SIMULATION OF HDH DESALINATION SYSTEM USING TILTED, TWO-PASS SOLAR AIR HEATER

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ABSTRACT

The present work represents a theoretical investigation of the performance of a solar air-heated desalination system using humidification-dehumidification (HDH) technique based on closed-water, open-air cycle under the geographical conditions of Dhahran (26.5°N, 50.2°E), Saudi Arabia. The HDH desalination system is suitable for small-scale decentralized fresh water production. It essentially consists of a tilted, two-pass solar air heater, a humidifier, a dehumidifier in addition to a storage tank. In this system, air alone is heated in the solar air heater. A simulation program is developed based on mass and energy balance. The governing equations are simultaneously solved using Engineering Equations Solver (EES) to investigate the effect of the main design and operating parameters on the productivity of the water desalination system. It is found that the tilted solar heater outperforms the horizontal one by about 7% whereas the humidifier performance has a significant effect on the system productivity. Using a selective surface an increase the desalted water productivity by 39% compared to the units that do not have a selective surface.

Keywords: HDH, Water, Technology, simulation, air—heated, solar energy

1. INTRODUCTION

Due to the monotonic increase of population, industrialization and development worldwide, the need for more energy and clean water is growing a in fast rate. In the absence of natural potable water resources in many places in the world, desalination remains as a vital solution to increased water needs. The majority of worldwide desalination plants are based on distillation process that requires significant amount of energy. Desalination is the strategic choice to supply an adequate amount of drinking water to people in many places in the world including the Kingdom of Saudi Arabia. Between 50 to 70 percent of the Kingdom's drinking water is desalinated, a process that requires a substantial amount of energy. Furthermore, Saudi Arabia uses 1.5 million barrels of oil per day at its desalination plants. In recent years prices for desalinated water is increasing in Saudi Arabia. The gradual cost reduction due to improvement in desalination technology has been mostly offset by increased material and labor cost. Fresh water demand in the Kingdom is largely increasing and this demand cannot be met by the existing natural water sources. Existing water sources are becoming scarce and insufficient, and also, they are being polluted.

Production of fresh water using solar energy is a viable –environment friendly- solution especially to remote areas. Abundant solar energy is available in the Kingdom with the large amount of underground and saline water. Therefore, it is possible to produce fresh water from underground saline water using solar energy. Consequently, increasing fresh water demand in the Kingdom can be solved partially by using solar desalination technologies. Different solar desalination processes have been used to produce fresh water from saline water. The conventional multi-effect distillation, multi-stage flashing, and reverse-osmosis technologies are among these methods. In contrast, humidification-dehumidification (HDH) desalination represents a relatively new desalination method based on heat and mass-transfer processes. Atmospheric air is employed as the medium to convert saline water to fresh water. HDH desalination process involves two processes. Saline water is first converted to water vapor by evaporation into dry air in a humidifier. This water vapor is then condensed out from the air in a dehumidifier (condenser) to produce freshwater. Because of the moderate operating-temperature requirement, HDH desalination process can easily be driven by sustainable solar energy and this makes HDH desalination particularly attractive for small-scale decentralized fresh water production. Several studies are available in the literature that explore HDH as an effective means for desalination.

The early work includes models of HDH desalination systems that adopts solar water heating such as (Al-Hallaj et al. [1], Muller-Holst et al. [2], Al-Hallaj and Selman [3]), Dai et. al.[4], Orfi et al. [5] and Shaobo et al. [6]). Solar air heating HDH systems were investigated by (Chafik et al. [7.8.9], Yamali and Solmus [10], Fath and Ghazy [11]). It is worth to mention that a low cost solar collector based on polymeric materials was proposed by Chafiq et al. However, it has low efficiency compared to commercial units.

Nafey et al. [12] (2004) used dual solar heater for heating both air and water separately in an HDH system. Xiong et al. [13,14] used a steam generator and water heating tank in a HDH system where only one baffled shall and tube column is used instead of using a separate humidifier and dehumidifier units. Yanniotis and Xerodimas [15] considered two types of air humidifiers as a part of multi stage solar desalination process. The first one is the tubular spray humidifier and the other one is the pad humidifier. They also presented some computational results for the pad humidifier. Their results showed no substantial differences between both types in terms of pressure drop. Evaporation rate was higher for a thicker pad system at high air to water flow rate ratios. Fath and Ghazy [11] reported that air heated HDH system productivity improved with increased solar energy for air heating, decreased wind velocity and increased air flow rate up to a certain value. They also reported that the dehumidifier size has an insignificant effect on the system performance. The latter is an issue of controversy among investigators that requires further exploration.

A thorough review of water desalination systems was presented by Goosen et al. [16] and an updated one by Narayan et al [17]. Where comparisons of different components, systems and gain output ratio limit for each layout were made and presented.

The objective of this simulation study is to investigate the performance of a sun powered desalination system using humidification-dehumidification (HDH) technique based on closed-water, open-air cycle under the geographical conditions of Dhahran (26.5°N, 50.2°E), Saudi Arabia. This study is expected to fill an existing gap in the literature regarding the effect of solar heater tilt angle, using selective surface for the solar heater and considering humidifier performance in terms of the relative humidity of air leaving the humidifier on the system productivity.

2. DESCRIPTION OF THE PROPOSED SYSTEM

The proposed desalination system is shown in Figure 1. It essentially consists of a tilted, two-pass solar air heater with two glass covers, a humidifier, a dehumidifier and a storage tank. In this system, air alone is heated in a solar air heater. The system is composed of three main fluid-circulation lines identified in Fig. 1 as saline water, air/vapor, and freshwater. The saline water which is circulated in the humidifier is in contact with a continuous flow of ambient air already heated in a solar collector. Then, air is cooled and humidified as it passes upward through the falling saline water in the humidifier. The humidified air is passed through a dehumidifier where it is cooled using cooling water stream in the condenser. The partially dehumidified air leaves the unit, while the distillate (condensate) is collected as fresh water. The saline water leaving the humidifier is collected in a storage tank and recirculated to the humidifier. In this study, air is heated by using a tilted two-pass solar air heater whereas water is only heated by bringing it to contact with air in the humidifier and a inside the storage tank so that a constant temperature in the storage tank is accordingly maintained. The effect of the air temperature on the system productivity is examined at different values of air mass flow rates.

3. SYSTEM ANALYSIS

In order to analyze the proposed desalination system, the following assumptions are made:

- The performance of the unit is time-dependent.
- The climatic conditions are averaged through an hour.
- There is no air leakage from the system, when air passes through the air heater, humidifier and dehumidifier in that sequence.
- Inlet water temperature to the humidifier is equal to the storage tank water temperature.
- Cooling water temperature is constant during the day.
- Temperature gradient inside the water storage tank is neglected.
- There is no leakage of water vapor-air from the system.
- Heat losses or gains from the edges of the solar air heater, water storage tank humidifier and dehumidifier to the ambient are neglected.

The following energy balance equations (1) to (6) is given by Yamali and solmus [10] and it is repeated here for the sake of completeness.

Upper layer of glazing:

$$m_g C_{p-g} \frac{dT_{g2}}{dt} = I\alpha_g A_c + q_{r_{g1-g2}} - q_{c_{g2-amb}} - q_{r_{g2-sky}} + q_{c_{g1-g2}} \tag{1}$$

Lower layer of glazing:

$$m_g C_{p-g} \frac{dT_{g1}}{dt} = I\alpha_g \tau_g A_c - q_{r_{g1-g2}} - q_{c_{g1-a1}} + q_{r_{p-g1}} - q_{c_{g1-g2}} \tag{2}$$

First air pass:

$$m_a c_{p-a} \frac{dT_{a1}}{dt} = q_{c_{p-a1}} + q_{c_{g1-a1}} - \dot{m}_a c_{p-a} \left(T_{a1-e} - T_{a-i} \right) \tag{3}$$

Absorber plate:

$$m_p C_{p-p} \frac{dT_p}{dt} = I\alpha_p \tau_g^2 A_c - q_{c_{p-a2}} - q_{c_{p-a1}} - q_{r_{p-g1}} - q_{r_{p-b}} \tag{4}$$

Second air pass:

$$m_a c_{p-a} \frac{dT_{a2}}{dt} = q_{c_{p-a2}} + q_{c_{b-a2}} - \dot{m}_a c_{p-a} \left(T_{a2-e} - T_{a-e} \right) \tag{5}$$

Base plate:

$$m_b C_{p-b} \frac{dT_b}{dt} = q_{r_{p-b}} - q_{c_{b-a2}} - q_{l_{b-amb}} \tag{6}$$

The following energy balance equations (7) to (9) can be written for the water storage tank, humidifier and dehumidifier , respectively as follows:

Water storage tank:

$$m_{w1} c_{p-w} \frac{dT_{w1}}{dt} = m_{w2}^{\cdot}(t) c_{p-w} T_{w2}(t) + m_{mw}^{\cdot}(t) c_{p-w} T_{mw} - m_{w1}^{\cdot}(t) c_{p-w} T_{w1}(t) - q_{l_{w1-amb}} \tag{7}$$

Humidifier:

$$\dot{m}_a \left[h_{a3}(t) - h_{a2-e}(t) \right] = m_{w1}^{\cdot} c_{p-w} T_{w1}(t) - m_{w2}^{\cdot}(t) c_{p-w} T_{w2}(t) \tag{8}$$

Dehumidifier:

$$\dot{m}_a \left[h_{a3}(t) - h_{a4}(t) \right] = m_{w3}^{\cdot} c_{p-w} \left[T_{w4}(t) - T_{w3} \right] + \dot{m}_c(t) c_{p-w} T_{w3}(t) \tag{9}$$

The various heat transfer coefficients are evaluated as given in Duffie and Beckman [18] and Yamali and Solmus [10]. The basic design and operating parameters used for the simulation study are given in Table 1.

Table 1. The basic design and operating parameters used for the simulation

Parameters	Value
Location of collector	Dhahran (26.3° N ,50.2° E)
Date	June 11
Length of collector	1 m
Width of collector	0.5 m
Air Channel depth	50 mm
Plate-to-cover spacing	25 mm
Absorber Plate/ back plate emissivity	0.95
Glass emissivity	0.9
Absorber Plate absorptivity	0.95
Glass absorptivity	0.05
Transmissivity of glass	0.95
Collector tilt	Latitude of Dhahran
Air mass flow rate	0.027 kg/s
Water mass flow entering the humidifier	0.028 kg/s
Water mass flow rate entering the dehumidifier	0.05 kg/s
Water temperature entering the dehumidifier	20 °C
Water temperature in the storage tank	20 °C
Mass of glass cover	3.75 kg
Mass of absorber plate/ back plate	4.5 kg
Mass of water in the storage tank	500 kg
Over all heat transfer coefficient	0.75 W/m^2K
Area of the storage tank	1 m^2
Glass Heat capacity	800 $J/kg°C$
Water Heat capacity	4178 $J/kg°C$
Air Heat capacity	1006 $J/kg°C$
Absorber plate/ Bake plate Heat capacity	385 $J/kg°C$

Simulation procedure

A computer simulation program based on the energy balance equations has been developed using Engineering Equation Solver (EES) software to study the effect of the various parameters that affect the productivity of the desalination system. EES is a powerful mathematical program that provides many built-in mathematical functions and contains the thermophysical properties of many common substances used in thermal science application.

The time interval is chosen to be one second and the initial values of $T_{g1}, T_{g2}, T_{a1,} T_{a2}, T_{w1}$ are assumed to be nearly equal to the ambient temperature and T_b, T_P are assumed to be 10°C and 15°C above the ambient temperature, respectively as carried out by Yamali and Solmus [10]. However, it must be noted that they used circular pipe correlation to determine the Nusselt number for turbulent flow in the solar air heater,. For the present study, the following correlation has been used (Duffie and Beckman, [18]) :

$$Nu_{g1-a1} = 0.0158\,\mathrm{Re}^{0.8} \tag{10}$$

The convection heat transfer coefficients between the plate and the air stream inside the lower channel of the air heater are also evaluated using the correlation given by equation (10).

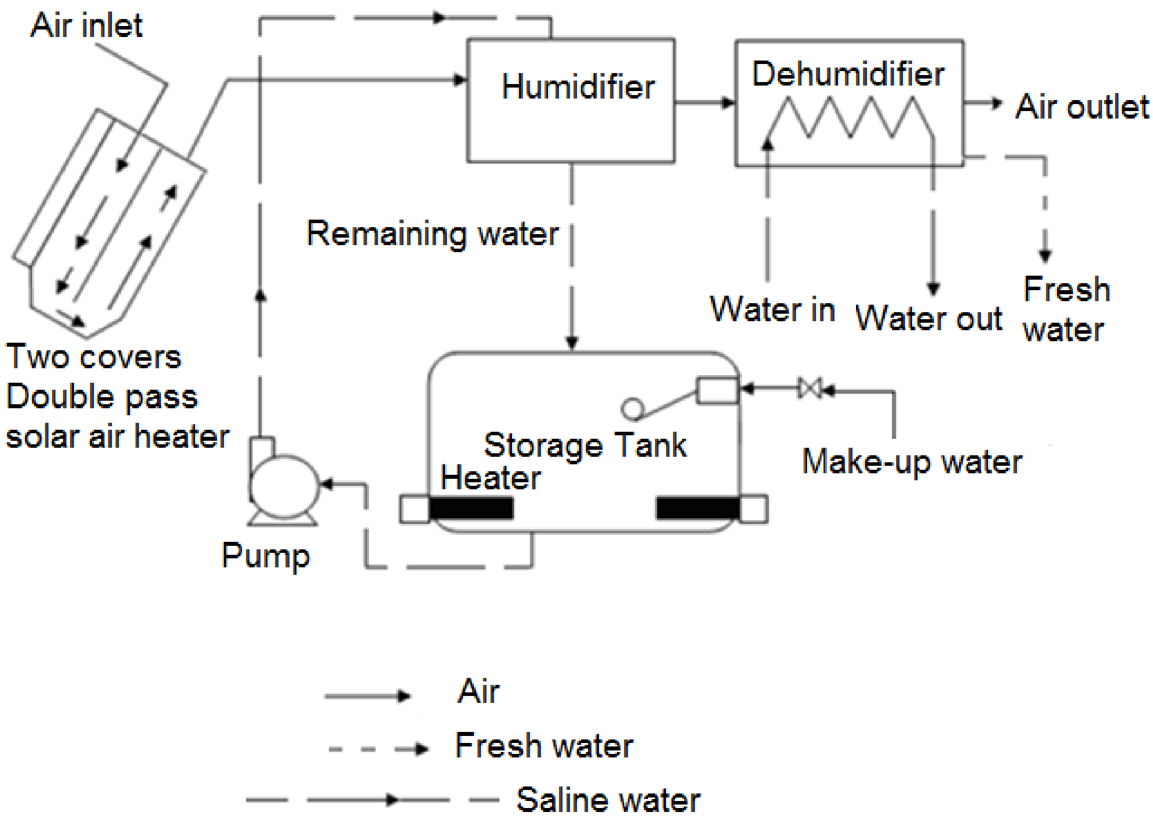

Figure1. Schematic of the desalination system

The solar air heater absorbs the diffuse and direct radiation from the sun. The thermal losses from the cover are considered. In order to reduce the heat loss and increase the area of heat absorbing plate, a tilted solar collector with evacuated double-glass cover (two-pass) is used. Solar radiation passes through the evacuated double-glass cover and is absorbed by the plate. The ambient air is preheated when it flows through the upper channel of the two-pass air heater and is further heated by passing it through the lower channel of the collector. The gap between the lower and the top layers of glass cover is under vacuum. The collector dissipates the heat from the top glass into the environment by the convection and radiation heat transfer.

4. RESULTS AND DISCUSSION

The simulation was performed with the climatic data pertaining to Dhahran, Saudi Arabia for the average day of June. The parameters, solar intensity on the horizontal surface, ambient temperature, relative humidity and wind velocity were used as input parameters for the simulation program. The above climatic variables are given in Table 2.

Table 2, Climatic variables measured in Dhahran for the average day in June

	Solar time, h														
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Insolation, W/m^2	15	66	219	419	619	783	904	959	940	847	683	502	305	114	10
Ambient temperature, °C	30.6	31.6	32.4	33.3	35.6	38.4	39.2	39.5	39.9	40.0	39.9	39.2	38.2	37.2	36
Relative humidity, %	42	32	29	28	25	22	23	24	24	24	23	24	23	24	27
Wind speed, m/s	5.4	5.9	6.3	5.5	5.7	4.1	4.1	4.7	3.9	4.2	5.0	5.3	6.7	5.8	3.8

The performance of the solar air heater is substantially influenced by its orientation and angle of tilt with the horizontal. This is due to the fact that both the orientation and tilt angle change the solar radiation reaching the surface of the collector. Both the orientation and tilt of the solar air heater will affect the desalination system's performance. Solar air heater should be oriented geographically to maximize the amount of daily and seasonal solar energy received.

Extended studies on the orientations were carried out by various investigators where a rule of thumb is given so that the optimum orientation for a solar collector in the northern hemisphere is true south as indicated by Duffie and Beckman (2006). For maximum annual energy availability, the collector surface slope should be equal to the latitude of the location. Hence, simulation was performed for two surface orientations of the two pass solar air heater. The results of the diurnal variation of the productivity of desalination system for two surface orientations of the solar air heater namely, horizontal and tilted to an angle of the latitude of Dhahran, are shown in Fig. 2. It can be seen from the figure that the productivity of the system is increased up to 7% by using a tilted two -pass solar air heater compared to a horizontal flat plate two-pass solar air heater.

Yamali and Solmus [10] studied the effect of various design variables such as air flow rate, water flow rate, water mass in the storage tank, cooling water mass flow rate, wind speed, etc. on the desalination system productivity in detail. Hence, in this paper, the effects of selective surface and the relative humidity of the air at the outlet of the humidifier are investigated.

The objective of the design of a solar collector is to maximize the absorption of solar radiation but minimize thermal loss from the plate to the surroundings. The efficiency of the solar collector depends on the characteristics of the absorbing surface and its optical as well as thermal characteristics.

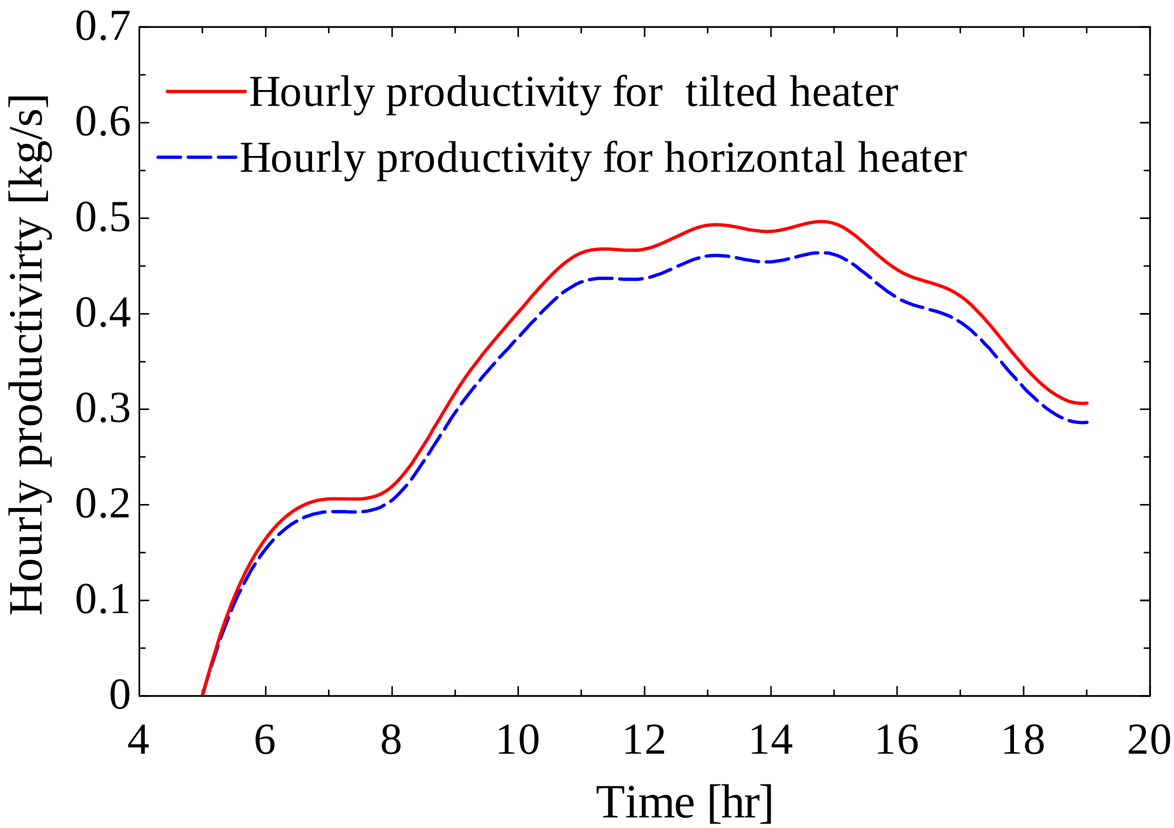

Fig. 2 Diurnal variation of the productivity for horizontal and tilted solar air heater

The efficiency can be increased by increasing the absorbed solar energy and decreasing the thermal losses. The absorber plate surface must exhibit the characteristics of high absorptivity for incoming solar radiation and a low value of emissivity for outgoing re-radiation. Hence, a surface having high solar absorptivity in the visible and near infrared spectrum and low long-wave emissivity in the infrared spectrum, namely a selective surface, is considered to analyze the performance of the desalination system and the results are shown in Fig. 3. It can be seen from the figure that the productivity of the desalination system is increased up to 39% by using a selective and tilted surface two- pass solar air heater compared to a two-pass horizontal solar air heater.

It is to be noted that in [10], it was assumed that the effectiveness of the humidifier is equal to one which is the ideal condition. That means, the air leaving the humidifier has the relative humidity of 100%. Actually, this is difficult to achieve. Hence, the effect of relative humidity of air at the outlet of the humidifier on the desalination system productivity has been studied and the results are shown in Fig. 4.

Figure 4 shows that lower relative humidity of air at the outlet of the humidifier leads to a decrease in the system productivity. For example, when the relative humidity of air reaches 90% at the outlet of the humidifier, the desalination system productivity decreases by 13% and if the relative humidity of air decreases to 80%, the system productivity decreases by 30% with respect to the ideal case. This is due to the fact that the potential for mass transfer in the dehumidifier decreases.

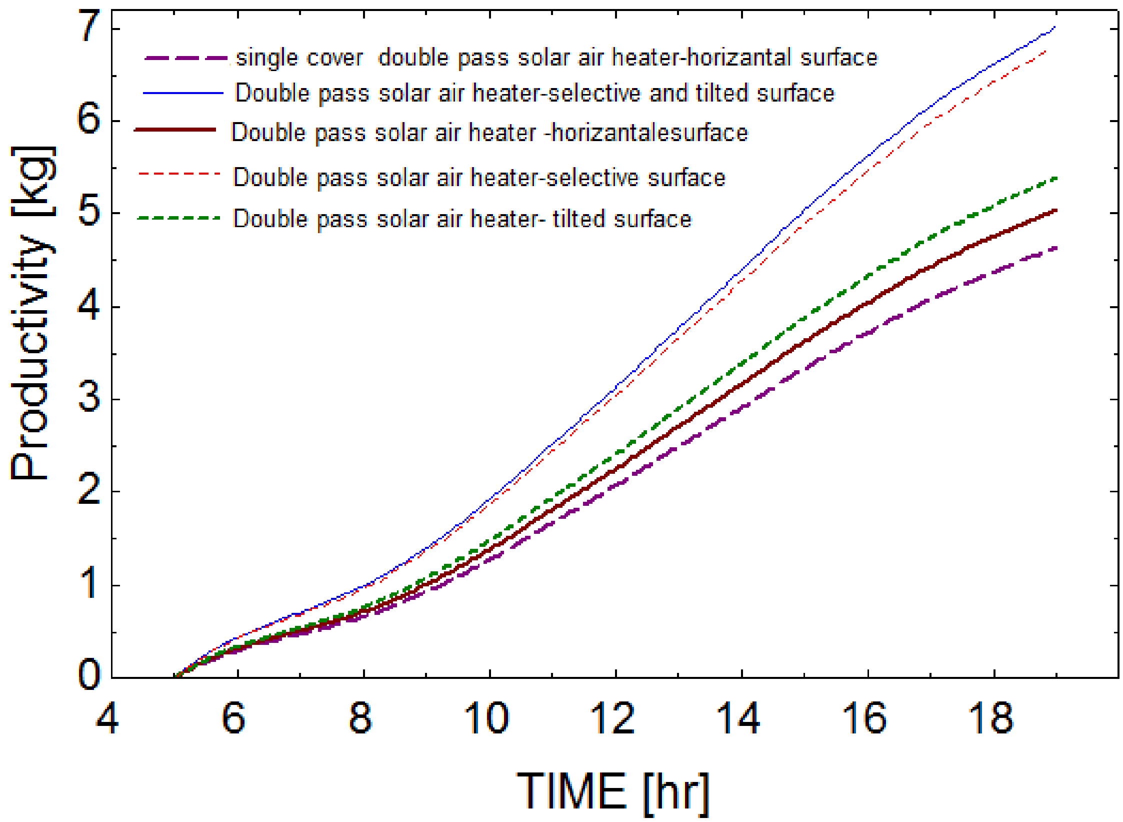

Fig 3. The influence of the selective surface on the system productivity

5. CONCLUSIONS

A simulation study of HDH desalination system is carried out based on energy balance equations and the governing equations are simultaneously solved using Engineering Equations Solver (EES) to investigate the effect of various designs and operating parameters that affect the productivity of the system. It is found that the system productivity is increased up to 7% by using a tilted, two-pass solar air heater compared to a horizontal, two-pass solar air heater. The two-pass solar air heater with selective and tilted surface has a significant influence on the system productivity rather than the two-pass flat plate solar air heater by about 39%. Results also indicate that the relative humidity of air at the outlet of the humidifier has a significant impact on the system performance. This result is important as a guideline for system designers and engineers to opt for high performance humidifiers for better mass transfer and accordingly system productivity.

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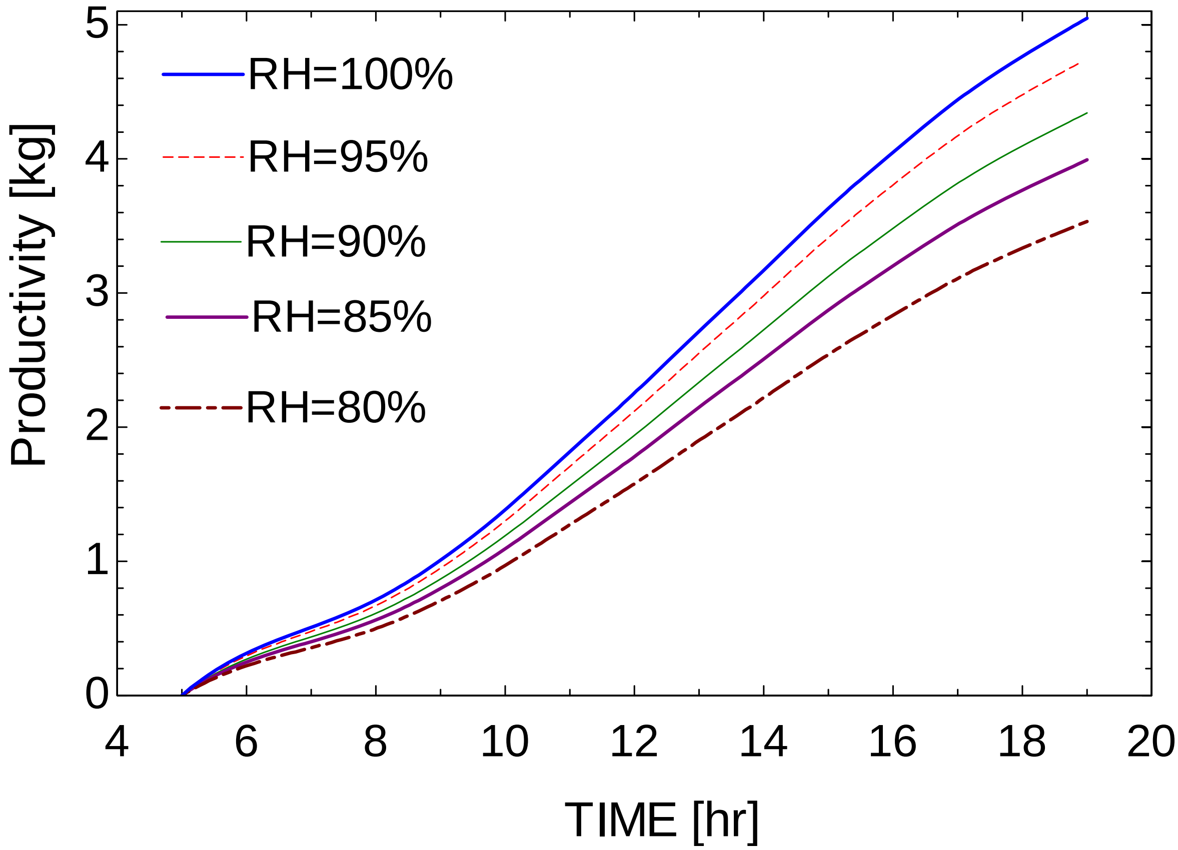

Fig 4.The effect of the relative humidity on the system productivity

NOMENCLATURE

A_c	Collector area, m^2
c_p	Specific heat, J/kg °C
h	Enthalpy of air, J/kg
I	Solar intensity, W/m^2
m	Mass, kg
$\dot{m}$	Mass flow rate, kg/s
Nu	Nusselt number
q_c	Heat transfer rate by convection, W
q_r	Heat transfer rate by radiation, W
Re	Reynolds number
T	Temperature, °C
t	Time, s

Greek letters

α	Absorptivity
τ	Transmissivity

Subscripts

amb	Ambient
a	Air
a1	First air pass
a1-i	Air inlet to the upper channel of the solar air heater
a1-e	Air outlet from upper channel of the solar air heater
a2	Second air pass
a2-e	Air leaving from lower channel of the solar air heater
a3	Air inlet to the dehumidifier
a4	Air outlet from the dehumidifier
g	Glass cover
g1	First glass cover
g2	Second glass cover
mw	Make-up water
p	Absorber plate
w	Water
w1	Water in the storage tank
w2	Water outlet from the humidifier
w3	Cooling water inlet to the dehumidifier

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