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# New solar desalination system using humidification/ dehumidification process

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**Abstract**
An innovative solar desalination system is successfully designed, manufactured and experimentally tested at Makkah, 21.4 ºN. The system consists of 1.15 $m^2$ flat-plate collector as a heat source and a desalination unit. The unit is about 400 liter vertical cylindrical insulated tank. It includes storage, evaporator and condenser of hot salt-water that is fed from the collector. The heated water in the collector is raised naturally to the unit bottom at which it is used as storage. A high pressure pump is used to inject the water vertically up through 1-mm three nozzles inside the unit. The hot salt-water is atomized inside the unit where the produced vapor is condensed on the inner surfaces of the unit outer walls to outside. The system was experimentally tested under different weather conditions. It is obtained that the system can produce about 9 liter a day per quadratic meter of collector surface area. By that it can produce about 1.6 liters per kWh of solar energy. Moreover the water temperature has a great effect on the system performance although the scaling possibility is becoming significant. By that way the cost of a liter water production is relatively high and is obtained as 0.5 US$.


**Keywords:** Flat-plate collector; Solar desalination; Humidification-dehumidification; Multi-effect; Thermosyphone phenomenon.

## 1. Introduction
Water desalination is the unique method to produce drink water in KSA and gulf countries but it becomes a dramatic problem in the Middle East. It consumes a huge amount of energy and national income. Using of solar energy in that important sector can play a considerable role to save energy.
Process of consequence humidification-dehumidification was used efficiently to desalinate the salt water using solar energy. The productivity is widely improved using this process; it produces many times of the simple distiller productivity. Perhaps the initial and running costs are raised but in general the system efficiency is improved [1]. In that process the salt water is heated in a solar collector before it is flashed and evaporated simultaneously inside a separate chamber. Then the vapor is condensed to provide desalinated water.
In that work the process is considered to design, manufacture and test an efficient desalination chamber. In this chamber an evaporator and condenser are located in the same place to eliminate the heat losses as concluded by the author [2, 3]. In addition the injection is occurred vertically up to duplicate the contact time between the injected hot water and the surroundings as indicated by the author [4].

Forced convection has no significance effect in system performance [5, 6], so it is not considered in this work. Moreover ambient air is used to cool the condenser surface because it was found that the condensation is not a problem for such systems in the edited systems while the evaporation was found low and limited [4]. As indicated by [4, 7-10], mixing hot air with the injection water improves the evaporation and condensation processes and is used as a media of heat and mass transfer. On the other hand it raised the system initial and running costs. As concluded by authors, that method can improve the performance of the system. Therefore it is taken in consideration in this work by mixing the vapor with the enclosed air in the desalination chamber. On the other hand, thermosyphone solar water heater is considered in this research as used by [2, 10].

In the humidification/dehumidification process the salt water is heated in a collector and is flashed in a separate chamber as evaporator, and consequently condensed on a cooled surface as a condenser. By that way the quality of the produced water can be controlled and improved. Many researchers used the flat-plate collector as a heat source [11-13] while others used concentrating parabolic trough collector [14, 15]. It is considered in the work that the desalination unit includes both evaporator and condenser. That design was considered by the researchers [1- 4, 16, 17] where it was used a separate chamber for each by others [18, 19]. The comparison between two designs was not developed for the published work in terms of the productivity. The system has both solar loop and desalination chamber, the system performance includes the performance of both collector and desalination chamber.

From above description an efficient system can be developed if it considers the advantages of the previous edited research. Therefore the present system includes a flat-plate collector that heats the salt water and feeds it naturally to a storage tank. In the storage tank the hot water is injected through nozzles that evaporate the hot water. The evaporated water is condensed between the tank walls.

## 2. System setup and operation

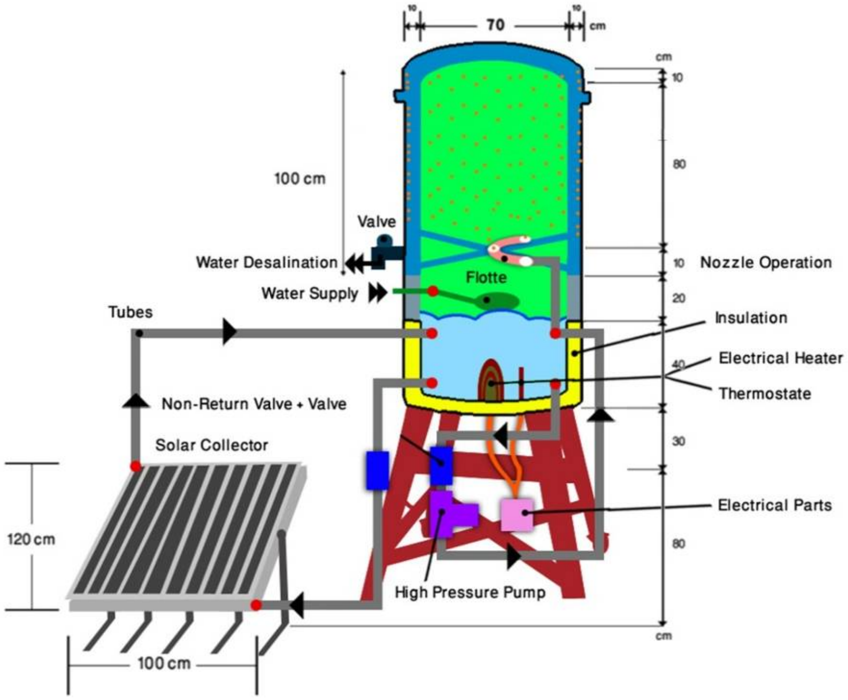
The system consists of 1.15 $m^2$ flat-plate collector and a storage/desalination tank as shown in Figure 1 (a, b). The collector has a maximum efficiency $F_R\tau\alpha$ of 0.78 and heat loss coefficient $F_RU_L$ of 7.5 $W/m^2 K$. The storage/desalination tank is about 400 liters and made from galvanized steel with about 70 cm diameter and about 160 cm height. About 40 cm height (about 100 liters) of water is considered as storage of hot water at the bottom of the tank. A back up of fresh water into the tank with a float controls the water level inside the tank bottom. The rest of the tank is used as evaporator. The bottom of the tank has a drain for tank washing.

The heated water inside the collector is raised naturally to the storage part where the cold water from the tank bottom is fed to the collector. The hot water inside the storage part is pumped by 70-W high pressure pump (located outside the tank) to three 1-mm nozzles. The nozzles are installed inside the tank just above the water at a height of 60-cm from tank bottom. The nozzles are carefully supported with the pump outlet pipe. The nozzles are installed to flash the water vertically up to let water to be evaporated during up and down paths. The storage desalination tank consists of two cylindrical walls. The wall surrounded the storage part is insulated by glass wool insulation where the rest part is left empty. This part is used as condenser. The vapor evaporated inside the chamber goes up and exits from inner wall through upper outlets and condensates on the inner surface of the outer wall and on the outer surface of the inner wall. The condensate water is collected down the walls to outside of the chamber. Additional air should be forced inside the tank to improve the evaporation and condensation process from a hole in the storage walls. Moreover a 3-kW electrical heater is installed on the tank bottom to heat the salt water to study the effect of higher temperatures and if a constant water temperature is proposed. The system is installed and tested in the solar lab of the college of Engineering and Islamic Architecture, Umm Al-Qura University, Makah 21.4 °N.

## 3. Measurements and instrumentations

To testify the system, productivity of the system is measured and the system efficiency is estimated. Additionally the performance of the collector and desalination unit is considered in the study. Therefore, the weather conditions of solar radiation and ambient temperature are taken from the University weather station for the corresponding measurement days.

The measured temperatures are the temperatures of the storage-water inner enclosure of the desalination chamber and outlet desalinate water. All temperatures are measured using calibrated k-type thermocouples. The productivity is simply measured by collecting the desalinated water in a scaled beaker. Moreover the moisture inside the evaporator and condenser sides is measured to explore the status of evaporation and condensation using a relative humidity anemometer. In addition, the water salinity is measured by a TDS meter before and after desalination process.




(a)

(b)

Figure 1. (a) Schematic diagram of the solar desalination system; (b) Photograph of the solar water desalination system

## 4. System design

The system includes a thermosyphone solar water heater and a desalination tank. A 10-bar high pressure pump is used to be able to pump the hot-salt water from the tank to three 1-mm nozzles inside the tank at humidifier section. In the following subsections design of each system component is demonstrated.

### *4.1 Solar water heater*

The natural circulation is chosen in the solar water heater due to its high efficiency. An available flat-plate collector with 1.1 $m^2$ is used to heat about 100 liters of salt water inside the desalination tank. The salt water volume in the tank is determined according to the collector surface area of 1.1 $m^2$. That quantity of water is enough for the pumping circulation. Regarding the tank height, the evaporation is improved by increasing the path length of the injected hot water that improves the contact time between the water and surroundings. Therefore the height is taken as 160 cm where the inner diameter is limited to 50 cm. With that diameter the height of the water inside the storage tank is switched to 40 cm to make 100 liters. The heat gain from the collector ($Q_u$) can be estimated from the Hottel-Whillier equation as:

$$Q_u = A_c\left(F_R(\tau\alpha)I_t - F_R U_L\left(T_i - T_a\right)\right) = m_w C_p\left(T_o - T_i\right) \tag{1}$$

where $A_c$ is the collector surface area, $I_t$ is the total radiation incident on the collector and $T_i$, and $T_a$ are the inlet and ambient temperatures respectively.
Accordingly the energy gained from the tank to the evaporator ($Q_e$) can be simply obtained as:

$$Q_e = m_w C_p\left(T_w - T_o\right) \tag{2}$$

where $m_w$ is the water mass flow rate inside the collector, $T_w$ is the tank temperature and $T_o$ is the collector outlet temperature.

### *4.2 Evaporator*

The evaporator occupies the rest of the tank which its height is 100 cm. Three 1-mm nozzles inject the pumped water to upward. Lower diameter nozzles can be blocked from the salt in water. On the other side if more than three nozzles are used the flow paths of nozzles can be intersecting. Accordingly the outlet flow from the nozzle can be considered as a cone. The angle of the cone head is difficult to determine and that is based on the flow pressure and flow rate. Therefore the number of the nozzles cannot be estimated accurately. Therefore three nozzles can be considered enough for 50-cm diameter tank.

### *4.3 Condenser*

The inner surface of the outer walls of the tank is mainly used to condense the raised vapor that has no other path. The outer surface of the inner walls is also considered as a condensing surface. The height of the available surface area can be estimated as 100 cm, the rest of walls above the storage section. The tank outer diameter is known as 70 cm. To examine if that area is enough for the condensation, design steps must be provided. Moreover the desalinated water temperature is assumed constant as 30 ºC. The condensate water is assumed as laminar film condensation on a cylindrical outer and inner surface. Therefore the latent heat of condensed desalinated water, $Q_1$ equals to the heat of the condensed water, $Q_2$ (heat balance of the condenser surface). The heat transfer coefficient formula can be found from Ref. [20].

$$Q_1 = M_d h_{fg} = Q_2 \tag{3}$$

where

$$Q_2 = A h_x\left(T_{sat} - T_s\right) \tag{4}$$

$$h_x = \left[\frac{g\rho_L\left(\rho_L - \rho_v\right)\left(k^3 h'_{fg}\right)}{4\mu_L\left(T_{sat} - T_s\right)x}\right]^{0.25} \tag{5}$$

$$h'_{fg} = h_{fg}\left(1 + 0.68 J_a\right) \tag{6}$$

$$J_a = \frac{C_{pL}\left(T_{sat} - T_s\right)}{h_{fg}} \tag{7}$$

where: $A$ = area of annular cylindrical space of condensation ($m^2$), $M_d$ = condensate rate (kg/s), $h_{fg}$ = latent heat of the condensate (J/kg), $h_x$ = heat transfer coefficient of condensation at a distance x from the surface edge (W/m$^2$.K), x equals 100-cm, $T_{sat}$ = saturation temperature at atmospheric pressure of 100 kPa (ºC), $T_s$= tank surface temperature, it is assumed constant and relatively equals to the ambient temperature as 40 ºC (ºC), $\rho_L$ & $\rho_V$ = liquid and vapor density (kg/$m^3$), $k$ = thermal conductivity of the condensate ($W/m.K$), $\mu$ = Viscosity of the condensate (Pa.s).

Inserting water properties to the above equations, $h_x$ can be estimated and $M_d$ is obtained accordingly. By that method $M_d$ is estimated as 0.1167 kg/s or 420 kg/h. That value is larger than the system expected production. The surface area seems more enough as a system condenser.

**5. System testing**

The system was tested during different seasons to testify the system under different seasonal conditions. To start the system operation the tank bottom is filled with fresh water to the switched level, the backup float adjusts the water level. After sunrise the collector starts to heat the water inside the tank. The system is normally left a complete sunny day before developing the experiments.

Generally the system is started by switching-on the pump to inject the hot water. Normally the system spends about half an hour to start producing desalinated water. In that time the system is warming up. Decreasing the weight of the system can decrease the warming-up time. On the other hand the experiments are developed along the day.

To study the system performance, the system efficiency may be demonstrated. The system efficiency can be defined as:

$$\textit{System Efficiency } (\eta) = \frac{M_d h_{fg}}{\left(I_t A_c + E_p\right) or \left(HeaterPower + E_p\right)} \tag{8}$$

where: $I_t$ is the total solar radiation (W/m$^2$), $A_c$ is the collector surface area (m$^2$) and $E_P$ is the pumping energy consumption where the pumping power is constant during the system operation, 70 W.

Figure 2 presents the performance of the system including the system production and efficiency, and the accumulated water production along the day as well. The trend of the system efficiency variation is relatively similar to the water production variation. The trend is normally similar to the solar radiation variation. The maximum of efficiency and $M_d$ are found around the solar noon as expected. The accumulated water production during the day is presented. As shown in the figure the system can produce more than 9 liters at a moderate day length in autumn season, about 9 liters per quadratic meter of collector surface area. That value can be accepted according to the published values in references [2-4, 11-13, 17]. The system efficiency is good (up to 40%) due to lower heat losses as shown in Figure 2 as proposed. Higher operating pressure is used and that is the atmospheric pressure, the desalination unit is open to the atmosphere. If lower pressure (vacuum pressure) is used the production is improved and efficiency accordingly. Also the temperature of desalinated water is low and equals about 30 ºC. That lowers the efficiency according to Eq. (8). At 8 o'clock early morning the efficiency is 24% and is lowered at 9 o'clock where the solar radiation is still low. That because $M_d$ is collected actually from sunrise to 8 o'clock, the experiment-start time. The desalination chamber is relatively cold in that time and that makes much condensation of evaporated water. That is similarly occurred at 18 o'clock where the solar radiation and the ambient temperature are lowered.

Similarly the system is tested during the spring at May as illustrated in Figure 3. The system production is slightly improved because the ambient temperature is raised in that season. The desalinated water is slightly higher than 9 liters a day before 6 PM. The variation is smooth along the day due to clear days of the experiments. Accordingly the temperature of the hot water ($T_w$), condenser enclosure ($T_v$) and the ambient temperature ($T_a$) were measured as presented in Figure 4. Similarly the temperatures are varied around the solar noon. They are maximized at about 3 PM where the ambient temperature is maximized.

The hot water temperature is relatively low, it is lower than 65 ºC. That value is expected from a natural circulation (thermosyphone) solar water heater without any auxiliary heater.

The relative humidity was measured inside the condenser enclosure as presented in Figure 5 to demonstrate the effectiveness of the proposed condenser where the condensation process is based mainly on the ambient temperature. The relative humidity is low (up to 60%) along the day. That provides a fact that the condenser surface area is large enough to condensate the evaporated water vapor. As shown in the Figures 4 and 5 while the ambient temperature is maximized around the solar noon, the relative humidity is maximized also depending on that variation. Moreover that rise in relative humidity is based also on the rise in evaporated water in that period due to rise in the water temperature. At afternoon the relative humidity is higher than that before noon due to relative higher ambient temperature in that time. The measurement of the relative humidity inside the evaporator side indicates that it equals about 100%. That explains that the evaporation process is effective. In addition the water hardness, TDS, of the desalinated water is about 10 ppm where drink water is used in the system. That can be changed if salt water is used in the experiments.

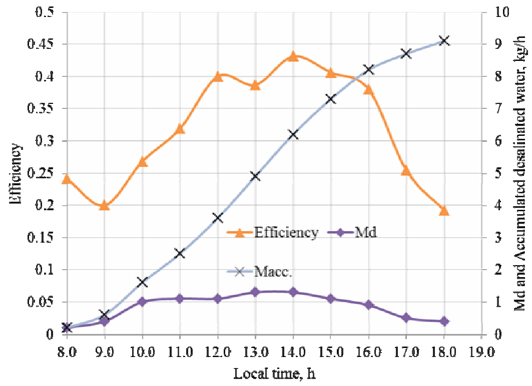



Figure 2. Time variation of the system production and efficiency using solar energy only at Sept. 16, 2010

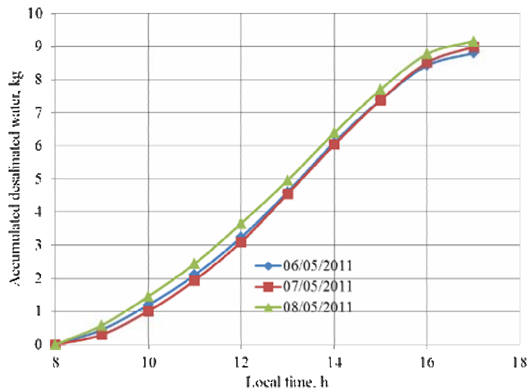



Figure 3. Performance of the system at May days

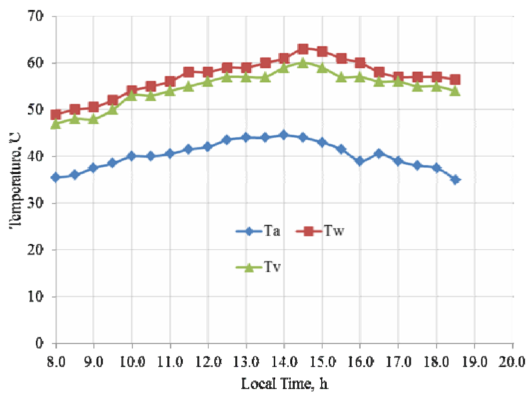



Figure 4. Time variation of the system temperatures using solar energy only at Sept. 16, 2010

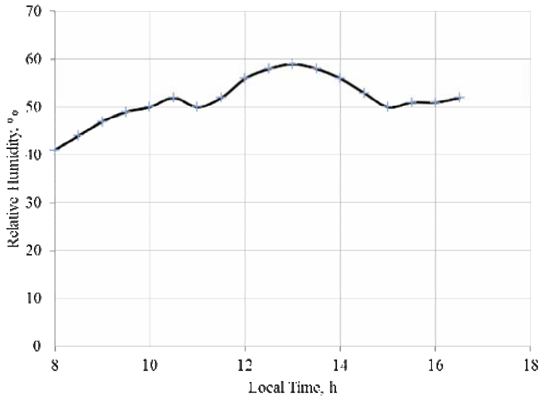



Figure 5. Time variation of relative humidity inside the condenser humidity using solar energy only at May 7, 2010

## 6. Error analysis of the measurements

The measurements include water, and vapor temperatures, solar radiation, relative humidity and desalinated water volume. The consumed electrical energy of the heater is measured by kWh meter. In addition the system efficiency is estimated from those parameters. The uncertainty of each instrument as presented in their catalogues is indicated as follows:

1- Water temperature ($T_w$)

k-thermocouple accuracy equals ±0.5 ºC and resolution of 0.1 ºC that produces uncertainty $U_T$ of ±0.5 ºC of temperature.

2- Total solar radiation ($I_t$)

Pyranometer error, $U_{It} = \pm\ 0.1$ w/m$^2$.

3- Relative humidity and vapor temperatures

Thermal anemometer resolution is 0.1 ºC and accuracy of 0.5 ºC that obtains about ±0.5 ºC uncertainty for vapor temperature. Accordingly 0.1 % resolution and 5% accuracy for relative humidity and that makes about ±5% uncertainty of relative humidity.

4- Desalinated water mass and salinity

It is considered that the measuring error in water mass flow rate is the same as the volume flow rate. Therefore the measuring error in the mass flow rate is the error of the beaker and it can be considered as the resolution error. Therefore mass flow rate error, $U_{Md} = \pm 0.05$ kg where TDS meter has 2% accuracy and 10 PPM resolution.

5- kWh meter

Measuring error, $U_{kWh} = \pm 0.001$ kwh

The system efficiency is estimated from Eq. (8), therefore the uncertainty in the system efficiency might be estimated from that equation. The 'first derivative method' is used to estimate the efficiency uncertainty $U_\eta$ as a resultant error [21]. The measuring errors in the enthalpy and in the collector surface area are ignored.

$$U_\eta = \sqrt{\left(\frac{\partial \eta}{\partial M_d} U_{M_d}\right)^2 + \left(\frac{\partial \eta}{\partial I_t} U_{I_t}\right)^2} \qquad (9)$$

It is clear from Eq. (9) that $U_\eta$ depends on $h_{fg}$ which is a function of desalinated water temperature. Also $U_\eta$ is based on the varied $I_t$ along the day. Therefore $U_\eta$ is varied during the experiments. The desalinated water temperature is not largely varied, it is around 30 ºC but $I_t$ is widely varied from zero to about 950 W/m$^2$. Then it can be estimated the error of the daily efficiency. If the daily solar radiation is about 5 kWh with about 10 kg of produced desalinated water. It can be easily estimated $U_\eta$ and equals about ±0.002. If the electrical heater is used, $U_\eta$ can be estimated by replacing the symbol $I_t$ with kWh in Eq. (9).

**7. Effect of salt-water temperature**

The electrical heater is used to study the system performance at preset heating temperatures. By that way it can study the system performance for higher temperatures. The same above parameters are measured for the system for the water preset temperature of 75 ºC. The experiments were developed for about four hours to perform the measurements at the steady state. It is clear that the system reached the steady state, constant temperature, after two hours. After that the system performance is relatively constant. That is clearly presented in Figure 6, the system output of water production is relatively constant at 4 kg/h. Accordingly the system efficiency is constant at about 43%. The accumulated produced water is relatively linearly varied. The system can produce about 4 liters per hour and about 96 liters each 24 hours (day).

The hot-water and vapor temperatures seem constant at the steady state and fortunately the ambient temperature is relatively constant. The hot-water temperature remains around 75 ºC and that exceeds about 5 ºC from the vapor temperature. That is resulting from heat and mass transfer inside the evaporator enclosure and heat losses. The difference between the water and ambient temperatures is big, it is about 37 ºC. That big difference results the high quantity of condensed desalinated water.

Similarly the system was studied for 97 ºC hot-water set point temperature, the maximum allowed temperature before boiling. Figure 7 indicates the water production and accumulation of the system during and after the steady state. The system performance is improved with higher temperature as expected. It produces about 6 liters/h where only 4 liters/h was produced for 75 ºC heating temperature. That means the system is able to produce about 144 liters per 24 hours a day and about 52560 liters per year at 97 ºC without boiling. Also the system efficiency is improved from 43% at 75 ºC to about 63% at 97 ºC.

As shown in Figure 8, it will be better to get higher water temperature by using more collectors, or reduce the water volume instead of using electrical heating to improve the system efficiency using solar energy only. Moreover optimization of the system should be done and maybe some more measures like heat recovery should be discussed.

The water and vapor temperature presented in Figure 9 are constant at relatively constant ambient temperature. The difference between the water temperature and ambient temperature is increased at higher temperature and that improves the condensation process and the desalinated water production as well. The difference between the water and vapor temperatures is slightly increased; it equals about 7 ºC. That can be understood because the mass and heat transfers are improved at higher temperatures. The flow rate of the injected water is similar for all experiments using the same pump at constant speed with the same number of nozzles. Therefore the flow rate of the hot water is not a parameter in that comparison. On the other side increasing of water temperature improves possibility of salt scaling inside the desalination unit and blocking the nozzles is possible accordingly.

The temperature of salt-water is illustrated as a main parameter to improve the system performance under the same operating pressure; atmospheric pressure. The figure shows the quantity of produced water per kWh of input energy to the system. There is no big difference if the solar energy is used or electrical heater is used as an energy source. The system produces about 1.6 kg/kWh if it is used solar energy only where it produces about 2.9 and 4.3 kg/kWh if the heater is the energy source at 75 & 97 ºC respectively. Although the higher temperature can improve the productivity it raises the possibility of salt scaling causing the nozzles blockage.

Figure 10 compares between the above cases in terms of desalinated water quantity.

Finally the system production was measured for different heating temperatures as indicated in Figure 11. The system is running to reach the steady state for each temperature value and the produced desalinated water was collected for an hour. As expected the system performance is improved with higher temperatures. The relation between $M_d$ and $T_w$ is fitted as a linear relation with about 2% fitting error. An empirical equation can be estimated from the linear relation as:

$$M_d = 0.0942T_w - 2.9348 \tag{10}$$

That equation can be applied from about 38 °C to about 97 °C. Fortunately the system can produce desalinated water at temperature lower than 40 ºC, perhaps the quantity is low and it is about 1 kg/h. It is increased gradually with the higher temperature.

## 8. Economics of the desalination system

The cost of water production per cubic meter of desalinate, *C*, can be estimated as edited by [22]

$$C = \frac{I(Ap + MR + T) + L \cdot W}{M_d} + S \tag{11}$$

$$AP = r\left[1 + \frac{1}{(1+r)^n - 1}\right] \tag{12}$$

where *Ap* is annual payment of the total capital investment as a percent of the investment per year, *MR* is annual maintenance and repair (labor and materials) as percent of investment per year (≈ 1%), *T* is effective annual tax and insurance charges as a percent of investment per year (≈ 0.5%), *L* is annual operating man hours, *W* is wage of the operating labor per man hour, *r* is annual fraction inflation rate (= 10% per year), *n* is pay-back period (≈ 20 years) and *S* is total cost (fixed + operating) of the saline water supply per $m^3$ of product (≈ 0.03 US$/kg).

The initial (capital) cost of the system is about US$ 500. If the annual operating man hours is 365 hours, one hour a day, at a wage of 5 US$/h and the average annual productivity ($M_d$) of about 3650 kg (3.65 $m^3$) if the solar energy is used alone. Then estimating the liter cost of the distilled water is about 0.524 US$/liter. If the system can work 24 hours a day the cost is reduced to 0.258 US$/liter. Probably it is higher than that produced by the conventional energy as concluded by [23] but the system is a small-scale system and the cost can be reduced if it is used a large-scale system.

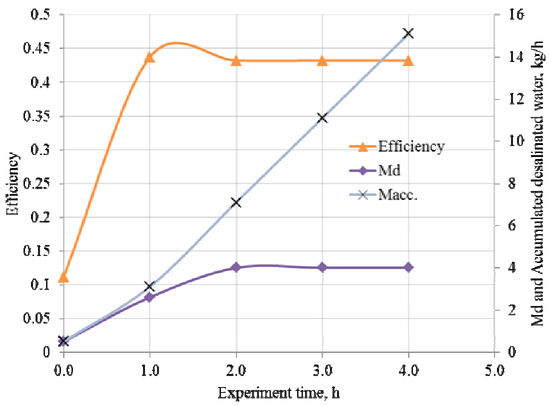



Figure 6. Time variation of the system production and efficiency using electrical heater only at 75 ºC set point

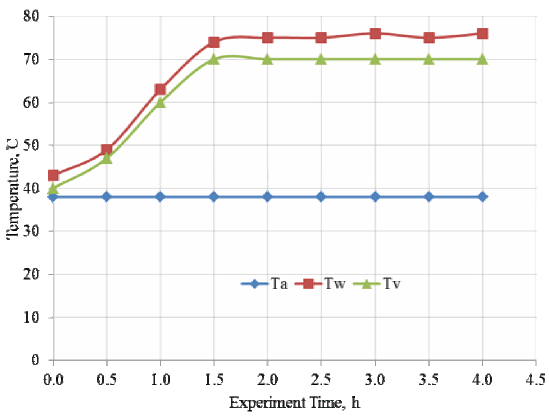



Figure 7. Time variation of the system temperatures using electrical heater only at 75 ºC set point

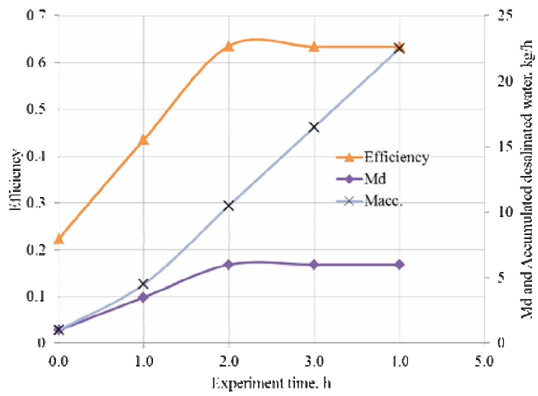



Figure 8. Time variation of the system production and efficiency using electrical heater only at 97 ºC set point

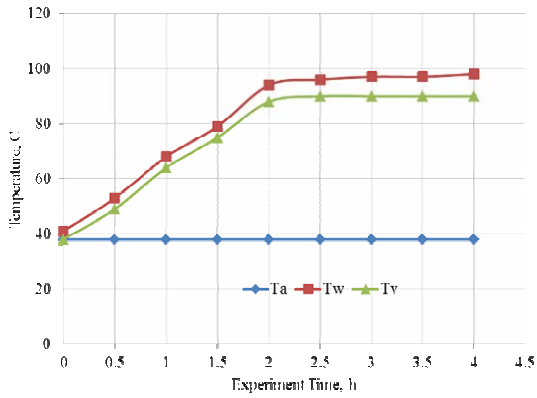



Figure 9. Time variation of the system temperatures using electrical heater only at 97 ºC set point

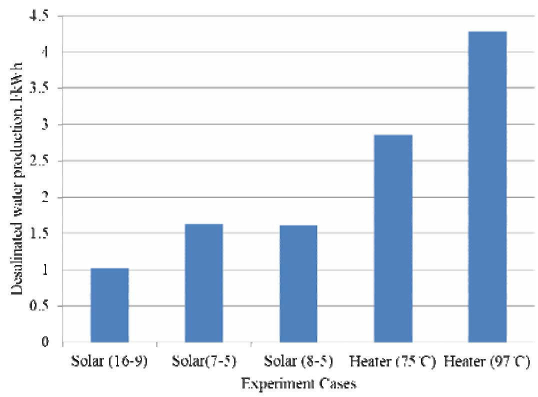



Figure 10. Desalinated water production per kWh of input energy

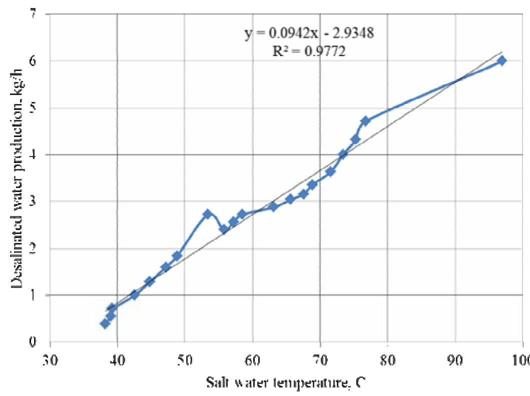



Figure 11. Effect of the salt-water temperature on the desalinated water production

## 9. Expected annual performance

Figures 12 and 13 demonstrate the annual variation of the measured local ambient temperature and relative humidity simultaneously. The maximum ambient temperature is about 43 °C and that is similar to the ambient temperature during the testing of the system as shown in Figure 4. Therefore the condensation process that is dependent to the ambient temperature can be improved under lower ambient temperatures during winter, spring and autumn seasons. Accordingly in the summer the relative humidity is low where it is increased to about 70% in winter. That condition is helpful to improve the condensation process and the system performance as well. Then the system efficiency is expected to be better during the winter months.

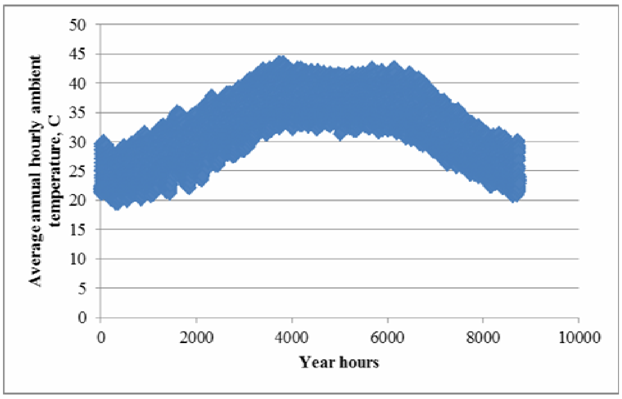



Figure 12. Annual variation of the ambient temperature

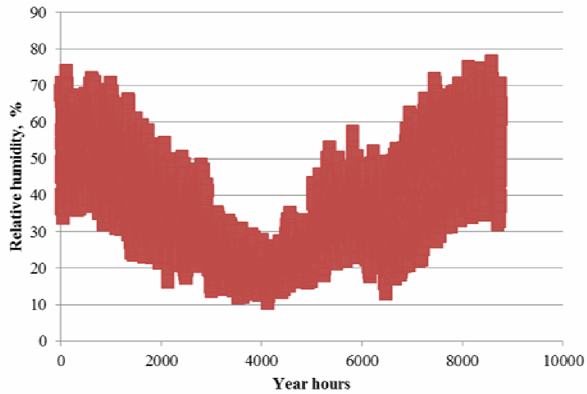



Figure 13. Annual variation of the relative humidity

## 10. Conclusion

An innovative solar desalination system considering humidification/dehumidification process was successfully designed, manufactured, and experimentally tested in Makkah city (21.4 ºN). Pumped injected salt water is evaporated and condensed simultaneously inside a storage tank of a flat-plate collector where it is working naturally. The system is simple, cheap and compact. It can produce about nine liters a day for a quadratic meter of collector surface area. That means the system can produce about 1.6 liters per kWh of solar energy input. Increasing of salt-water temperature improves gradually the system performance. The cost of production was estimated at about 0.5 US$ per liter.

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