table 1. The Figure 2 illustrate the schematic and pictorial view of humidifier and dehumidifier.

Table 1. Detailed specification of components used in setup.

| Descriptions | Value |
|---------------------------|----------------------|
| Collector | Double-ends open ETC |
| Quantity | 60 |
| L | 180 cm |
| DGlass | 5.7 cm |
| DAbsorber | 4.54 cm |
| Area | 9.374 m ² |
| Angle | 21° |
| Blower rating | 93 W |
| Humidifier | |
| L×W×H | 0.4×0.4×2 (m) |
| Packing material | Honeycomb pads |
| Initial quantity of water | 50 liters |
| Pump | 0.018 kW |
| Dehumidifier with DEC | |
| L×W×H (heat exchanger) | 0.4×0.4×0.4 (m) |
| Working fluid | Ambient air |
| L×W×H (DEC) | 0.4×0.4×1 (m) |
| Packing material | Cellulose |
| Pump | 18 W |

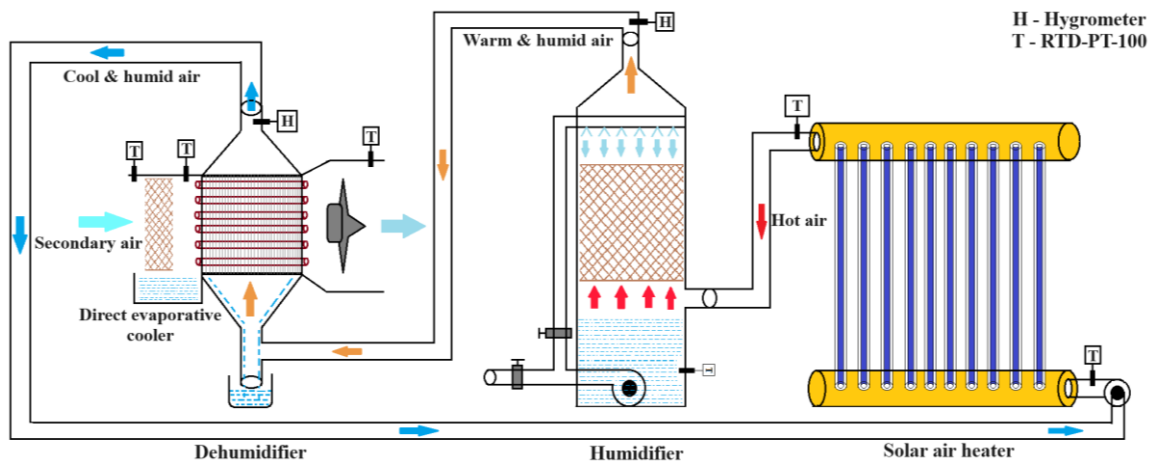


Figure 1. (a) Schematic



(b)
 Figure 1. (b) image of setup.

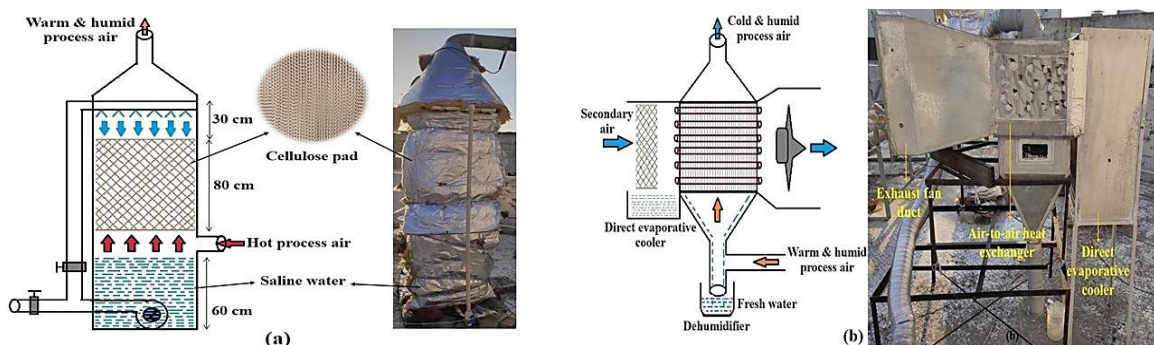


Figure 2. Schematic and pictorial view of (a) humidifier and (b) dehumidifier.

Working Principle

The working principle of H-DH desalination system is as follows:

1. The very first process is the heating of air with the help of solar air heater, which increase the moisture carrying capacity of the air.

2. Then, this heated air is passed over the seawater or sprayed into it to increase its humidity. As the heated air absorbs moisture from the seawater, it becomes saturated with water vapor, effectively humidifying the air.
3. Then, the humid air is cooled down. Cooling can be achieved through various methods such as passing it through a condenser or contacting it with a cold surface.
4. As the air cools, its ability to hold moisture decreases, causing the excess water vapor to condense back into liquid form.
5. The condensed water is collected as fresh water. Meanwhile, the cooled and dehumidified air is reheated and recirculated back into the humidification stage to repeat the process.

Performance metrics

The performance metrics of proposed test-ring are assessed by energy and economic analysis.

Energy Analysis

The test-ring energy efficacy is given as (21):

$$\eta_e = \frac{\dot{M}_{fw}L}{(S_{I}A_{ETC}+W_E)\times 3600} \quad (1)$$

Economic analysis

Economic analysis is carried to check whether the proposed test-ring can be implemented practically. The price of each component and cost per liter (CPL) are presented in table 2 (22):

Table 2. Equipment's price and CPL of test-ring.

| Assets | Total cost (\$) | Factors | Value |
|---------------------------|-----------------|---------|--|
| SAH | 492.26 | CRF | 0.1331 |
| Humidifier | 60.5 | FYP | 109.44 \$ |
| Heat exchanger | 215.50 | SFF | 0.0138 |
| Direct evaporative cooler | 15 | SP | 2.27 \$ |
| Miscellaneous | 10 | RP | 52.64 \$ |
| Total | 822.26 | MP | 10.944 \$ |
| | | OAC | 170.754 \$ |
| | | TP | 4644 L/year (case 1)6156 L/year (case 2) |
| | | CPL | 0.036 \$/L (case 1)0.027 \$/L (case 2) |

RESULTS AND DISCUSSION

This portion provides the discussion about the achieved results from the test-ring. The test-ring is run at two airflow rates namely, case 1: 75 kg/h and case 2: 150 kg/h. The flow rate of salty water is 300 kg/h. The data observed were DBT and specific humidity of process air and ambient air at different locations.

Variation in DBT And Specific Humidity

The figure 3 (a,b) displays the discrepancy in DBT and solar irradiance. The average solar irradiance is case 1: 724.75 and case 2: 742.18 W/m². The average DBT at the departure of SAH is case 1: 126.3 °C and case 2: 98.5 °C. The duration of heat transfer from the surface of the absorber glass to the air in case 1 is longer, leading to a greater DBT at the exit of SAH. Moreover, raising the airflow rate leads to a reduction in the disparity between the DBT at the intake and exit of both the humidifier and dehumidifier. This is caused by a decrease in the time interval during which heat is transferred at the cellulose pad interface within the humidifier, as well as at the tube surface inside the dehumidifier. The average disparity in DBT of the air in the humidifier is 81.2 °C and 54.4 °C, while in the dehumidifier, the values are 7 °C and 5.6 °C for case 1 and 2, respectively.

Additionally, Figure 4 (a,b) illustrates the changes in specific humidity (S.H.). The average ambient air S.H. for case 1 and 2 is 14.5 and 14.9 g/kg_{dry air}, respectively. The average disparity in S.H. between the intake and outflow of the humidifier is 28.2 g/kg_{dry air} for case 1 and 19.4 g/kg_{dry air} for case 2. The disparity diminishes as the airflow velocity escalates, due to the shortened duration of mass and heat exchange in the humidifier. Therefore, the process air is unable to hold a greater quantity of moisture, resulting in a fall in the S.H. of air. However, augmenting the airflow rate directly enhances the rate at which salty water evaporates. Therefore, a greater quantity of water vapors is present at the entrance of the dehumidifier when the airflow rate is increased.

Additionally, Figure 5 (a,b) illustrates the variations in ambient air's DBT. The difference between the DBT and WBT of the ambient air at the DEC outflow is observed to be between 1% and 2.5%. This suggests that the DEC exhibits strong performance in both scenarios. The average DBT of the ambient air at the DEC outflow is 23.9 °C for case 1 and 23.8 °C for case 2. In addition, the average DBT at the DEC intake is 34.5 °C for case 1 and 32.5 °C for case 2. In scenario 2, the DBT of the ambient air at the DEC intake is lower compared to scenario 1. This leads to more effective condensation of the humidified air.

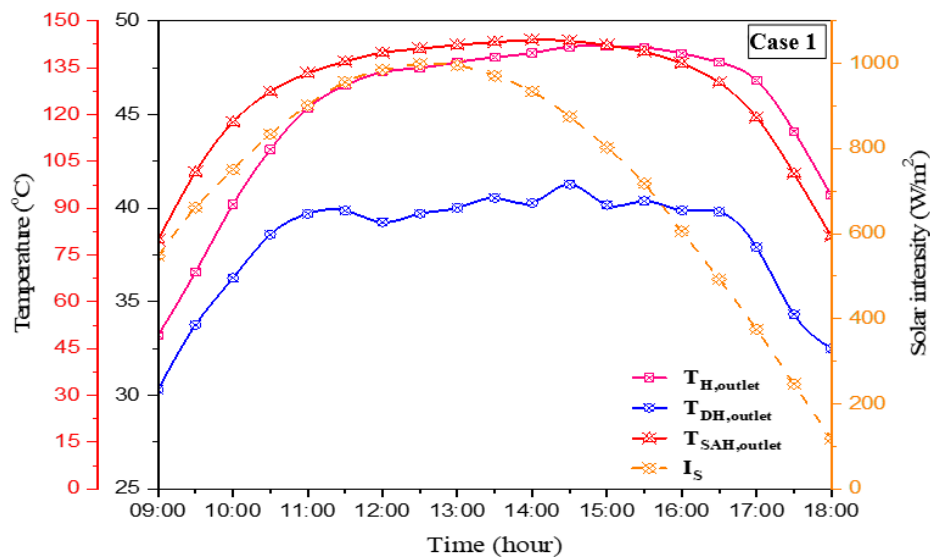


Figure 3. (a, b) Disparity in solar flux and temperature for case 1 and 2.

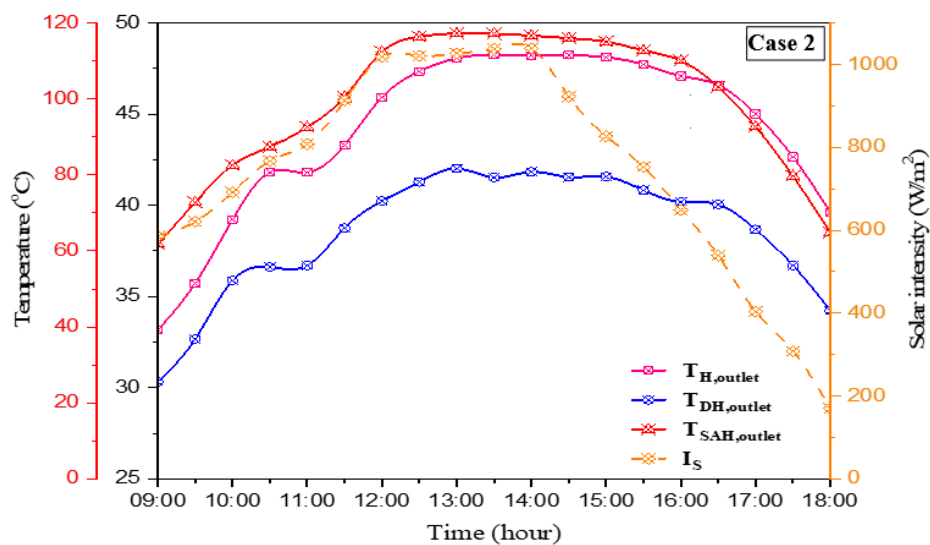


Figure 3. (a, b) Disparity in solar flux and temperature for case 1 and 2.

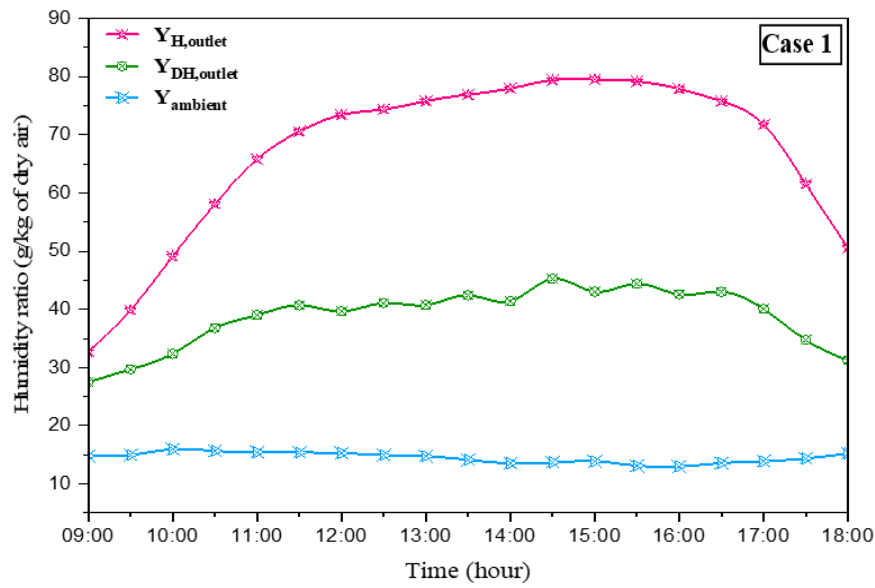


Figure 4. (a, b) Disparity in specific humidity for case 1 and 2.

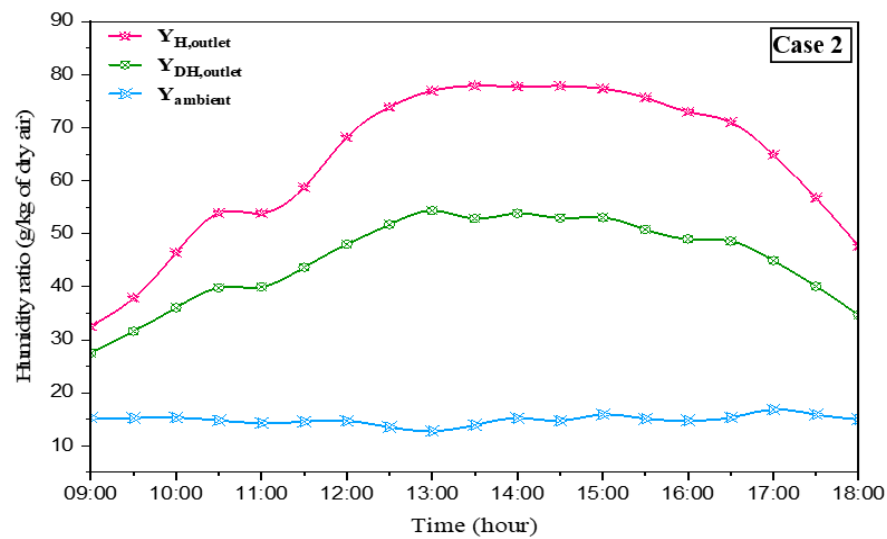


Figure 4. (a, b) Disparity in specific humidity for case 1 and 2.

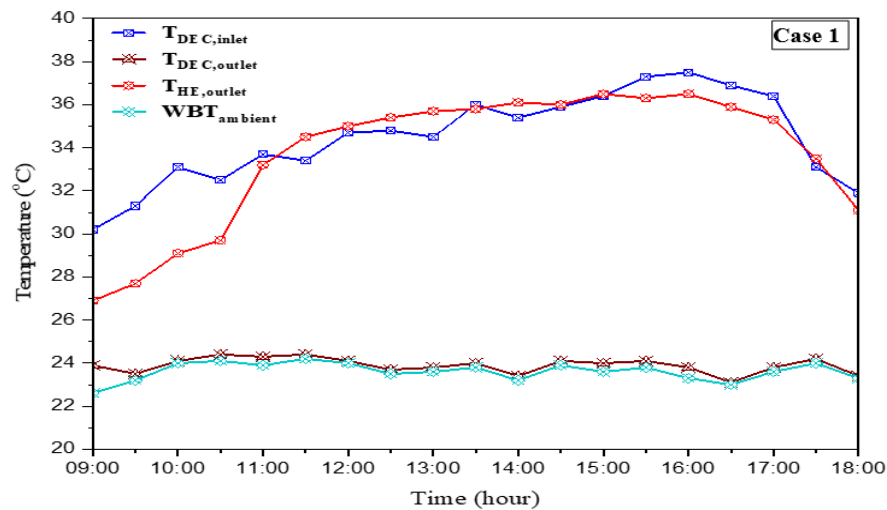


Figure 5. (a, b) Disparity in ambient air temperature for case 1 and 2.

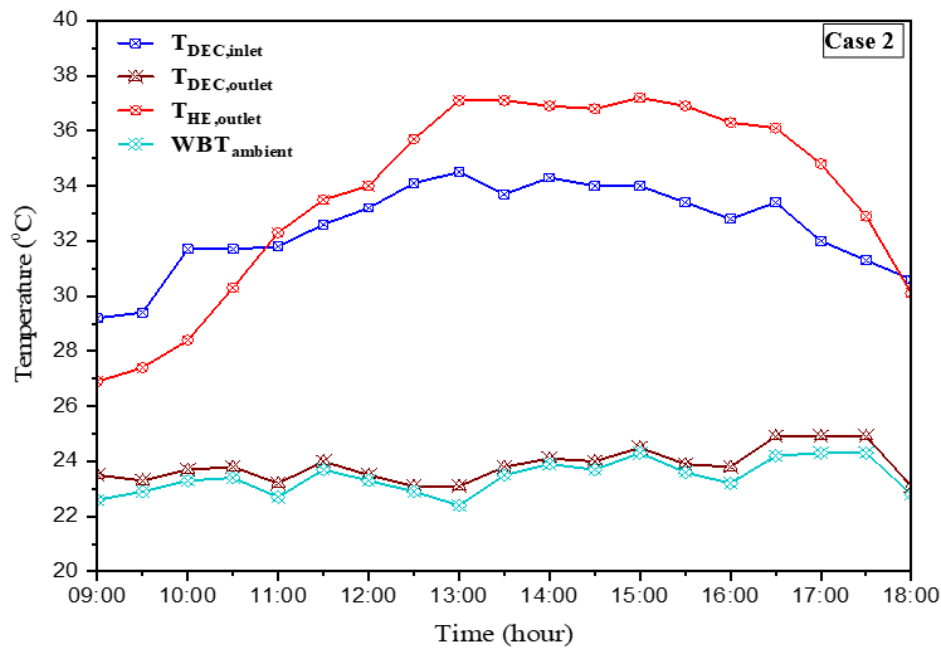


Figure 5. (a,b) Disparity in ambient air temperature for case 1 and 2.

Effect on yield, efficiency, and CPL.

The figure 6 illustrate the yield and energy efficacy. The overall achieved yield in case 1 and 2 are 17.2 and 22.8 kg/day, respectively. The highest yield is achieved when the proposed test-ring is run at 150 kg/h. The yield is 32.5% higher in case 2 when comparing with case 1. This is due to the fact that when the airflow rate is increased, the process air carries a greater quantity of moisture. As a consequence, at the entrance of the dehumidifier, the process air has a greater quantity of moisture content, leading to a greater yield from the system. Further, the factors on which energy efficiency depends are yield and available solar intensity. The average energy efficacy is case 1: 22.18% and case 2: 25.39%. It has been noticed that with a greater flow rate, the average energy efficacy is the greatest compared to case 1. This is due to the increased evaporation rate of salty water, which therefore leads to a greater yield from the proposed test-ring. This also contributes to cost reduction in achieved yield. The CPL for case 1 and 2 are 0.036 and 0.027 \$/kg, respectively.

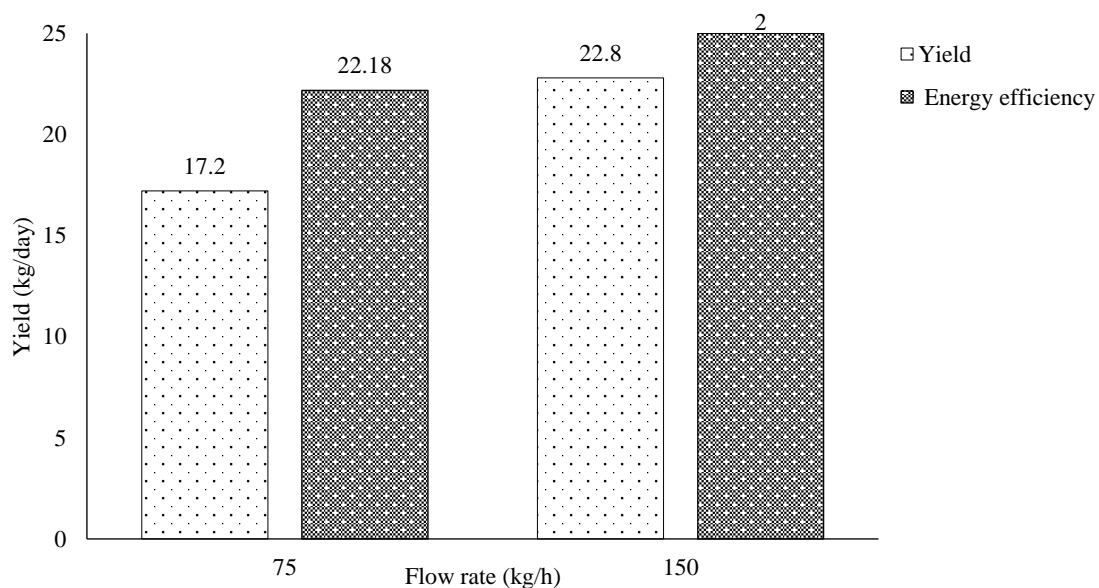


Figure 6. Variation in productivity and energy efficiency.

Conclusions and Recommendation

The present research investigates the test-ring under two airflow rates. The test-ring performance is assessed based on energy and economic analysis. The results of the ongoing effort are:

- The SAH, using DEO-ETC, can produce hot air temperatures above 100°C. This led to improved efficacy of the humidifier, leading to a higher productivity.
- The test-ring performance improved as the rate of airflow raises. Increasing the airflow rate leads to a corresponding increase in the rate of evaporation of salty water in the humidifier. The optimal production rate for achieving the highest output and energy efficacy at 150 kg/h, resulting in a daily productivity of 22.8 kg and an efficacy of 25.39%.
- The ambient air for condensation helps to extend the longevity of the dehumidifier by minimizing the fouling. In addition, the DEC increases the pace at which water vapors condense.
- The present technique yields a minimal cost of 0.027 \$/kg. This demonstrates the practical viability of the proposed desalination method.

The promising outcomes of the present H-DH setup that utilizes ambient air for condensation, using phase change material (PCM) may enhance the system's efficiency. The use of PCM enables the system to function efficiently in the absence of sunlight, resulting in a higher production of freshwater.

Nomenclature

| | |
|----------------|-------------------------------------|
| A_{ETC} | Overall area (m ²) |
| L | Water latent heat (kJ/kg) |
| \dot{M}_{fw} | Yield (kg/h) |
| S_I | Solar radiation (W/m ²) |
| W_E | Electrical power input (W) |
| η_e | Energy efficacy (%) |
| Abbreviations | |
| FYC | First year cost (\$/year) |
| OAC | Overall annual cost (\$/year) |
| MP | Maintenance amount (\$/year) |
| SP | Salvage amount (\$/year) |
| RP | Cost of running (\$/year) |
| TP | Total freshwater (L/year) |
| CPL | Cost per liter (\$/L) |

Declaration of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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