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Solar desalination system integrated to use waste heat of air conditioners for continuous output: suitable for coastal areas

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ABSTRACT

In this work, a solar desalination system working through cyclic humidification and dehumidification and also utilizing waste hot air of air conditioner is analyzed numerically for the production of potable water during day and night both operations. The productivity of the proposed system is investigated for different operating and design variables and compared with a conventional system by simulation of a mathematical model based on energy and mass conservation of considered components in transient behavior using MATLAB. During simulations, climatic and geographic condition of Mumbai (India) is used due to the availability of saline water, humid air and the high annual operation of air conditioners. In proposed system air is heated by a double pass solar air heater whereas the saline water is heated by the hot air coming out from the air-cooled condenser of air conditioning unit particularly during day hour operation. The same arrangement is used to heat both air and water during night hours. The use of hot air from the condenser of air conditioner proved beneficial by increasing the yield by 21%–31% per day that depends under different operating and design conditions. Air mass flow rate of 0.032–0.035 kg/s in air heater found suitable and resulted in maximum productivity of 6 kg/d. The mass flow rate of cooling water at 0.038 kg/s has been found suitable with a maximum productivity of 7 kg/d. Need for higher Initial water temperature in a storage tank with a productivity of 8.2 kg/d at water temperature 46°C and low temperature of cooling water in a dehumidifier with a maximum productivity of 10 kg/d found by the analysis. Productivity variation in the range 4–10.2 kg/d has been found as the heater area varied from 0.5 to 2.5 m^2. The proposed system found suitable to work in a region with higher wind speed and ensured better utilization of thermal energy with gained output ratio close to 1.

Keywords: Desalination; Humidification; Dehumidification; Solar energy; Heat transfer

1. Introduction

Water is a basic human requirement but continuous rise in the world's population and industrial growth has resulted in a growing demand for fresh water supply. Water is available in abundant quantities in nature in the form of saline water but natural resources of freshwater are limited and declining in quality due to industrial, agricultural and domestic wastes. Desalination seems to be a promising solution to face water shortage problem but most of the commercially famous techniques are expensive due to high energy consumption[1] and suitable for large scale production (100–50,000 m^3/d) [2]. Humidification-dehumidification (HD) desalination technique is emerging as a successful source of freshwater as it can be easily coupled with renewable energy sources for the thermal requirement and suitable for small scale water production. HD desalination system coupled with solar energy can perform effectively only during day hours when solar radiations are available.

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In the night, the productivity of the desalination unit is affected badly due to the unavailability of solar energy for water and air heating. This work aims to introduce an innovative approach to the HD desalination process by utilizing the waste hot air of air conditioners for continuous water production during the day and night hours for climatic conditions of Mumbai where air conditioners operate for 10–12 months in a year.

Various arrangements of Humidification de-humidification (HDH) system have been proposed by researchers to utilize the waste heat of the heat pump. Lawal et al. [3] proposed an HDH system assisted by a heat pump. In the proposed system condenser heat was used to raise the temperature of seawater before entering the humidifier and the evaporator absorbed the heat from water supplied to the dehumidifier. A mathematical model has been developed based on energy and mass balance of different components of the proposed system working under steady-state to analyze the performance. The study showed significant improvement in the gained output ratio (GOR) compared to the conventional cycle. El-Maghlany et al. [4] performed an experimental investigation on the HD desalination system using a heat pump condenser for increasing the moisture absorbing capacity of air. Additionally, two-stage dehumidification was used to increase water production. The system under investigation was found most efficient under a parallel flow spraying system with a water production rate of 4.44 L/h and maximum specific productivity of 2.02 L/kWh. Santosh et al. [5] experimentally investigated the performance of the HDH desalination system operated through the waste heat of the vapor compression refrigeration system. In proposed air entering the humidifier was heated by the waste heat of the vapor compression refrigeration system during entire operational hours. The performance of the desalination system was examined under the hot and medium climatic condition and it was found that the water production rate decreased with an increase in space conditioning temperature. Xu et al. [6] experimentally investigated the performance of the solar water heater assisted HDH desalination system coupled with a heat pump cycle to fulfill the heating and cooling requirement of the desalination system. In the proposed system, both the solar water heater and condenser heat was used to heat the water during operational hours. The effect of the mass flow rate of air and mass flow rate of water on GOR and system yield was recorded which showed significant improvement in productivity.

Also, the performance of HD systems working with various innovations has been investigated by several researchers [7–10] for improvement. Orfi et al. [11] utilized the latent heat of condensate water vapor in the condenser of a solar HD desalination system to preheat the feed water. Al-Enezi et al. [12] evaluated the characteristics of the HD desalination process as functions of operating conditions by a small capacity experimental system. To optimize an HD desalination process, Nawayseh et al. [13] constructed a simulation program and solved a set of non-linear equations that described the desalination unit numerically. Their results had good consistency with the experimental results of two different units that were constructed in Jordan and Malaysia. Moreover, Nawayseh et al. [14] evaluated the heat and mass transfer coefficients in the condenser and the humidifier. By adding a solar system to their mathematical model Zamen et al. [15] optimized the total solar HD system. Such optimization was mainly intended to reduce freshwater production costs. Nafey et al. [16] experimentally investigated the HD process using solar energy at the weather conditions of Suez City, Egypt. A test rig was designed and constructed to conduct this investigation under different environmental and operating conditions. Different variables were examined and it was found that the results of the developed mathematical model by the same authors were in good agreement with the experimental results. Giwa et al. [17] viewed the HD process as an innovative method to obtain fresh water and discussed economic and environmental benefits along with design aspects. Giwa et al. [17] observed widely varying productivity (0.83–570 kg/h) of the HD desalination system that depends upon (i) configuration and (ii) properties of air and water streams and also of the carrier medium. The results were tabulated for productivity under different operating conditions listed above that have been suggested by researchers to provide the opportunity to improve the performance of the HDH unit. Abdelmoz et al. [18] viewed the HD process as the most suitable process for small scale water production, therefore, it can play a very important role in fulfilling the household requirement of freshwater in any coastal city like Mumbai.

Most of the HDH desalination systems coupled with a heat pump cycle found to depend on condenser for heating water or air during entire operational hours. Few works are also found to utilize renewable energy sources. In this work, a new concept that uses two different approaches for working of the proposed system during the day and night hours has been suggested and analyzed. During day hours, solar energy is used in heating air whereas waste hot air from the air-cooled condenser of air conditioning unit is utilized to heat water. During night hours, hot air from the condenser is partially allowed to flow through the humidifier and the remaining amount is utilized to heat water in the storage tank. Additionally, a mathematical model based on the un-steady state behavior of different components of the proposed system is used to reveal the effect of operating parameters on water production.

2. System configuration and description

The schematic arrangement of the proposed HD desalination system integrated with air conditioners for a continuous output of distillate is shown in Fig. 1, with all main components that include double pass air heater, humidifier, dehumidifier, storage tank and air conditioner (outdoor unit).

During day hours ambient air passes through the double pass solar air heater where it absorbs heat while passing over both sides of the absorber. Further, it moves forward through a humidifier to evaporate the water by opening damper D1, at the same time hot air from the condenser of air conditioning unit is allowed to pass through the storage tank by opening damper D3 while D2 remains closed. The opening of damper D3 ensures the passing of hot air from the outdoor unit of the air conditioner through a bundle of tubes that are thoroughly dipped into the water of the storage tank and is surrounded by saline water thus

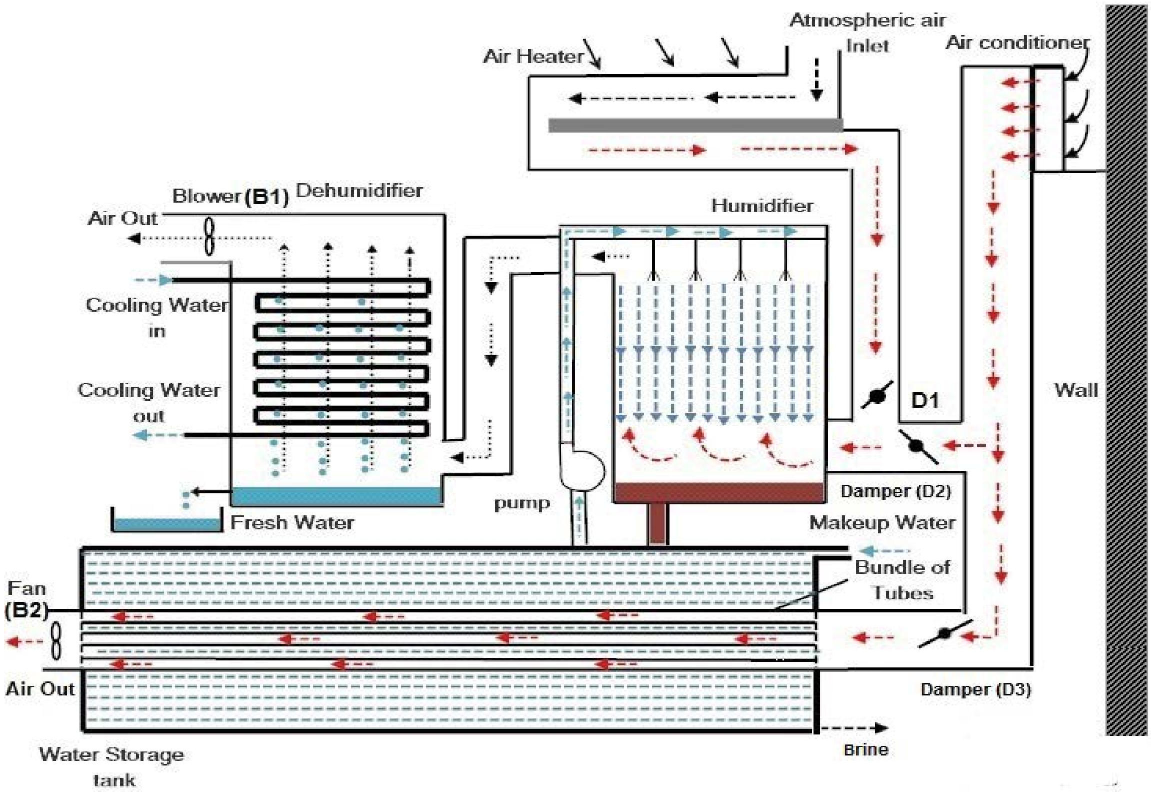

Fig. 1. Proposed desalination system.

increases the water temperature within a storage tank. The details of the intricate construction of the storage tank are shown in Fig. 2. This preheated water is sprayed in a humidifier with the help of a pump for the humidification of air coming from the air heater. In the proposed system air heater is preferred over water heater to utilize available solar thermal energy in a better way because of lower specific heat of air compared to water, which leads to increase air temperature more than the temperature of water by a similar amount of solar energy available to serve. After being heated in two passes of air heater, the water carrying capacity of air increases and this air is humidified by a spray of saline water in the humidifier and carries away a significant amount of water vapor with it. It is interesting to mention here that air follows an open cycle while the water follows a closed cycle to take the advantage of water heating due to recirculation of the same water from a storage tank to the humidifier and back to a storage tank. The storage tank acts as a reservoir of saline water with provisions of the addition of makeup water and removal of brine from time to time. These provisions maintain the constant amount of water in a storage tank with salinity up to a level that will not affect the working of the proposed system. Now, the rich humidified air passes over the dehumidifying coils, where water vapor is condensed to form freshwater because of the circulation of cool water through the cooling coil.

In the same arrangement discussed above, during the night hours humidification process will not be effective in a conventional way due to the absence of solar energy for heating the air using air heaters, thus results in a fall in productivity. To maintain the continuity of distillate the remedial measure proposed is that the total hot air coming out from the air-cooled condenser of air conditioner is partially provided to humidifier by opening damper D2 and closing damper D1 and remaining amount of air is directed towards the storage tank for heating the water through damper D3 as it was doing in day time. Damper D1 will remain closed during night hour to avoid the mixing of hot air from the condenser of the air conditioning unit and ambient air. Blower B1 and fan B2 are provided to maintain continuous airflow through the proposed system. Thus the proposed system is well equipped with features of air and water heating in a simple layout with a considerable reduction in cost by avoiding any use of water heater for the task and capable to produce a continuous yield of potable water by overcoming the limitation of conventional solar desalination units. Additionally, the states of air during the flow through the humidification and dehumidification desalination system are described by the psychrometric chart as shown in Figs. 3 and 4. During day hours of operation states followed by the process, the air is:

Process a-b: Sensible heating of ambient air in the solar air heater.

Process b-c: Humidification of the air up to saturation state by spraying saline water from the top of the humidifier.

Process c-d: Dehumidification of saturated air coming out from the humidifier by the cooling water to get the freshwater.

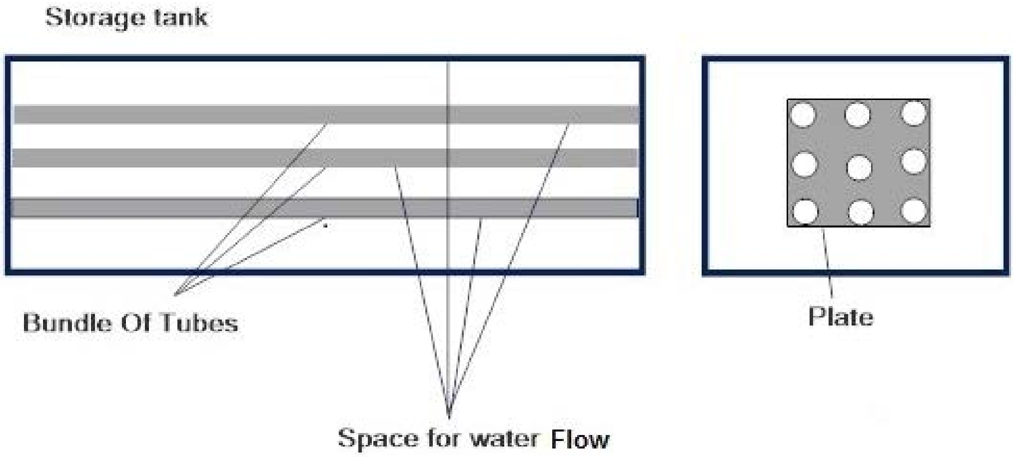

Fig. 2. Details of storage tank.

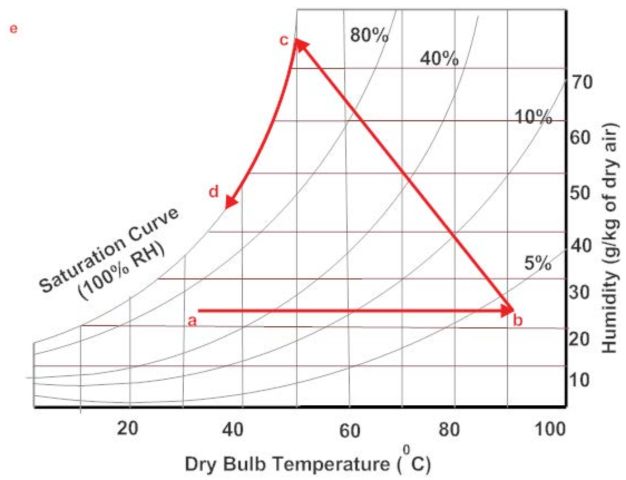

Fig. 3. During day hours of operation.

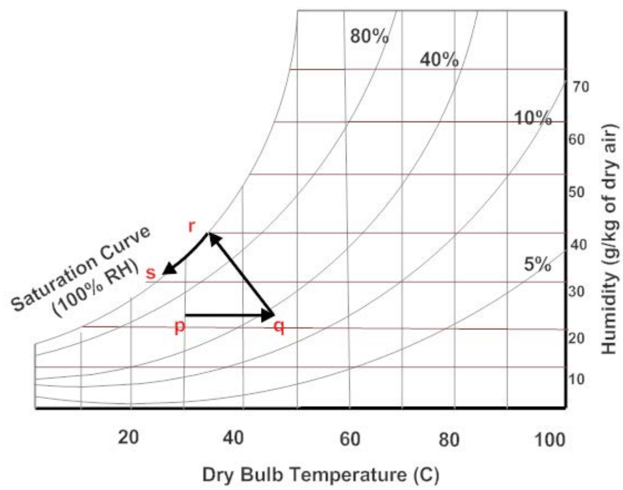

Fig. 4. During night hours of operation.

During day hours hot air from air-conditioner is not allowed to pass through the humidifier, however, it plays its role in freshwater production by heating the saline water in the storage tank.

In the absence of solar energy during night hours, solar air heater cannot provide the hot air to the system, therefore only hot air from air conditioner participates in freshwater production. The required amount of hot air from the air conditioner is allowed to pass through the humidifier and remaining air passes through the storage tank for heating the saline water. The various states followed by process air during water production are:

Process p-q: Sensible heating of ambient air in an outdoor unit (air-cooled condenser) of air conditioner.

Process q-r: Humidification of the air up to saturation state by spraying saline water from the top of the humidifier.

Process r-s: Dehumidification of saturated air coming out from the humidifier by the cooling water to get the freshwater.

The major parameters of various components of the proposed system are listed in Table 1.

3. Mathematical modeling

The mathematical model of the proposed desalination system that utilizes the waste hot air of air conditioner for freshwater production is based on energy and mass conservation. Initially, various convection and radiation heat transfer for different parts of the air heater has been considered to get the air temperature at the outlet of air heater by simultaneous solution of Eqs. (1)–(6). Then the energy balance of humidifier and dehumidifier are used to get related air temperature. These temperatures are used to calculate the productivity of the proposed system by the mass balance of humidifier and dehumidifier.

Energy balance equation for outer and inner glass cover.

$$m_g \cdot C_g \frac{dT_{\text{go}}}{d\tau} = I\alpha_g A_C + Q_{\text{gi/go}(R)} - Q_{\text{go/surr}(C)} - Q_{\text{go/sky}(R)} + Q_{\text{gi/go}(C)} \quad (1)$$

Table 1
Major parameters of various components of proposed system

Component	Parameter
Double pass air heater with 2 glass covers	Dimension (100 cm × 50 cm × 10 cm)
Glass cover	Thickness (3 mm)
	Distance between glass covers (2.5 cm)
Humidifier	Dimension (60 cm × 35 cm × 45 cm)
Dehumidifier	Dimension (50 cm × 35 cm × 40 cm)
	Heat transfer area (3.5 m^2)
Water storage tank	Capacity (500 L)
Duct (carrying hot air from air heater to humidifier)	Dimension (18 cm × 15 cm)
Duct (carrying hot air from air heater to humidifier)	Dimension (25 cm × 20 cm)
Fan	Sweep size (20 cm), power (220 V, 30 W)
Pump	Max flow (10 L/ min), rated power (220 V,40 W)

$$m_g \cdot C_g \frac{dT_{\text{gi}}}{d\tau} = I\alpha_g \tau_g A_C - Q_{\text{gi/go}(R)} - Q_{\text{gi/air}(C)} + Q_{\text{plate/gi}(R)} + Q_{\text{gi/go}(C)} \quad (2)$$

Energy balance equation for air in the first and second pass.

$$m_a \cdot C_a \frac{dT_{a1}}{d\tau} = Q_{\text{plate}/a1(C)} + Q_{\text{gi}/a1(C)} - M_a C_a \left(T_{a1\text{out}} - T_{a1\text{in}}\right) \quad (3)$$

$$m_a \cdot C_a \frac{dT_{a2}}{d\tau} = Q_{\text{plate}/a2(C)} + Q_{\text{base}/a1(C)} - M_a C_a \left(T_{a2\text{out}} - T_{a1\text{in}}\right) \quad (4)$$

Energy balance equation for absorber plate.

$$m_p \cdot C_p \frac{dT_{\text{plate}}}{d\tau} = I\alpha_g \tau_g^2 A_C - Q_{\text{plate}/a2(C)} - Q_{\text{plate}/a1(C)} - Q_{\text{plate/gi}(R)} - Q_{\text{plate/base}(R)} \quad (5)$$

Energy balance equation for base plate.

$$m_b \cdot C_b \frac{dT_b}{d\tau} = Q_{\text{plate/base}(R)} - Q_{\text{base}/a2(C)} - Q_{\text{base/surr}} \quad (6)$$

Various heat transfers involved in energy balance equation can be calculated as follows [19–22].

$$Q_{\text{gi/go}(R)} = (\text{wl}) \frac{\sigma\left(T_{\text{gi}}^2 + T_{\text{go}}^2\right)\left(T_{\text{gi}} + T_{\text{go}}\right)}{\frac{1}{\varepsilon_{\text{gi}}} + \frac{1}{\varepsilon_{\text{go}}} - 1}\left(T_{\text{gi}} - T_{\text{go}}\right) \quad (7)$$

$$Q_{\text{go/surr}(C)} = A_C\left(2.8 + 3V_i\right)\left(T_{\text{go}} - T_{\text{surr}}\right) \quad (8)$$

$$Q_{\text{go/sky}(R)} = A_C \varepsilon_{\text{go}} \sigma\left(T_{\text{go}}^2 + T_{\text{sky}}^2\right)\left(T_{\text{go}} + T_{\text{sky}}\right)\left(T_{go} - T_{\text{sky}}\right) \quad (9)$$

$$Q_{\text{gi/go}(C)} = A_C \text{Nu}_{\text{gi/go}} \frac{K_a}{x}\left(T_{\text{gi}} - T_{\text{go}}\right) \quad (10)$$

$$Q_{\text{gi/air}(C)} = A_C \text{Nu}_{\text{gi}/a1} \frac{K_a}{D_h}\left(T_{\text{gi}} - T_{a1}\right) \quad (11)$$

where D_h = 4 Area/wetted perimeter.

The moist air is assumed to be saturated after humidification and during dehumidification therefore its thermal properties can be evaluated by temperature-dependent relations suggested by [15]: thermal conductivity $K = 0.0244 + 0.6773 \times 10^{-4}$ T, thermal diffusivity $\alpha = 7.7255 \times 10^{-10} + T^{1.8}$, and kinematic viscosity $v = 0.1284 \times 10^{-4} + 0.00105 \times 10^{-4}\ T$.

$$Q_{\text{plate/gi}(R)} = \left(A_C\right) \frac{\sigma\left(T_{\text{gi}}^2 + T_{\text{plate}}^2\right)\left(T_{\text{gi}} + T_{\text{plate}}\right)}{\frac{1}{\varepsilon_{\text{gi}}} + \frac{1}{\varepsilon_{\text{plate}}} - 1}\left(T_{\text{gi}} - T_{\text{plate}}\right) \quad (12)$$

$$Q_{\text{plate}/a1(C)} = A_C h_{\text{plate}/a1(C)}\left(T_{\text{plate}} - T_{a1}\right) \quad (13)$$

Here convective heat transfer coefficient $h_{\text{plate}/a1(C)} = h_{\text{gi}/a1(C)}$

$$Q_{\text{plate}/a2(C)} = A_C h_{\text{plate}/a2(C)}\left(T_{\text{plate}} - T_{a2}\right) \quad (14)$$

$$Q_{\text{plate/base}(R)} = (wl) \frac{\sigma\left(T_{\text{plate}}^2 + T_{\text{base}}^2\right)\left(T_{\text{plate}} + T_{\text{base}}\right)}{\frac{1}{\varepsilon_{\text{plate}}} + \frac{1}{\varepsilon_{\text{base}}} - 1}\left(T_{\text{plate}} - T_{\text{base}}\right) \quad (15)$$

$$Q_{\text{base}/a2(C)} = A_C h_{\text{base}/a2}\left(T_{\text{base}} - T_{a2}\right) \quad (16)$$

$$Q_{\text{base/amb}} = A_C U_{\text{loss}}\left(T_{\text{base}} - T_{\text{amb}}\right) \quad (17)$$

Energy balance equation for the water storage tank.

$$m_{w1} \cdot C_w \frac{dT_{w1}}{d\tau} = M_{w2} C_w T_{w2} + M_{\text{mw}} C_w T_{\text{mw}} - M_{w1} C_w T_{w1} - Q_{w1/\text{amb}} \quad (18)$$

Energy balance equation for a humidifier.

$$m_a\left(h_{a3} - h_{a2\text{out}}\right) = M_{w,\text{in}} C_w T_{w1} - M_{w,\text{out}} C_w T_{w2} \quad (19)$$

Energy balance equation for de-humidifier.

$$m_a\left(h_{a3} - h_{a4}\right) = M_{w3} C_w\left(T_{w4} - T_{w3}\right) + M_{c,} C_w T_{w5} \quad (20)$$

Mass balance equation for the humidifier.

$$M_{w,\mathrm{out}} + M_a W_3 = M_{w,\mathrm{in}} + M_a W_1 \quad (21)$$

The mass flow rate and temperature at which air enters into the humidifier are important parameters that are related to the productivity of the proposed system as water carrying capacity of air during humidification of the same depends on it. During sunshine hours air is supplied to the humidifier from air heater and during night hours source of hot air is from condenser of air conditioning unit thus air will enter to the humidifier at different temperature in day and night hours, however mass flow rate of air is controlled by partial supply to humidifier and partially to water of storage tank. The productivity of the desalination system (M_{fw}) can be calculated by the rate of condensation of water vapor in a dehumidifier that is given by:

$$M_{\mathrm{fw}} = M_a\left(W_3 - W_4\right) \quad (22)$$

To measure the advantage of using hot air of air conditioner in the proposed HD desalination system the GOR can be calculated by relation.

$$\mathrm{GOR} = \frac{M_{\mathrm{fw}} h_{\mathrm{fg}}}{Q_{\mathrm{in}}} \quad (23)$$

where M_{fw} = freshwater production rate, h_{fg} = heat of vaporization at ambient condition, Q_{in} = rate of heat input.

The various parameters related to the proposed system that are used in the simulation are listed in Table 2.

4. Results and discussion

The productivity of the proposed system has been calculated by a computer simulation program that is prepared in MATLAB to solve energy and mass balance equations. Energy balance equations for various parts of air heater are in the form of ordinary differential equations where temperature varies with time are solved by the Runge-Kutta method. The climatic condition of Mumbai on 31/05/2018 has been used to give the initial conditions to run the simulation program. Initial temperatures are assumed to be near the atmospheric condition. The variation of solar irradiance is shown in Fig. 5 the data of which has been collected from [24].

Table 2
Parameters used for simulation [20–23]

Parameter	Value
Location	Mumbai (India)
Air mass flow rate (M_a)	0.027 kg/s
Water mass flow rate (M_w)	0.028 kg/s
Water mass flow rate in dehumidifier	0.05 kg/s
Width of air hater (w)	0.5 m
Length of air heater (L)	1 m
Distance between glass covers (x)	0.025 m
Mass of absorber plate (m_p)	4.5 kg
Mass of base plate	4.5 kg
Mass of glass	3.5 kg
Emissivity of glass	0.9
Storage tank capacity	500 L
Ambient air temperature and relative humidity	31°C and 71% RH
Air flow rate from condenser	16 cm/ton
Air temperature leaving the condenser	T_{amb} + 16°C

The proposed system is a new and innovative approach to utilize the waste hot air of air conditioners for improving the performance of the HD desalination system. Thus experimental validation of mathematical model and results used in this simulation is not possible with the literature available so far, however, the experimental study of solar HD desalination system working in climatic condition of Ankara, Turkey presented by Yamali and Solmus [25] is used to validate and further compare the results of proposed system. A good agreement between experimental and simulated results has been found and is tabulated in Table 3.

Figs. 6–12 show the effects of different operating and design variables on the productivity of proposed system and compare day time water production (as hot air of air conditioner is not used in humidifier so system cannot work during night hours) and combined day and night water production (because use of hot air of air conditioner enables the desalination system to produce fresh water during night hours also). The legends on graphs show as:

4.1. Hot air from the air conditioner is not used

The hot air from the air conditioner becomes unusable during day time because of the presence of the sun and solar air heater. The air coming out from the solar air heater attains sufficiently high temperature where any heat addition from the hot air from the air conditioner is not feasible in a humidifier. Thus the production of potable water when the hot air from the air conditioner is not used (is sunshine hours) is the production at day time when the sun is there. The proposed system utilizes the hot air from the air heater during day hours for water production but solar

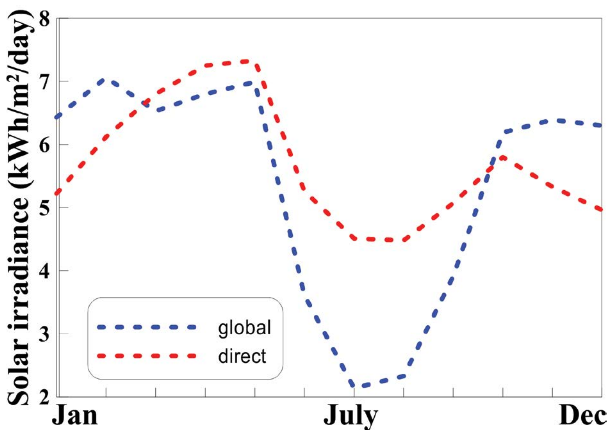

Fig. 5. Solar data for Mumbai.

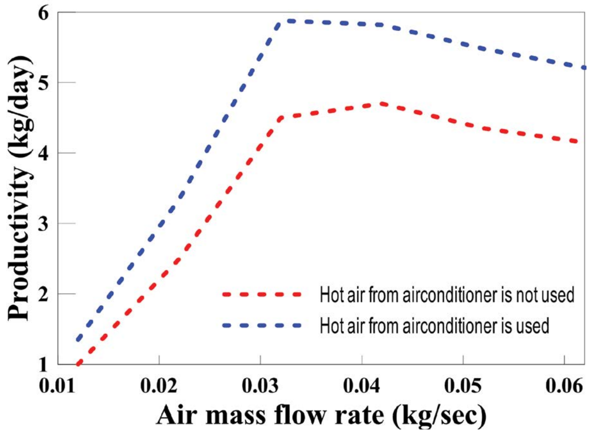

Fig. 6. Effect of inlet air mass flow rate on the productivity.

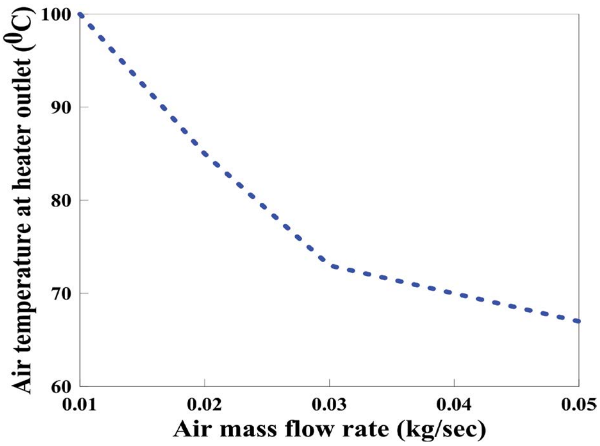

Fig. 7. Effect of air mass flow rate on air temperature at heater exit.

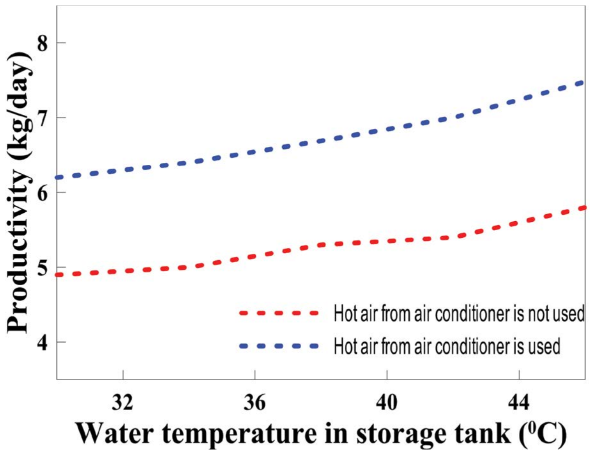

Fig. 8. Effect of storage tank water temperature on productivity.

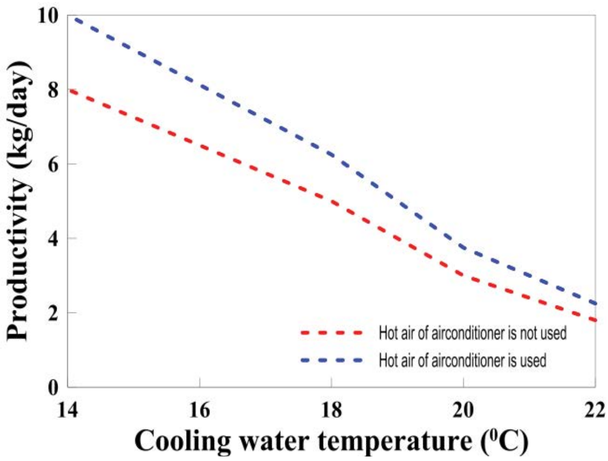

Fig. 9. Effect of cooling water temperature on productivity.

air heater cannot operate during night hours in absence of sun thus water production ceases, and the remedial measure proposed in our manuscript is utilizing the heat of hot air coming from air conditioner in humidifier particularly during non-sunshine hours, that is, night time.

4.2. Hot air of air conditioner is used

As clarified above this hot air from the air conditioner is usable in a humidifier during night time thus the production of water can be maintained uninterrupted for the whole day. Production of water is continuous during day and night however the necessary heat is being contributed by the sun during the day and by hot air from air conditioner during the night. Fig. 6 shows explicitly the constant increase (of the order of 0.35 kg/d) in productivity for any flow rate of air from 0.012 to 0.032 kg/s if hot air of air conditioner is also used. The difference of this increase is being found more (of the order of 1.38 kg/s) at the air flow rate between 0.032 to 0.042 kg/s. However, it is interesting to note that after the flow rate more than 0.042 kg/s the yield for both the cases reduces because of less retention time of air in air heater that leads to reduce the temperature of air that ultimately reduces water carrying capacity of air and finally the yield. This is also very clear in Fig. 7 where the temperature of air coming out from the air heater reduces steeply and this rate of reduction slows down after the flow rate of 0.03 kg/s because of the high mass flow rate. Thus the best yield which is of the order 4.5–6 kg/d can be obtained at air flow rate ranges within 0.032–0.042 kg/s for both the cases. However, at this best flow rate range, the air from both air heater and air conditioner gives 31% more yield with comparison to if air from the air conditioner is not used. These results are very useful to select the optimum mass flow rate of air through the humidifier for higher water production.

Water temperature in the storage tank rises and it is because of using hot air from the condenser of the air conditioner. The amount of hot air directed towards the storage tank increases the temperature of the water before entering the humidifier. In humidifier air temperature also increases due to energy exchange with water. This increase in temperature also increases the moisture absorbing capacity and finally results in an increase in productivity that is being shown in Fig. 8. It is very clear from Fig. 8 that over a

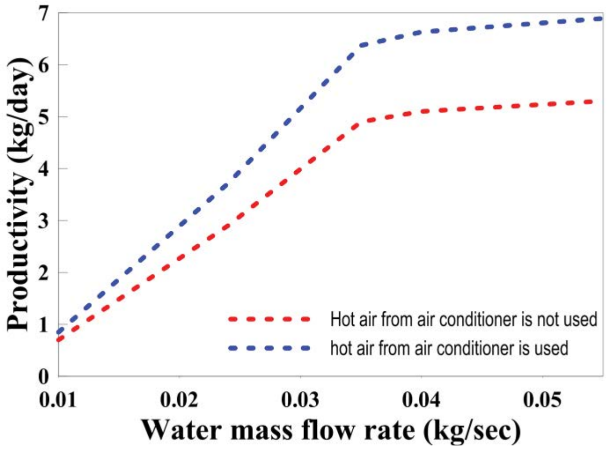

Fig. 10. Effect of mass flow rate of water in dehumidifier on productivity.

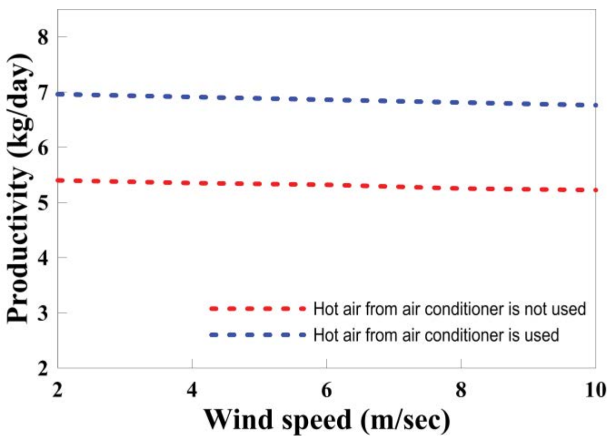

Fig. 11. Effect of wind speed on the productivity.

temperature gain of 12°C (from 32°C to 44°C) the increase in productivity can be observed by 18% and 20% for if air from air conditioner is not used or used with maximum productivity of 5.2 and 7.1 kg/d. However, the supremacy of yield obtained in the case when air is used from the air conditioner remains always higher by 18%–20% for water temperature from 32°C to 44°C. It is also clear that in both cases whether air from conditioner is used or not there is an increase in productivity by 20.6% and 28.9% if compared for 30°C and 46°C respectively and the productivity of the proposed system is in range 6–8.2 kg/d for the same temperature range. The proposed system has another advantage of not using a water heater which significantly reduces the complexity and cost of the entire setup.

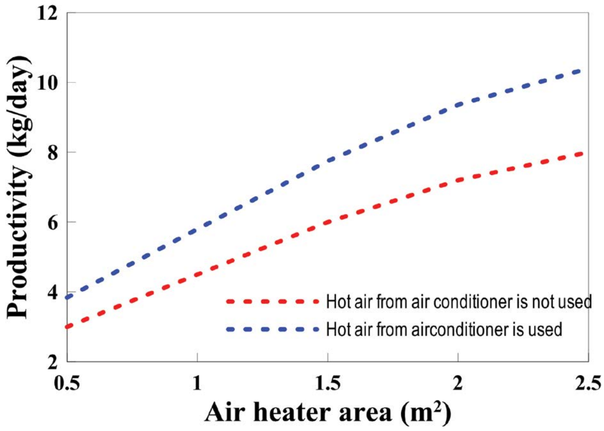

Fig. 12. Effect of air heater area on productivity.

Figs. 9 and 10 reveal the effect of cooling water on the productivity of the proposed system. Fig. 9 shows the advantage of higher productivity with lower temperature cooling water supplied to the dehumidifier. It is clear from the figure that the productivity of the proposed system increases considerably with decreasing the cooling water temperature. The increased rate of condensation of water vapor in a dehumidifier is responsible for higher productivity. Over a temperature range of 8°C productivity is found to be increased 4 times for both the arrangements. A system using hot air from air conditioner yields about 25% more freshwater compare to the system not using hot air when cooling water temperature changes from 22°C to 14°C. The productivity of the proposed system varies from 3 to 10 kg/d for the same temperature range. Fig. 10 shows the variation of productivity for different values of cooling water mass flow rate through the dehumidifier. It is clear that as the cooling water mass flow rate increases productivity also increases because of enhanced heat transfer from moist air to cooling water that decreases the temperature of the cooling coil thus more condensation takes place. It can be seen that by increasing cooling water mass flow rate from 0.01 to 0.05 kg/s, the productivity of the system using hot air of air conditioner, increases by 21.64%–30% compared to if the same is not used and it is in the range 4–7 kg/d. It can also be seen that the rate of increase in productivity is more for water mass flow rate up to 0.038 kg/s for both systems. Thus up to a certain level increasing the mass flow rate of cooling water is beneficial otherwise at a higher mass flow rate, it does not contribute much in terms of yield and becomes almost constant. This optimum values of cooling water temperature and mass flow rate helps to avoid the unnecessary storage and need for cooling arrangement of water.

Table 3
Validation of simulated results

Solar radiation (W/m^2)	A (m^2)	T_{amb} (C)	M_a (kg/s)	M_w (kg/s)	T_{w1} (C)	T_{cw} (C)	Productivity Cemil and Ismail [20] (kg/d)	Productivity present work (kg/d)	Error
750	0.5	32	0.045	0.115	35.5	19	5.6	5.87	4.64%
750	0.5	32	0.045	0.115	50	19	7.9	8.28	5.28%

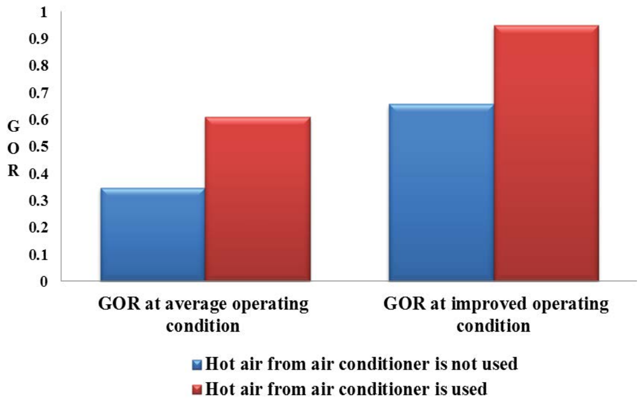

Fig. 13. Comparison of GOR for two operating conditions

Fig. 11 shows the effect of ambient air speed over the glass of air heater on system productivity. While analyzing the effect of wind speed on the productivity once again the use of hot air from the conditioner has been found beneficial as productivity remains always 30% higher and of the order 7 kg/d for what so ever is the wind speed. This result of the proposed system for both arrangements appears to be equally suitable for the places on earth where the ambiance is highly windy because it is not affecting adversely the productivity. Fig. 12 shows the variation of productivity with an area of air heater keeping mass flow rate constant. The productivity increases significantly by increasing the heater area which contributes to raising the temperature of air coming out from the air heater and ultimately higher yield in a dehumidifier is found due to higher moisture content. As heater area increases 5 times the yield increases 2.7 times for both arrangements however here also productivity remains higher by 30% if the air from conditioner is used with variation in productivity in the range 4–10.2 kg/d. Finally, the performance of the HD desalination system with and without using hot air from the air conditioner has been evaluated and compared in terms of GOR under two operating conditions as shown in Fig. 13.

The first operating condition is based on the parameters given in Table 1 which represents an average operating condition for the desalination system whereas the second condition represents the improved operating condition based on the results of the simulation. The advantage of using waste hot air from the air conditioner in the HD desalination system can be clearly seen from Fig. 13 as an increase in GOR is about 90% under average operating conditions whereas a 55% increase can be observed in improved operating condition. Higher values of GOR represents the better utilization of thermal energy thus proposed a system in which GOR is close to unity when working in improved operating condition ensures better recovery of thermal energy compared to conventional systems.

5. Conclusions

Solar assisted HD desalination system utilizing also the waste hot air of air conditioner for continuous operation is simulated for time-dependent behavior. Results are proved the benefit of utilizing the hot air for freshwater production and summarized below:

- For both the systems (with and without the use of hot air from the air conditioner) the best yield (of the order 4.5–6 kg/d) can be obtained at air flow rate ranges within 0.032–0.042 kg/s.
- For the best airflow rate range, the system using hot air from the air conditioner gives freshwater of 6 kg/d which is 31% more compared to the conventional system.
- The increase in productivity has been observed by 18% and 20% over a temperature gain of 12°C for if air from the air conditioner is not used or used respectively with a maximum productivity of 5.2 and 7.1 kg/d for the same.
- System using hot air has resulted the productivity in the range of 6–8.2 kg/d for humidifying water temperature range 30°C–46°C and there is an increase in productivity by 20.6% and 28.9% if compared for same temperature range.
- The productivity of the system using hot air of air conditioner found to be about 25% higher compared to the system not using hot air over the cooling water temperature range of 14°C–22°C. The productivity of the proposed system varies from 3 to 10 kg/d for same temperature range.
- The productivity of the system using hot air of air conditioner increases by 21.64%–30% compared to if the same is not used and it is in the range 4–7.1 kg/d, however rate of increase in productivity is more up to water mass flow rate of 0.038 kg/s for both systems.
- System has been found suitable even for regions with higher wind speed in both arrangements (with and without the use of air from conditioner) but 30% more yield has been obtained if air from the conditioner is used with the productivity of order 7 kg/d.
- If air heater area increases 5 times the yield increases 2.7 times for both arrangements keeping mass flow rate constant, however here also productivity remains higher by 30% if the air from conditioner is used with productivity variation in range 4–10.2 kg/d.
- System using waste hot air has resulted in higher GOR compared to a conventional system, thus ensured better utilization of thermal energy with GOR close to unity.

Symbols

A_c	—	Air heater area, m^2
C	—	Heat capacity, J/kg k
D	—	Channel thickness, m
h	—	Heat transfer coefficient, W/m^2 k
H	—	Enthalpy, J/kg
I	—	Solar intensity, W/m^2
K	—	Thermal conductivity, W/m k
M	—	Mass flow rate, kg/s
m	—	Mass, kg
Q	—	Heat transfer, W
T	—	Temperature
V	—	Velocity, m/s
w	—	Width of channel, m
W	—	Specific humidity
W_3	—	Humidity at dehumidifier inlet
W_4	—	Humidity at dehumidifier outlet

Greek

α — Absorptivity
ε — Emissivity
τ — Time, s

Subscripts

a_1 — Air in first pass
a_2 — Air in second pass
B — Base plate
C — Convection
cw — Cooling water
g_i — Inner glass cover
g_o — Outer glass cover
g — Glass
fw — Fresh water
R — Radiation
$w1$ — Water in storage tank

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