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Potential of a dual purpose solar collector on humidification dehumidification desalination system

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HIGHLIGHTS

- Packed bed HDH system is tested with a dual purpose solar collector.
- Effect of turbulators on the system performance is also analyzed.
- Turbulator augments the fresh water production rate of the system.
- Peak distillate of 15.23 kg/m^2.day is collected.

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ABSTRACT

An experimental investigation on a humidification dehumidification (HDH) desalination system integrated with a dual purpose solar collector (DPSC) is reported in this work. The DPSC is used to simultaneously heat the water and air needed for the distillation process. Air flows over the top surface of the absorber plate and the water flows through the riser tubes, attached in the bottom side of absorber plate. The heated air and water from the collector is supplied to the humidifier, where the air gets humidified and moves towards dehumidifier for condensation. The performance of the system is analyzed by providing semi circular turbulators (convex and concave) in the air flow field. The system ability is investigated by varying the flow rate of air, hot water in humidifier and cooling water in dehumidifier. The system distillation capacity enhances with the air and water temperature and flow rate of air, hot water and cold water. The highest productivity of 12.36, 14.14 and 15.23 kg/m^2.day is collected for the without turbulators, convex and concave turbulators in absorber plate respectively. The overall efficiency of the system reaches the value of 67.6% with the concave turbulators in the DPSC.

1. Introduction

Increase in water demand leads to the development different desalination technologies like solar still [1], flash evaporation desalination [2], multi effect distillation, humidification dehumidification desalination, vapour compression desalination, freeze desalination and adsorption desalination [3]. Solar still and solar based humidification dehumidification desalination technology are suitable for low capacity fresh water production. Ability of solar still has been improved by minimizing the water depth, reduction in inclination angle [4], installation of reflectors, coupled with solar collectors, increase in surface area [5] and recovering of latent heat for preheating the saline water [6].

Pin finned wicks [7] and vertical fins [8] were improved the heat transfer rate in the solar still and thereby distillate rate. Energy storing materials increase the basin heat capacity by absorbing the heat during the sunshine hours and release it in evening or cloudy hours. Solar still was augmented by adding the materials like sand, black rubber, gravels [9], phase change material [10], mild steel pieces in basin [11]. Integration of solar still with the parabolic dish concentrator [12], evacuated tube solar collector [13] and parabolic concentrator with cover cooling [14] enhanced the solar still productivity.

The latent heat of condensation was successfully utilized to heat the upper basin water and thereby augmented the solar still productivity [15]. Reduction of water mass in upper basin was increased the distillate output of double basin solar still [16]. Temperature difference between the evaporation and condensation surface is increased by using the thermoelectric module in a solar still. It leads to the higher condensation rate of the system and improved distillate output [17]. A solar still was tested with a thermoelectric module and increased the production rate by 3.2 times greater than the conventional one [18]. A solar still was tested with a separate evaporation and condensation section and a thermoelectric module for increase the condensation rate [19]. A CFD analysis was carried out in a tubular solar still and compared with

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Nomenclature

A_c	area of solar collector, m^2
C_{dw}	distilled water cost, \$/kg
h_{fg}	latent heat of evaporation, J/kg
I_s	solar radiation, $W/\cdot m^2$
M	annual yield, kg/year
m	mass of distilled water, kg
t	time, s
T	temperature, °C
u	uncertainty
$q_{electrical}$	heat flux of electrical components, W
TAC	total annualized cost, \$
η	efficiency, %

the experimental results [20]. An attempt was made to improve the performance of single basin solar still by installing partition in basin and glass cover [21]. A stepped solar still integrated to a humidification dehumidification process showed better performance with improved distillate output [22]. Performance of a humidification dehumidification desalination system was enlightened by connecting with a cascade solar still [23].

The main reason for lower distillate output in the solar still is the occurrence of evaporation and condensation in the same component. In the HDH system, the humidification and dehumidification process occurs in separate chamber, which ensures the higher distillate compared to the solar still. The inlet water temperature and humidity plays a vital role in the performance of HDH system and the distillate was enhanced with these parameters [24]. Results of the cost optimization analysis were reported that the solar humidification dehumidification desalination is a suitable choice for the small scale fresh water production in the remote arid areas [25]. A two stage humidification desalination system was experimentally analyzed and found that the two stage system reduced the required number of solar collectors and minimized the initial investment [26]. A desalination system was evaluated with the air flows over the hot saline water (heated by solar and electrical energy) and observed that the distillate yield was increased with water temperature [27]. A numerical study to investigate the performance of humidification desalination system with solar air heater was carried out and the result indicated that the presence of solar air heater significantly influenced on the system productivity [28]. A double pass solar air heater was integrated with the humidification desalination system and noticed a considerable improvement in the distillate yield [29]. Higher performance in humidification desalination system was obtained with the integration of evacuated tube solar collector [30]. Performance of a humidification dehumidification desalination system was improved by using a solar air heater [31]. Developments of low cost and high efficient solar air heaters reduce the distilled water cost of HDH desalination system [32]. Experimental study on bubble column HDH desalination was carried out by connecting with the solar air heater [33] and dual purpose solar collector [34].

The presence of rib grooves with different angles in absorber plate showed the higher performance compared to the conventional system [35]. Impinging of air into the solar collector augments the heat transfer rate between the air and absorber plate and the higher outlet air temperature was observed [36]. A solar collector was tested and augmented the outlet air temperature by providing the aluminum cans in absorber plate [37]. The presence of transverse and inclined ribs on absorber plate of solar air heater was resulted in the higher effective efficiency [38]. Presence of conical cut out turbulators in the air heater flow field enlightened the system ability [39]. A packed bed HDH desalination system was tested by using the different ratios of twisted tape inserts, conical cut out turbulators and half perforated circular turbulator in the air heater. The production rate of the modified system enhanced by 45% compared to conventional system [40]. Energy and exergy efficiency of the dual purpose solar collector was found to be higher than the single purpose solar collector, due to effective utilization of thermal energy [41]. Three different fluid flow channels have been used in a dual purpose solar collector and the higher potential is observed with the rectangular fin channel [42]. The efficiency of the single purpose collector has been noted that the 3 to 5% lower than the dual purpose collector [43].

The literature shows that the humidification dehumidification desalination system has greater opportunity for the decentralized fresh water production over solar still. It is observed that the distillation capacity of the system enhances with the humidifier inlet temperatures. Also the presence of turbulator enhances the ability of solar collectors and the dual purpose solar collector is efficient. In most of the previous works, humidification dehumidification desalination system is integrated with the different solar collectors (Flat plate solar collector, evacuated tube collector, parabolic trough collector) to heat the water and air separately.

Thus an attempt is made in this work to analyze the effect of integrating a dual purpose solar collector with a packed bed HDH desalination system. The dual purpose collector supplies the required hot water and hot air for desalination system. Also semi circular turbulators (concave and convex) are used in the air flow passage of a dual purpose solar collector. It augments the humidifier inlet air temperature by means of creating the turbulence in air flow field. The performance of the system is analyzed by varying the mass flow rate of air (0.84 to 1.08 kg/min), hot water (1 to 3 kg/min) and cooling water (1.5 to 3.5 kg/min).

2. Experimental setup

Schematic and photographic view of the solar packed bed humidification dehumidification desalination system is shown in the Figs. 1 and 2. It consists of a dual purpose solar collector humidifier and dehumidifier. The outer cover of a dual purpose solar collector is constructed as a rectangular hollow box in the size of 0.95 m × 0.75 m × 0.12 m and extended as duct on both sides. The dual purpose solar collector setup is kept in a stand with the inclination of 10° which is equal to the latitude

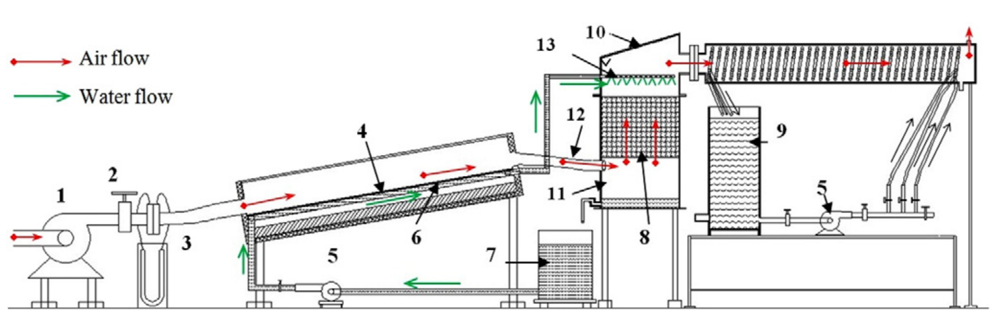

Fig. 1. Schematic diagram of HDH system with dual purpose collector. (1) Blower, (2) flow control valve, (3) orifice arrangement, (4) absorber plate, (5) pump, (6) riser tube arrangement, (7) feed water tank, (8) packed bed, (9) cooling water tank, (10) condensing cover, (11) humidification chamber, (12) hot air inlet, (13) hot water spray pipe.

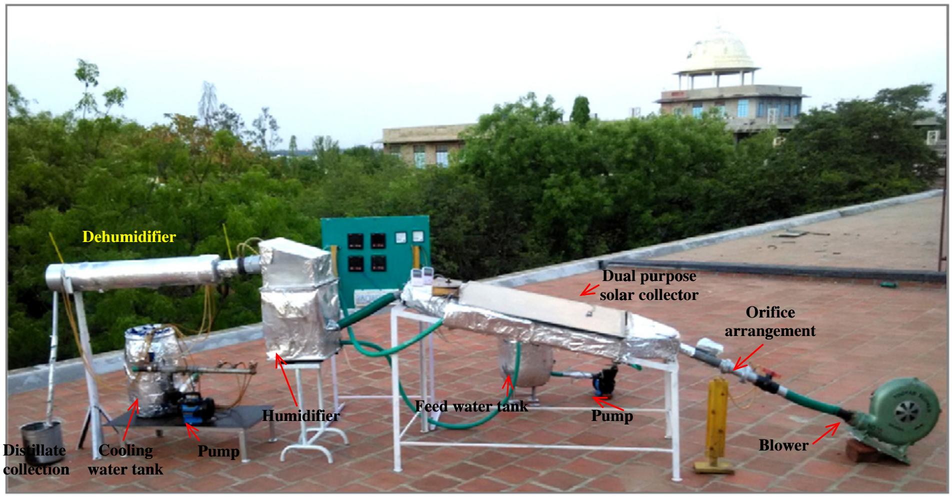

Fig. 2. Photographic view of HDH system with dual purpose collector.

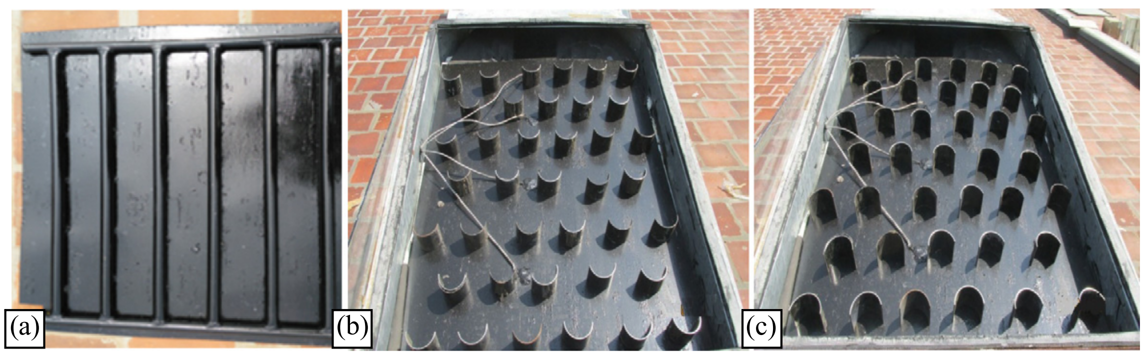

Fig. 3. Photographic view of (a) riser tube arrangement, (b) convex turbulators and (c) concave turbulators.

of test place. A 2 mm thickness mild steel plate is used as absorber plate and the air pumped (by a 1 hp blower) over this plate and gets heated. A 0.5 hp pump supplies the saline water to the dual purpose solar collector from a storage tank. There are six riser tubes with the diameter of 0.019 m is attached in the back side of the absorber plate as shown in Fig. 3a. The riser tube inlet is connected with the feed water tank and the outlet is connected with the humidifier spray pipe. The saline water flows through the riser tubes and gets heated from the absorber plate. The hot saline water sprayed from the humidifier top and the heated air enters into the bottom of humidifier. The humidification chamber is constructed using the mild steel sheet with the area of 0.09 m^2 and with height of 0.5 m in one end and 0.6 m at another end. The humidifier chamber is set with a packing material (jute cloth) as shown in the Fig. 1. Top cover has the inclination of 10° to guide the condensate and collect in the distillate collection rate. The hot saline water and the air get contact with the help of packing materials.

Some of the humid air gets condensed in the top cover and the remaining moves to the dehumidifier. The dehumidifier is a shell and coil heat exchanger where the humid air flows around the three concentric copper coils (0.05 m, 0.08 m, and 0.11 m) and the cooling water flows through the copper coil in counter direction. These coils are located in a 0.15 m diameter hollow pipe. Cooling water feed into the copper coils by using a 0.5 hp pump and three separate flow control valves are used to control the flow rate. The water in the cooling water tank is often replaced to maintain the lower cooling water inlet temperature. The experiments are extended by using the semi circular turbulators in absorber plate in the 6 × 4 zig-zag configuration [44] as shown in Fig. 3b (convex) and Fig. 3c (concave). In this work, operational range of air flow rate [44], hot water [45] and cold water [45] flow rate was selected based on the system operational capacity and to give the maximum system performance. Increasing the hot flow rate beyond this limit reduces the system capacity. The experiments are carried

Table 1
Uncertainty analysis of measuring instruments.

Sl. no	Instrument	Accuracy (a)	Range	Uncertainty
1	Thermocouple	±1 °C	−100–1300 °C	0.06 °C
2	Pyranometer	±1 W/m^2	0–2500 W/m^2	0.58 W/m^2
3	Manometer	1 mm	0–500 mm	0.58 mm
4	Anemometer	±0.1 m/s	0–15 m/s	0.06 m/s
5	Hygrometer	±1	0–100%	0.58%
6	Measuring Jar	±10 ml	0–500 ml	5.77 ml

Table 2
Capital cost of solar HDH desalination system.

S. no	Components	Cost ($)
1	Solar collector setup	68
2	Humidifier	45
3	Dehumidifier	120
4	Blower	90
5	Pump	46
6	Accessories	20
Total cost		389

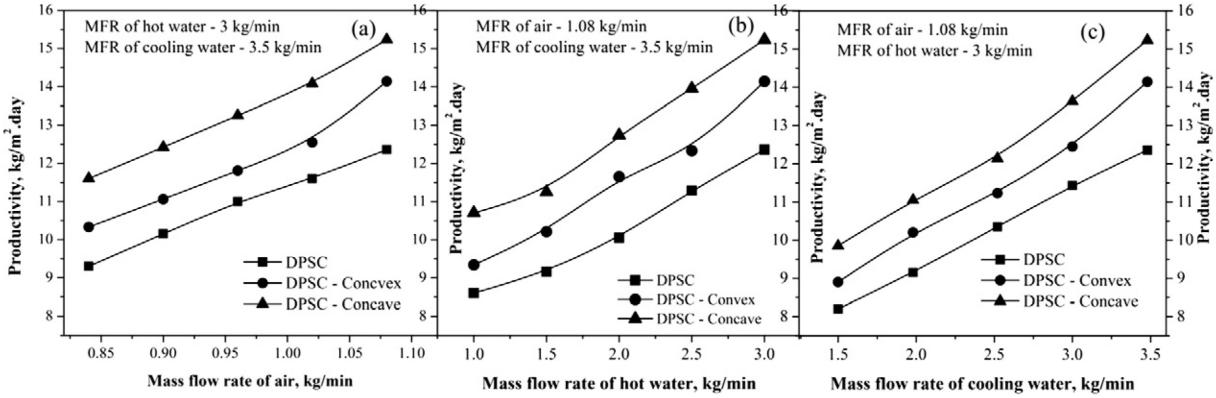

Fig. 4. Variation of flow rate on productivity.

out in the period of October 2015–February 2016 at Thiagarajar College of Engineering, Madurai, India.

3. Uncertainty analysis and data reduction

The temperature at different points in the dual purpose solar collector, humidifier and dehumidifier is measured with the help of K type thermocouples. A hygrometer is used to measure the relative humidity of ambient air, humid air and dehumidified air. The uncertainty analysis for the remaining parameters is given in Table 1. Standard uncertainty is evaluated by the following equation [17,19,46].

$$u = \frac{a}{\sqrt{3}} \tag{1}$$

The uncertainty associated with the daily efficiency is given by [18,19]

$$u(\eta) = \eta\left[\frac{u(\dot{m})^2}{m^2} + \frac{u(I_s)^2}{{I_s}^2}\right]^{1/2} \tag{2}$$

The maximum uncertainty efficiency of 1.94% is evaluated from the Eq. (2).

The system overall efficiency is the ratio of total latent heat of evaporation of the distilled water to the total energy input (solar and electrical energy).

$$\eta = \frac{m \times h_{fg}}{((I_s A_c) + q_{electrical})\ t} \tag{3}$$

The latent heat of evaporation is evaluated by the following equation [47,48]

$$h_{fg} = 2.495 \times 10^6 \times\left[1-\left(9.4749 \times 10^{-4}T + 1.3132 \times 10^{-7}T^2 - 4.7947 \times 10^{-9}T^3\right)\right] \tag{4}$$

The cost associated with different major components of the system is plotted in the Table 2. The economic analysis is performed as given by [27,49]

$$C_{dw} = \frac{TAC}{M} \tag{5}$$

4. Results and discussion

The major parameters varied in this study are mass flow rate (MFR) of air, water and cooling water. The effect of change in these parameters on the system performance is presented in the Fig. 4. The mass flow rate of hot water and cooling water is fixed and the air flow rate is varied in the first set and displayed in the Fig. 4(a). Similarly other two parameters are fixed and one is varied in Fig. 4(b) and Fig. 4(c). It is observed that the distillate of the system enhances with the increase in mass flow rate of air, hot water and cooling water. The increase in mass flow rate of air enhances the mixing rate in packed bed and also resulted in the circulation of higher volume of air per unit time in the desalination system. The improved mixing of air with the water and higher volume circulation leads to carry the more amount of water vapour with the air and resulted in the enhanced distillate output. With the increase in hot water flow rate, the temperature in the humidifier raises and

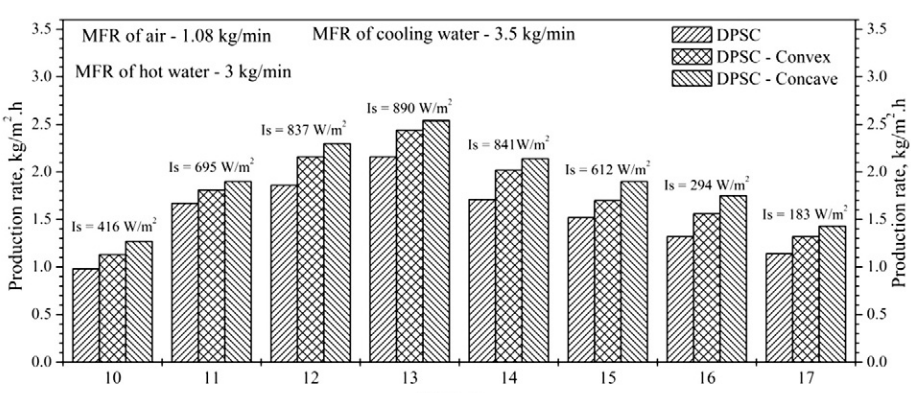

Fig. 5. Productivity variation in HDH system.

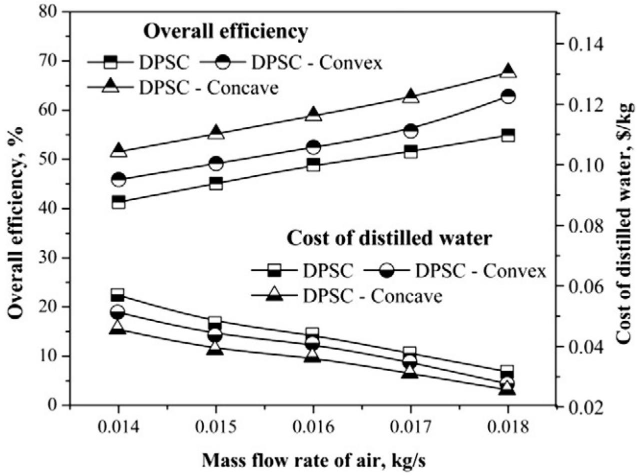

Fig. 6. Overall efficiency and distilled water cost of the system.

resulted in the higher heat and mass transfer rate between water and air. It guides to the increase in and higher specific humidity of outlet air in turn condensation rate (Fig. 4b). The raise in cooling water flow rate increases the heat transfer rate from the humid air to the water. It leads to the reduction in outlet humid air temperature and higher distillate output. The heat loss from the humid air to cooling water increases with the flow rate and it leads to the condensation of more water vapour from humid air (Fig. 4c). The highest distillate of 15.23 kg/m^2.day is collected with the concave turbulators and which is 23% higher than the conventional system and 7.7% higher than the convex turbulators system.

Fig. 5 represents the hourly distillate variation of the system with and without of turbulators. The average solar radiation for the different days of experimentation is provided in the Fig. 5. The distillate output of the system increases with the solar radiation for all configurations and reaches the maximum at noon and thereafter start to fall. Also it is noted that the turbulators augment the distillate rate by increasing the humidifier inlet air temperature. The moisture content carrying capacity of air increases with the air temperature. It leads to the absorption of higher moisture into air and resulted in the enhanced distillate output. Also the increase in solar radiation raises the water and air outlet temperature from the solar collector which is resulted in the higher system capacity. Concave turbulators create the higher turbulence in the flow field rather than the convex turbulators due to the orientation. The peak hourly distillate of 2.54 kg/m$^2\cdot$h is obtained when DPSC integrated with the convex turbulator which is 17.6% higher than the without turbulator system.

The overall efficiency and distilled water cost of the system is represented in the Fig. 6. The efficiency of the system enhances and the cost of distilled water decreases with the increase in mass flow rate of air. It shows that the efficiency of the system has a considered impact on the distilled water cost and this water cost. The system efficiency reaches the maximum value of 68% for concave turbulator configuration and it is about 55% for without turbulators in the solar collector. The minimum distilled water cost of 0.032, 0.027 and 0.0257 $/kg is achieved for the conventional, convex and concave turbulators with the air flow rate of 0.018 kg/s.

5. Conclusion

A dual purpose solar collector is fabricated and tested with a packed bed humidification dehumidification distillation unit. Semi circular turbulators with the convex and concave shape is used in the dual purpose solar collector to create the turbulence and the performance is compared with the conventional system. The system is investigated in terms of mass flow rate of air, hot water and cooling water in actual solar condition. It is observed that the system capacity increases with the flow rate of air, hot and cold water. The presence of turbulator enhances the DPSC outlet air temperature and thereby increases the moisture content carrying capacity of air. The air with high specific humidity is resulted in the enhanced condensation rate. The highest distillate of 15.23, 14.14, and 12.36 kg/m^2.d is collected for the concave, convex and conventional system respectively. The overall efficiency of the system reaches about 68% with the presence of turbulators in the collector. The cost of distilled water reaches lowest value of 0.0257 $/kg for the modified system.

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