*Desalination and Water Treatment*
www.deswater.com

51 (2013) 1319–1326
January


doi: 10.1080/19443994.2012.722775

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# Novel multiple effect direct solar distillation system of integrated solar still and HDH system

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Received 29 February 2012; Accepted 16 August 2012

ABSTRACT

A novel stand alone direct solar distillation system of integrated solar still with humidification–dehumidification (HDH) sub-system is presented and numerically studied. The integrated system utilizes the heat of condensation of the still for additional water production in the HDH sub-system. Both forced and naturally driven HDH air circulation is studied. A numerical model is developed to simulate the integrated distillation system for 24 h of operation on a typical winter and summer days of Abu Dhabi (UAE). The effect of various environmental, design and operational parameters on the system's operational performance, productivity and efficiency is studied. The results show that natural air circulation can replace the forced circulation and simplify the system complexity and reduce its CAPEX and OPEX. For selected operational parameters, the system productivity was found to be near 10 kg/m$^2$.day for a typical summer day which is almost double the normal still production.

*Keywords:* Solar desalination; Humidification–dehumidification; Energy efficiency

## 1. Introduction

While almost 50% of the world's population lives in rural areas with about 91% of the populace living in the developing nations, rural areas in most developing nations are faced with a major water crisis. In addition, and due to the changing climate patterns, many areas on earth are fast coming under severe water stress. Addressing water scarcity in these areas is very challenging, with affordability being one of the major problems facing people whose daily wages is less than \$2/day.

Desalination has become one of the most reliable alternative non-conventional fresh water resources. Market available desalination processes (like MSF, MED or RO) are difficult to be introduced in rural regions as they are complex and expensive for the production of small amounts of fresh water. Simplicity and robustness are the main requisites for any technology to be sustained in areas where access to sophisticated means of maintenance and operational devices is difficult. On the other hand, the use of conventional energy sources (hydrocarbon fuels) to drive desalination technologies has a negative impact on the environment. Thus, if renewable energy is integrated with desalination processes, it could counteract the problems of pollution, fuel depletion and water cost.

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*Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012, Barcelona, Spain*

## 2. Solar distillation

Most of the arid zones receive tremendous amount of sunlight for most of the year. Direct solar distillation, solar stills, as a simple technology, have following advantages:

(i) It suits few families or small communities in remote areas.
(ii) Owing to the use of below boiling temperature and ambient pressure, the process device can be made from inexpensive material.
(iii) It produces fresh water with low cost when compared with the other small capacity solar desalination processes.
(iv) Reliability can be obtained because of the modest level of technology employed, the simplicity of design and the option of being manufactured locally.
(v) It is possible to set up such systems in remote locations completely off the grid and only requiring minimal maintenance in terms of cleaning and salt removal.

Solar stills have been used for desalinating water for centuries and with the maturity of the technology they are not, however, commercialized except for a few individual units. Models and configuration for solar stills have been presented in great detail in the literature [1–9] and different researches have tried to improve the solar still's productivity and efficiency targeting lower water production cost. Different methods were proposed to reduce/recover the condensation energy losses and increase the efficiency, including: a double glass cover, reduced pressure, study of single versus double slope basin stills, added a passive condenser in the shaded region of a single-slopped still by, storing it using various energy storage materials and preheating of the feed water by passing it over the glass cover.

A full recovery of still condensation energy is not possible; however, it could be partially used for additional water production via humidification–hehumidification (HDH) process. A novel integration of solar stills with HDH sub-system in an air loop is developed and studied in this paper.

## 3. System description; forced air circulation

Fig. 1 illustrates the integrated solar distillation system. The system consists of a solar still of 5.4 $m^2$ base areas, vertical humidifier (of 3,000 vertical black cotton ropes of 5.0 mm diameter) of projected area of 4.7 $m^2$ and a vertical dehumidifier of water cooled condenser. Cooling water enters the dehumidifier condenser and is rejected out of the system. Small amount of the preheated outlet cooling water is used as a make-up feed to the system to maintain the humidifier mass and still basin water level constant. Air is forced in the gap between the still glass cover g3 and the system glass cover g1, to partially recover the energy from the glass cover g3. The heated air flows through the humidifier and dehumidifier (condenser), finally flowing out of the system. Solar irradiation incident on the system is partially absorbed and partially transmitted via the glass covers g1 and g3. The transmitted energy is absorbed by the still basin water and the humidifier while a minor part of this energy is lost through the still boundaries.

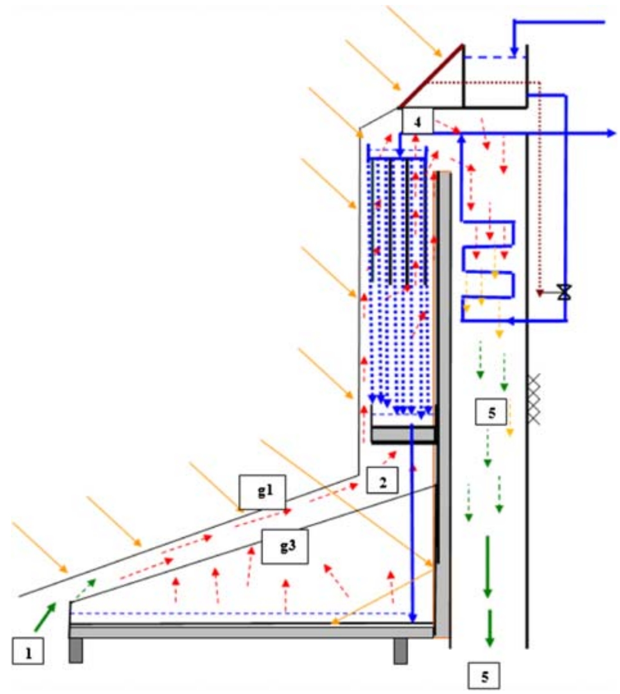


Fig. 1. Schematic representation of the distillation system.

Most of the energy absorbed by the saline water in the basin is transferred to the still glass cover (g3) by evaporation, convection and radiation energy where condensation takes place to produce the still distillate. These energy components are partially recovered by the HDH circulating air. The heated air then flows up to the humidifier where it follows in a non-adiabatic path to gain sensible heat as well as the energy of evaporation to get humidified. Saturated air out of the humidifier then flows to the dehumidifier where it is cooled and dehumidified at the condenser to produce the HDH distillate.

## 4. Numerical modelling

### 4.1. Governing equations

A lumped transient numerical model is developed with different assumptions including: air flowing out of the humidifier is saturated (due to the humidifier's very large surface area) and the dehumidification process takes place along the psychometric saturation curve. Details and justification of these assumptions is reported in reference [8]. For example, glass g1 gains its energy from the partial absorption of irradiation from the sun, radiation from the still glass cover g3 and by convection from the circulation air flowing between g1 and g3. The main losses are convection to the ambient and radiation to sky. The glass cover, g1, transient temperature and the average heat transfer rates are calculated as follows:

$$\boldsymbol{dT_{g1}/dt = Q_{g1}/M_{g1}/M_{g1}Cp_{g}}$$

where

$$Q_{g1} = Q_{abs\ g1} + Q_{rad\ g3_{g1}} + Q_{conv\ air_{g1}} - Q_{conv\ g1\_amb} - Q_{rad\ g1\_sky}$$

Details of these and other governing equations are given in Ref. [8]. An explicit finite difference approach is then used to solve for the sub-systems governing equations with iterative sequence as needed. The transient system productivity is calculated as the sum of still production and HDH production. The system efficiency is the total effective (distillate) energy $\sum Q_{evap}$ divided by the total incident irradiation $\sum$ (IA).

### 4.2. Site weather conditions

Fig. 2 shows collected data from the weather station at Masdar City. The winter data is the average for the month of January 2010 while the summer data is the average for the month of July 2010. The data include solar irradiation intensity, ambient temperature and wind velocity. The curve fitting of polynomial functions was developed for the measured data using MS Excel.

This set of weather conditions show that the daily average irradiation, ambient temperature and wind speed, respectively, are as follows: summer: $I_{avg} = 275\,W/m^2$, $T\_amb_{avg} = 35.9\,^\circ C$ and $V\_wind_{avg} = 3.4\,m/s$; winter: $I_{avg} = 238\,W/m^2$, $T\_amb_{avg} = 17.9\,^\circ C$ and $V\_wind_{avg} = 2.14\,m/s$. Note that irradiation, ambient

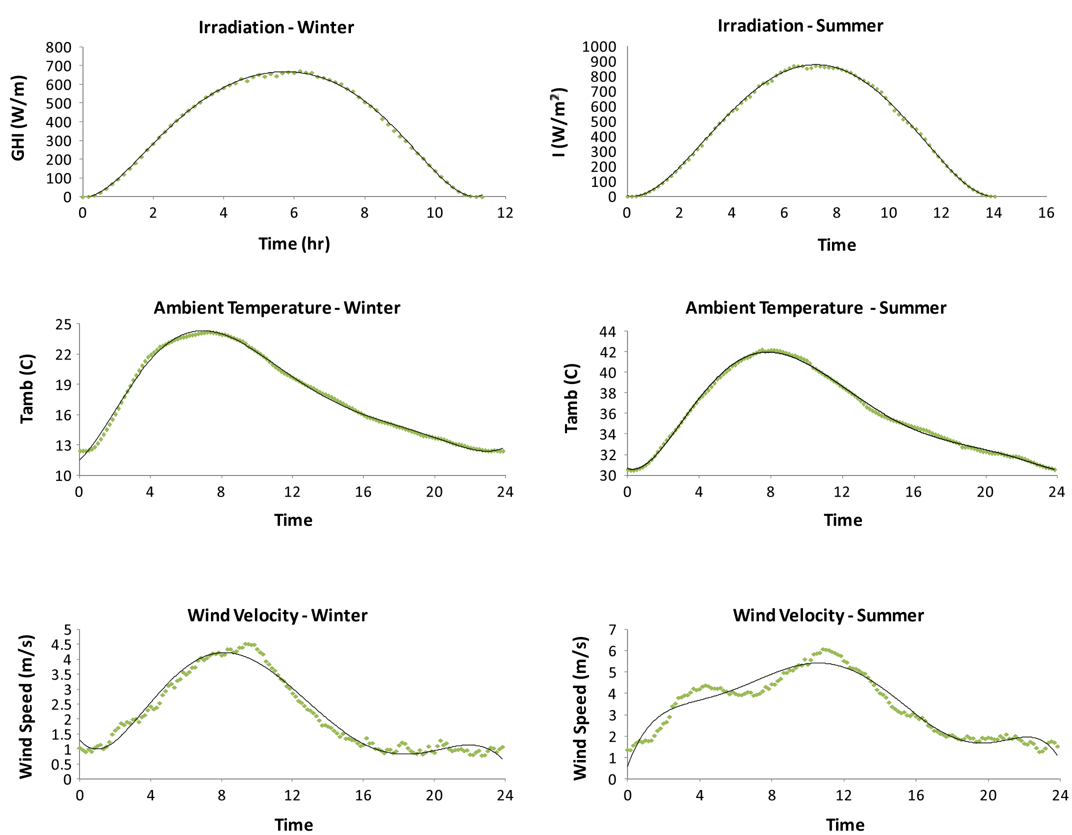



Fig. 2. Weather conditions—Abu Dhabi.

temperatures and the wind speed are higher in summer.

## 5. Results and discussion

Different parameters affect the system productivity and efficiency including: environmental (solar intensity, ambient temperature and wind velocity), design (condenser size, i.e. the temperature difference across the dehumidifier condenser and cooling water mass flow rate) and operational (mass of water in the still basin, mass of water in the in the humidifier and the mass flow rate of circulating air). Table 1 summarizes the studied reference case and the different parameters variation used for the analysis of the distillation system performance.

### 5.1. Temperature distribution

Fig. 3(a) shows the temperature distribution of the different stationary components in the system during the summer conditions for the reference case (Table 1). The total number of sun hours is 14 starting with 0 (on the time axis) which represents the sunrise at 5.30 am and the sunset at 7.30 pm. All components' initial temperatures are at ambient conditions. The temperature difference between the basin and the glass g3 has its maximum value of 12℃ near midday. The energy balance shows that 83% of basin glass energy is a heat of evaporation/condensation while the rest is transferred to g3 as convection and radiation.

Fig. 3(b) illustrates the circulation air at different points in the system. Air at the entrance to the system (point 1) is at ambient temperature *T*_amb, reaches its highest temperature *T*_a2, out of the still, then gets humidified (and partially cools down) as it flows through the humidifier. The humid air flows to the dehumidifier condenser losing part of its condensation energy, and leaves the dehumidifier at a temperature of Δ*T* (Table 1) above ambient.

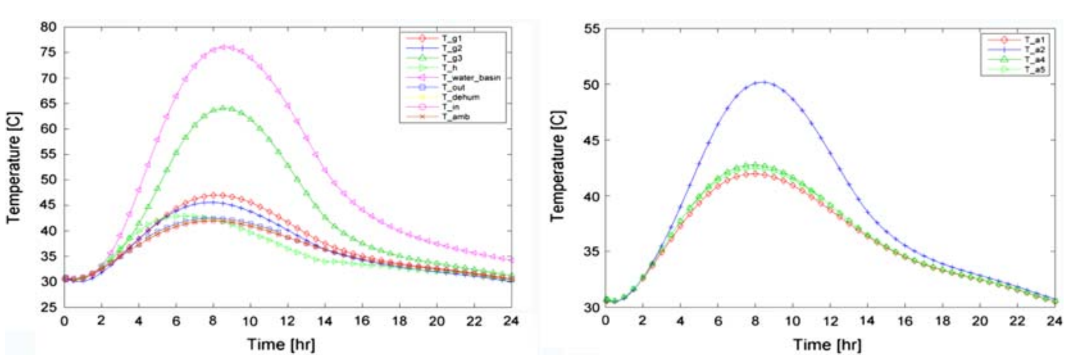
Table 1
Parameters affecting the system performance

| Parameter | Reference value | Other values |
|---|---|---|
| Condenser (*T*_out)–(*T*_in) | 0.5℃ | 1 and 2℃ |
| Mass flow rate of circulating air | 0.5 kg/s | 1.0 and 0.1 |
| Outlet air temperature (*T*_a5) | *T*_amb + 0.5℃ | +1.0℃ and +2.0° C |
| Water height in basin | 3 cm | 5, 1 and 0.5 |
| Humidifier water mass fraction (cotton ropes 100% full of water = 1) | 1 | 4, 2, 0.5 and 0.2 |

### 5.2. System production and performance

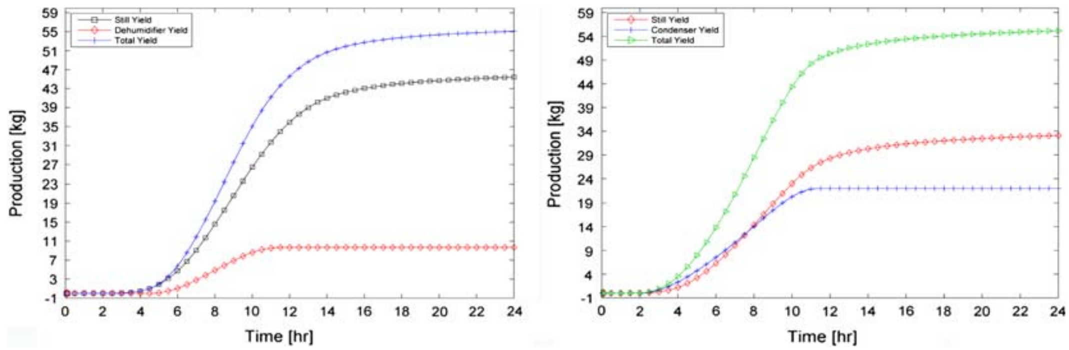
Fig. 4(a) illustrates the summer system accumulative productivity; in the still, HDH and the total system production. The 45.5 kg/5.4 $m^2$ (82.5%) distillate is produced in the still and 9.7 kg/4.7 $m^2$ in the HDH, and the total daily productivity is 55.7 kg/9.7 $m^2$ of system projected area (5.68 kg/$m^2$). This gives a daily average efficiency of 67.3%, which is similar to winter system efficiency. In winter, the 33.09 kg/5.4 $m^2$ (60%) distillate is produced in the still and 22.08 kg/4.3 $m^2$ in the dehumidifier. This gives a total productivity of 55.17/9.7 $m^2$ of system area (5.68 kg/$m^2$ day).

The total productivity in summer is almost the same as that in winter due to the balance of solar irradiation (input energy) and ambient temperature and wind speed (energy losses). It should be noted that these results are specific to the typical weather conditions used for Abu Dhabi City for these days and it



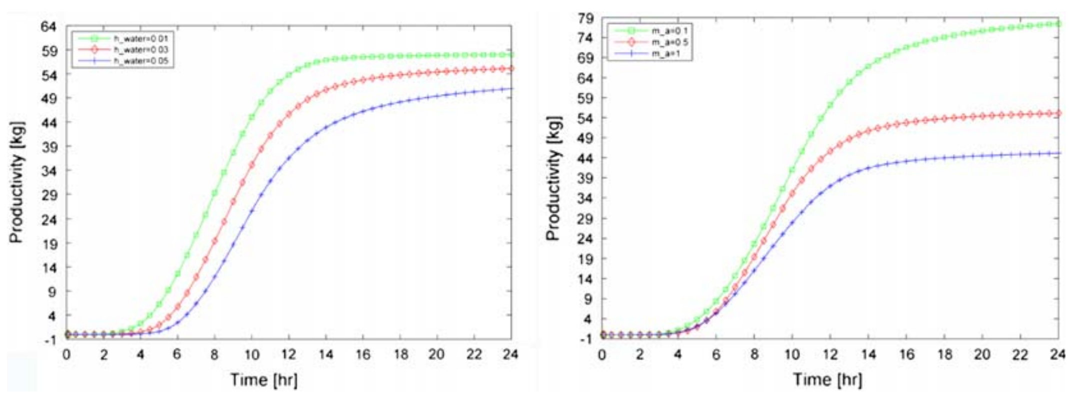

(a) Component Temperature (b) Circulating Air Temperature

Fig. 3. Temperature distribution in the systems components.




(a) Summer (b) Winter

Fig. 4. System productivity.




(a) Initial Water Height in the Basin (b) Mass Flow Rate of Circulating Air

Fig. 5. Effect of operating parameter on productivity.

could be different in other locations or different weather conditions.

The system performance was found to be influenced by two main operational parameters; the height of saline water in the still basin and the mass flow rate of circulating air. Fig. 5(a) shows the effect of initial water height in the still basin on the still productivity, in agreement with different publications including Fath et al. [3–6]. Lower basin water mass has also a relatively lesser initial lag in production while higher water mass has a higher thermal capacity and thus continues producing distillate after the sunset.

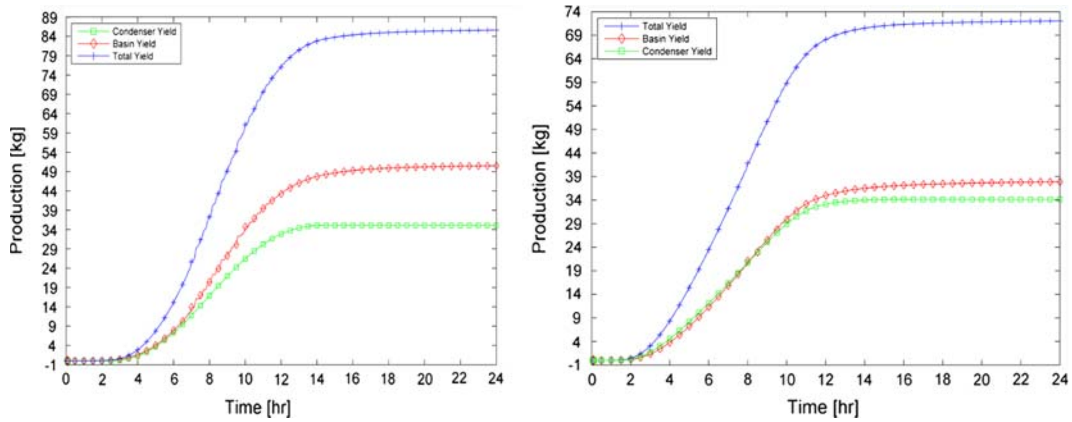
Fig. 5(b) shows the effect of changing the circulating mass flow rate on the total productivity. Decreasing the mass flow rate from 0.5 to 0.1 kg/s significantly increases the productivity from 55.13 to 74.4 kg (35%). It should be noted that reducing the mass flow rate affects the economics of the unit for possible utilization of natural air circulation instead of forced circulation. The results show the insignificant effect of the mass of water in the humidifier and the dehumidifier condenser cooling water flow rate on productivity.

For a typical selected condition of 1.0 cm water height in the basin and 0.1 kg/s mass flow rate of circulating air, the summer results, Fig. 6, show the total production is 85.36 kg/9.7 $m^2$ day which is equivalent to 8.8 kg/$m^2$.day. For winter, the total production is 72 kg/9.7 $m^2$ day which is equivalent to 7.43 kg/$m^2$ day.

## 6. System simplification; natural air circulation

### *6.1. Introduction*

Fig. 7 shows the schematic of the simplified solar distillation system to suits natural air circulation. The HDH components (humidifier and dehumidifier) are shifted to the down-comer side to enhance the natural air circulation as both humidifier and dehumidifier increases air density (due to temperature reduction and added humidity). Air density difference between the riser (1) (the channel between the two glass covers g1 and g3) and down comer (2) leads to the development of a driving pressure difference causing natural air circulation expressed as:




(a) Summer (b) Winter

Fig. 6. System productivity for selected operational parameters.

$$\Delta P_{\text{gain}} = (\rho_2 - \rho_1) * g * H$$

The resisting pressure through the system channels is:

$$\Delta P_{\text{Res}} = \sum K_e (\text{m})^2,$$

where $\sum K_e$ = sum for the loop equivalent losses coefficient.

Equating the sum of the pressure gain to the sum of the pressure loss, at each time step, the circulating air mass flow rate is calculated.

*6.2. System performance*

The temperatures of the circulating air, still water and glass covers in the system are plotted against time in Fig. 8. The transient trend seen during the day nearly follows the sinusoidal profile of the solar radiation profile. After the sunset, the temperature drops in all the components and the residual heat decay with time can be observed. The temperature profile for the summer conditions is similar to that of the winter conditions but with elevated temperatures. The maximum water basin temperature in the summer is about 68℃ while in the winter it is about 55℃.

The naturally circulated air mass flow rate varies with the driving air density force. Fig. 9 shows the air mass flow rate profile with time for both the winter and summer conditions. The maximum air flow obtained is near 0.4 kg/s in both the winter and summer. The high maximum air flow rate in the winter

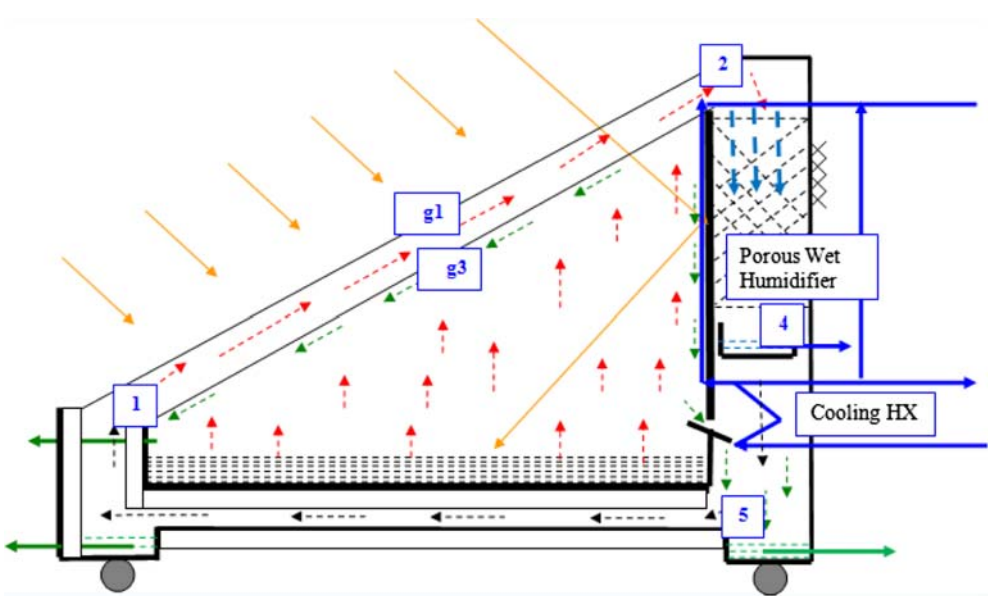



Fig. 7. Schematic representation of the multiple effect solar distillation system.

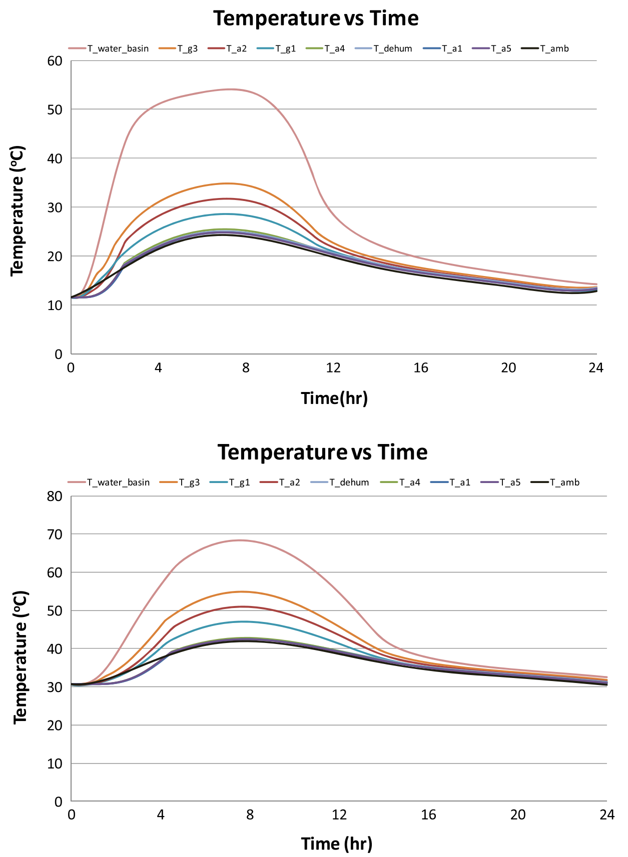



Fig. 8. Temperature distribution of air, glass and basin water (winter-top and summer-bottom).

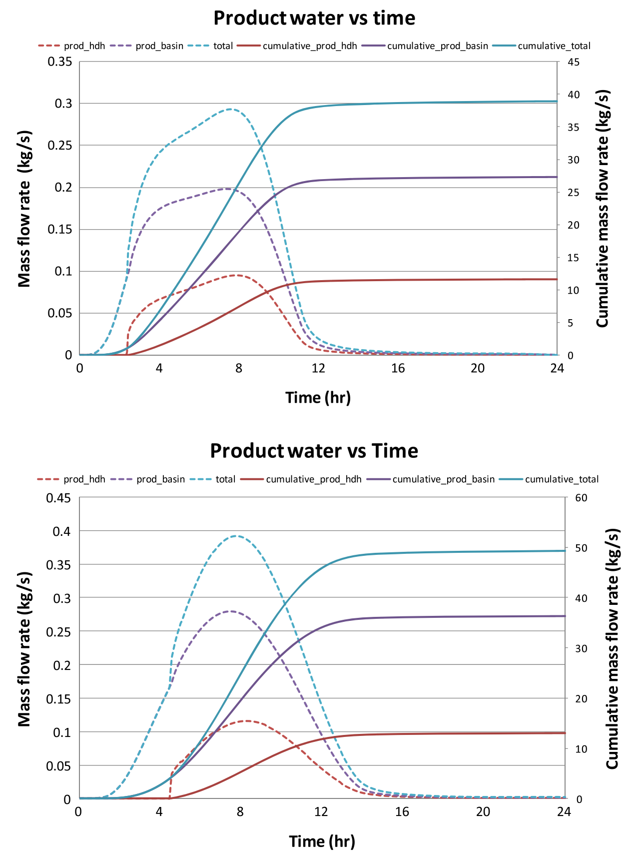



Fig. 10. Water production from still and HDH system (winter-top and summer-bottom).

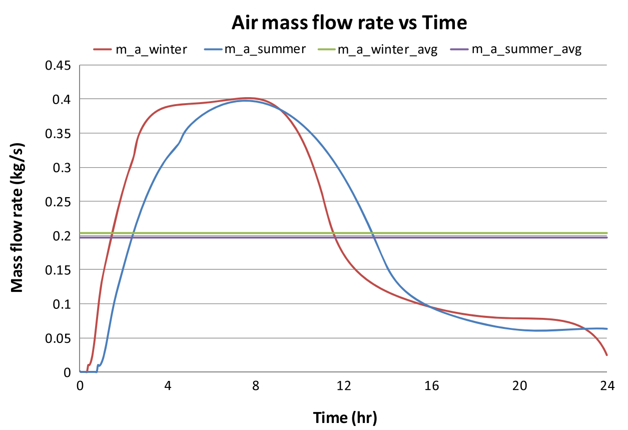



Fig. 9. Air mass flow rate in HDH system for the summer and winter conditions.

condition is due to the much lower cooling water temperature in the winter than summer (less than 25°C as compared to 42℃ in summer) which provides a higher temperature difference, and consequently a higher driving pressure. The average mass flow rate is near 0.2 kg/s. This mass flow rate can then replaces that of forced convection system presented above.

### 6.3. Water productivity

The productivity of the water follows a similar trend to that of the circulating air mass flow rate. The

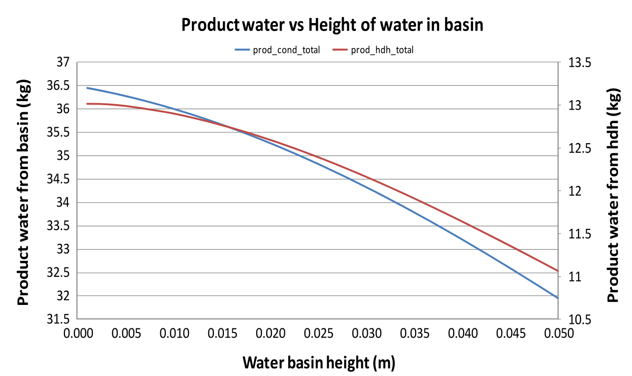



Fig. 11. Product water obtained for different height of water in basin.

product water obtained in the still and HDH system for the winter condition, Fig. 10, is 27.30 and 11.81 kg, respectively, and the total product water obtained is 39.11 kg (9.85 kg/($m^2$ day)). For the summer conditions, the values are 36.27 and 12.98 kg, respectively, and the total product water obtained is 49.3 kg (9.85 kg/($m^2$ day)). Decreasing the height of the water in the basin, the total product water increases with higher air flow rate, Fig. 11.

## 7. Conclusion

A novel solar distillation unit of solar still integrated with HDH sub-system is presented and simulated for 24 h of operation. The main objective is to improve the thermal efficiency and production by recovering the waste heat. The system is studied under both forced and natural air circulation for the real environmental data of Abu Dhabi City in both the summer and winter conditions. For a typical selected operating condition and with natural air circulation, the results show that the daily average air mass flow rates is around 0.2 kg/s and 9.85 kg/($m^2$ day) water production.

### Nomenclature

| | | |
|---|---|---|
| $A$ | — | area, $m^2$ |
| $C_p$ | — | specific heat capacity, J/kg K |
| $D$ | — | diffusivity, $m^2/s$ |
| $g$ | — | gravitational acceleration, $m/s^2$ |
| $H$ | — | height, m |
| $I$ | — | solar irradiation, $W/m^2$ |
| $K$ | — | equivalent flow resistance coefficient |
| $M$ | — | mass, kg |
| $m_a$ | — | mass flow rate of circulating air |
| $P$ | — | partial pressure, Pa |
| $Q$ | — | heat flux, W |
| $T$ | — | temperature, ℃ |
| $t$ | — | time, s |
| $V$ | — | velocity, m/s |
| ZBD | — | zero brine discharge |

### Greek letters

| | | |
|---|---|---|
| $\Delta$ | — | difference |
| $\rho$ | — | density, $kg/m^3$ |

### Subscripts

| | | |
|---|---|---|
| a, air | — | air |
| abs | — | absorption |
| amb | — | ambient |
| avg | — | average |
| conv | — | convection |
| evap | — | evaporation |
| g | — | glass |
| g1 | — | system glass cover |
| g2 | — | humidifier glass cover |
| g3 | — | basin glass cover |
| in | — | inlet |
| out | — | outlet |
| rad | — | radiation |
| Res | — | resistance |
| sky | — | sky |
| 1 | — | inlet to the system |
| 2 | — | humidifier inlet |
| 4 | — | humidifier exit/dehumidifier inlet |
| 5 | — | dehumidifier exit |

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