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Enhancing performance of low-temperature desalination using spray evaporation

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ABSTRACT

A design for a desalination unit using spray evaporation at atmospheric pressure and low temperature is investigated. The evaporation chamber is introduced inside the condensing chamber. An electric heater, heated the brackish water. The experimental setup is used to study the effect of temperature and mass flow rate of heating brackish water, and flow rate of cooling water on the productivity, power consumption and efficiency of the unit. The results show that the performance of the system is strongly affected by the temperature and mass flow rate of heating water. The unit starts to output freshwater after ten minutes of operation and becomes steady state about twenty later. At heating brackish water temperature and mass are75°C and 4.8 LPM, the maximum water productivity and system efficiency are 2.95 L/h and 85% respectively. The productivity and efficiency are less effected by high $M_{W,h}$ and $m_{w,c}$ The model is expected to be used in solar energy desalination units.

Keywords: Desalination system; Spray evaporation; Brackish water; Atmospheric pressure; Low temperature

1. Introduction

Energy and water shortage are two of the most important issues in the world today. The total amounts of global water reserves are about 1.4 billion cubic kilometers. The oceans constitute, is 97.5% of the total amount of water, and the remaining is 2.5% freshwater present in the atmosphere, polar ice, and ground water. This means that only about 0.014% is directly available to human beings and other organisms [1]. In addition to pollution, other environmental factors, such as global warming contribute to freshwater availability. Glacial melting will cause sea level rise and can lead to salt-water intrusion on fresh water sources. Therefore, development of new clean water sources is imperative. Desalination of sea and brackish water is an important alternative, since the only inexhaustible source of water is the ocean. So, efforts must be made to develop technologies, which will collect and use renewable energy more efficiently and cost effectively to provide clean drinking water besides developing technologies to store this energy to be used whenever is unavailable.

The possibility of using humidification–dehumidification (HD) techniques in the coastal regions of India was investigated, where many industries using sea water as coolant were implemented [2]. This water, when it was ejected at a temperature of about 55°C, can be used for appreciable recovery of freshwater. With this recovery, a contribution of 28% of the total cost can be achieved.

Higher productivity that it is better to use an external collector for the heating requirement of the MED unit was suggested [3]. In such a unit, the brackish water was preheated in the condenser and further heated through the collector before being fed to the evaporator. The hot and humid air of the evaporator was partially dehumidified in the condenser and recycled back to the humidifier.

The theory, design and appropriate models of a distillation system with natural vacuum technique was presented [4]. Theoretical models of this system were investigated and appropriate models are selected for practical applications.

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Also [5] studied natural vacuum distillation (NVD) process experimentally. The experiments were conducted at temperatures of 20 and 40°C and water was used as the working fluid. It was found that 2.5 and 2.6 kWh/kg of distilled water was experimentally used in the NVD system with free and forced mass.

Energy-efficient and sustainable desalination system at low temperature was developed [6]. The system operates under near-vacuum conditions created by exploiting natural means of gravity and barometric pressure head. An experimental study was used the electric power from the grid as an energy source was found that freshwater production rate of 0.25 kg/h can be sustained at evaporation temperatures as low as 40°C with specific energy input of 3370 kJ/kg at efficiencies ranging from 65 to 70% during the winter.

They improved the model performance at their work in [7–10] to include more source energy and to obtain better agreement with the measured results. The results showed that, the following renewable energy/waste heat recovery configurations might produce around 100 liters/day of desalinated water by solar collector area of 18 m^2 with the thermal energy storage (TES) volume of 3 m^3. Also, photovoltaic thermal collector area of 30 m^2 to provide 14–18 kW electricity and 120 L/d freshwater with an best mass flow rate of the circulating fluid around 40–50 kg/h m^2. In addition, a geothermal source at 60°C with a flow rate of 320 kg/h; and (4) waste heat rejected from the condenser of an absorption refrigeration system rated at 3.25 kW, supported by 25 m^2 solar collector area and 10 m^3 TES volume.

A method of performance optimization of solar multistage flash (MSF) desalination process using pinch technology with a temperature range of 30–100°C [11]. Three different situations were studied by using pinch analysis. At the same stage and pinch point temperature difference (2 k), the first situations have a higher gain output rate (GOR) was 17.5 and the second and third have lowered GOR, around 9.

A solar water desalination system using flashing process was constructed [12]. The system consists of a solar water heater (flat plate solar collector) working as a brine heater, and a single vertical flash chamber, which was attached to a condenser/pre-heater unit. The system daily productivity in the summer was about 4.2 to 7 kg/m^{2}d, and about 1.04 to 1.45 kg/m^{2}d during the winter.

A new design of a stepped solar desalination system with the flushing chamber to improve the freshwater productivity was developed [13]. The performance of stepwise water basin coupled with a spray water system by augmenting desalination productivity through using two air heaters was studied. The results showed that, the inlet seawater temperature and the power consumed was significantly affected on productivity and performance of the system. In addition, experimentally the effect of using the spray system for seawater at different velocities of the water spray's holder and flow rates on the performance of the solar still was investigated [14].

The study was to develop solar powered desalination system using condenser integrated with flat-plate solar collector and vacuum pump and compare its performance with the ordinary solar desalination system without vacuum pump under different operational conditions [15]. The experimental results show that the developed system was increased water productivity for all water salinities compared with the ordinary system due to the presence of vacuum pump. The same results also reveal that water productivity was increased and cost was decreased by increasing water flow rate using the developed system while the vice versa was noticed using the ordinary system. Maximum fresh water productivity was 10.94 and 7.27 L/d corresponding to cost was 0.031 and 0.030 $/L.

Experimental study on spray flash evaporation under high temperature and pressure was presented [16]. The effects of injection rate, injection direction, initial water temperature, and injection pressure were investigated. The experimental results showed that the increase of the injection rate and initial water temperature enhanced the flash evaporation. The injection pressure was found to result in better atomization and evaporation of the water on the premise that the injection pressure guaranteed complete flash evaporation.

Mathematical model considering droplet motion and droplet diameter distribution was developed to study spray evaporation [17]. The effects of key design parameters on thermal efficiency and evaporation rate of spray evaporator were estimated and discussed. The results showed that smaller droplet enabled faster evaporation process while higher initial droplet velocity was promoted water productivity.

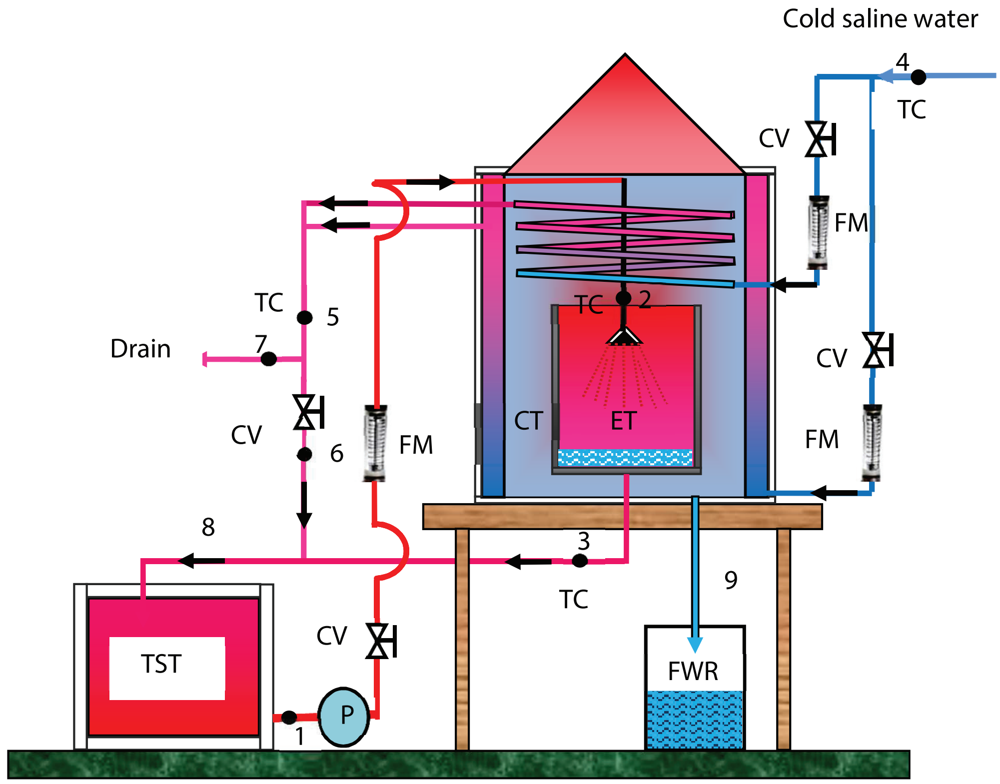
Based on the literature, it can be summarized that the desalination process still requires more studies to develop an efficient technique of evaporation and condensation at relatively low temperatures up to 75°C or less. The main objective of this work is to design a new model of the desalination system with spray evaporation to enhance the efficiency of the low temperature desalination system at atmospheric pressure by using a good arrangement of heat exchangers. The effect of different factors such as the inlet heating brackish water temperature, mass flow rate of heating brackish water, mass flow rate of cooling water and operating time on the productivity of freshwater, power consumption and efficiency are investigated.

2. Experimental setup

The experimental setup of desalination system is shown in Fig. 1. It includes three major parts: (a) heating water system, (b) cold water system, and (c) data acquisition system. Photographs of the experimental test rig and the instrumentation attached to the test section is presented in Fig. 2. The details of the apparatus are depicted as follows:

2.1. Heating brackish water loop

The heating brackish water system is shown in Fig. 1, the thermal storage tank (1) is filled with brackish water and heated by electric heater. This tank is made of galvanized steel sheet with thickness 1 mm and dimensions (400×350×310 mm). It is covered by 50 mm thickness of glass wool insulation covered by aluminum layer. The thermal conductivity is 0.036 W/m^2 K. The heated tank contains two electric heater coils of 1.1 kW power each. A



TST	thermal storage tank	CV	control value	FM	fl ow meter
ET	evaporation tower	CT	condensation tower	TC	Thermocouples
FWR	fresh water reservoir	P	pump		

Fig. 1. Schematic diagram of the experimental test apparatus.

Fig. 2. A photograph of the experimental test rig.

digital thermostat with an accuracy of ±0.5°C is controlling the temperature of heating brackish water. Heating brackish water enters the pump where the pressure is increased and goes to the valve then flowing to the flow meter which is measuring the mass flowrate.

The hot water enters to sprinklers (2) which reduces the pressure and causes a spray of water as vapor. Saline water not evaporated is collected in a basin at the bottom of the evaporation tower (ET) at (3) and then returned to the thermal storage tank (TST). The evaporation tower of diameter 32 cm and height 38 cm, insulated by a layer of thermal flex insulating tape 1 cm thick and covered by an aluminum layer.

2.2. Cooling water loop

The cooling saline water at (4) feds to the cooling coil (CC) which is made of copper tube with 5/8 inch diameter and heat exchanger (HEX) at different rates to condense the water vapor in the evaporation tower and exit at 5. A part of saline water at (5) flows to thermal storage tank (TST) at (6) to back up the water while the rest is drained at (7). The distilled water at (8) is collected in a basin at the bottom of the condensation tower (CT) and leaves to the fresh water reservoir (FWR) at (9). The heat exchanger (HEX) is constructed from two co-axial cylindrical of galvanized steel sheet with thickness 1 mm and are (500 × 700 mm) and (510 × 650 mm) dimensions. The heat exchanger insulated by a glass wool layer insulation with thickness of 30 mm, with thermal conductivity of 0.036 W/m K. A conical cover is put in the top of heat exchanger. The cooling coil is made of copper tube with 1.56 mm diameter that is wrapped in the form of a helix.

2.3. Data acquisition system

As shown in Fig. 1, the water mass flow rate is measured by using a flow meter with a range of 0 to 7.5 LPM with accuracy of ±0. 05 LPM. Four Iron–Constantan thermocouples type J with a range of –200 to 850°C is used to measure the temperature of the brackish water of the inlet and outlet of evaporator chamber and cooling water of the inlet and outlet. The thermocouples at points (2, 3, 4, and 5) are attached to a Digit-Sense 12 Channel Scanning Bench Top Thermometer with scale division of 0.1°C that was connected to a computer. The temperature was recorded every 60 s. The voltage and current of the electrical water heaters and pump are measured by using digital clamp meter type (KSR-266) with accuracy of ± 0.1 V and ± 0. 1 A. The desalinated water volume is measured by using a graduate tank with a range of 0 to 15 L with an accuracy of ± 0.01 L.

To estimate the uncertainties in the results presented in this work, the approach is applied [18]. The uncertainty in the measurements is defined as the root sum square of the fixed error of the instrumentation and the random error observed during different measurements. Accordingly, the resulting errors of the calculated temperature difference, the power input to the system, the mass of water in the heated water tank, the heat energy and the efficiency of the desalination system, respectively, are ± 0.27%, ± 1%, ± 0.5%, ± 0.57% and ± 1. 5%.

2.4. Experimental procedures

Each run is carried out for a fixed value of the certain problem parameters such as inlet water temperature and mass flow rate of heating water. The experimental procedure for each run is carried out as follow:

1. The water in the tank is heated to the required temperature.
2. The mass flow rate of the heating and cooling water is adjusted value through the regulating valve.
3. The unit starts to operate and the other parameters are kept in the range mentioned above.
4. The temperature of every measured point inside the unit is recorded 60 s.
5. The freshwater productivity of the unit is recorded every 5 min.
6. The Voltage and current of the electrical heaters and pump are measured.

2.5. Performance of the system

A mathematical model that describes the performance of each component of the system are presented in this section. To start and maintain distillation, continuous supply of heat is required, which goes to preheat the feed, evaporate the water and to offset the heat losses.

The heat consumption is calculated using the following equation:

$$E_t = E_p + E_h \quad (1)$$

$$E_t = I_P \times V_P \times t_P + I_h \times V_h \times t_h \quad (2)$$

where E_t is the energy consumed during the testing time, kW h; E_p is the energy consumed by the pump during the testing time, kW h; E_h is the energy consumed by heater during the testing time, kW h.

Heat consumed to produce freshwater can be calculated from the following equation:

$$Q_{w,t} = \frac{m_{w,t}\left[h_{fg} + C_p(T_{h,i} - T_{w,o})\right]}{3600} \quad (3)$$

where $Q_{w,t}$ is the heat energy added to the water, kW h; $m_{w,t}$ is the mass productivity of freshwater during testing time, kg; h_{fg} is the latent heat vaporization of water, kJ/kg; C_p is the specific heat of water at constant pressure, kJ/kg K; $T_{h,I}$ is the inlet heating water temperature, K; $T_{w,o}$ is the outlet temperature of condensed freshwater, K.

The performance of the system can be described in terms of the extent to which the heat added is used to evaporate the brackish water to produce fresh water. The extent of energy conversion can be expressed by the following ratio, which is known as thermal efficiency.

$$\eta_{th} = \frac{Q_{w,t}}{E_t} \quad (4)$$

where η_{th} is the thermal efficiency, %.

3. Results and discussion

The experimental results obtained in the present work are analyzed and discussed. Results for different experiments are given in graphical form to simplify the discussion. The experimental data are performed for heating brackish water mass flow rate of 0.96, 2.22, 3.57, 4.8, 5.24 and 6.2 LPM, inlet heating brackish water temperature of 60, 70 and 75°C, and cooling water mass flow rate of 3.46, 4.61, 5.44 and 7.1 LPM. The pump and heater are operated of 60 min and then shuts down while vapor inside the heat exchanger tank is condensates within 15 min after shutdown.

3.1. Effect of time duration on productivity and efficiency

The variation of the water accumulated productivity and efficiency with time at different test duration at $m_{w,h}$ = 4.8 LPM and $m_{w,c}$ = 4.58 LPM is presented in Fig. 3. As shown in Fig. 3, the accumulated productivity increases with same rate of time test. Also, the increases of operating time are not effected at the rate of productivity and efficiency.

3.2. Influence of $m_{w,c}$ on the desalination unit

The temperature variation within time is shown in Fig. 4 at heating brackish water temperatures of 60, 70 and 75°C respectively. The variation curve of freshwater productivity with the operation time is shown in Fig. 5. In addition, the effect of heating brackish water temperatures on freshwater productivity and efficiency is presented in Fig. 6.

The temperatures become steady state after five minutes as shown in Fig. 4. The temperature difference between the inlet and outlet of heating brackish water are 7, 10.5 and 11.5°C while the temperature difference between the inlet and outlet of cooling water are 3.2, 6 and 7.3°C at 60, 70 and 75°C respectively. In addition, the temperature difference between heating and cooling water are 40, 50 and 55°C.

The maximum freshwater productivity of about 1.3, 2.14, and 2.77 L/h have obtained at $T_{w,h}$ = 60, 70 and 75°C. Higher heating brackish water temperature increases the temperature difference between heating and cooling water. Hence, a high freshwater productivity is obtained as shown in Fig. 5. The unit starts to output freshwater after ten min-

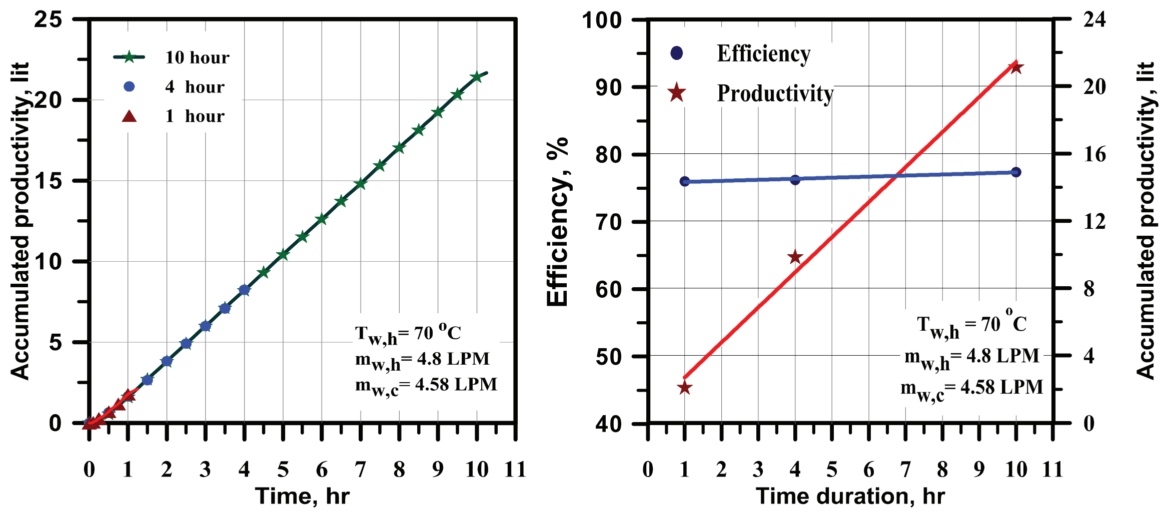


Fig. 3. The variation of the accumulated productivity and efficiency with time duration.

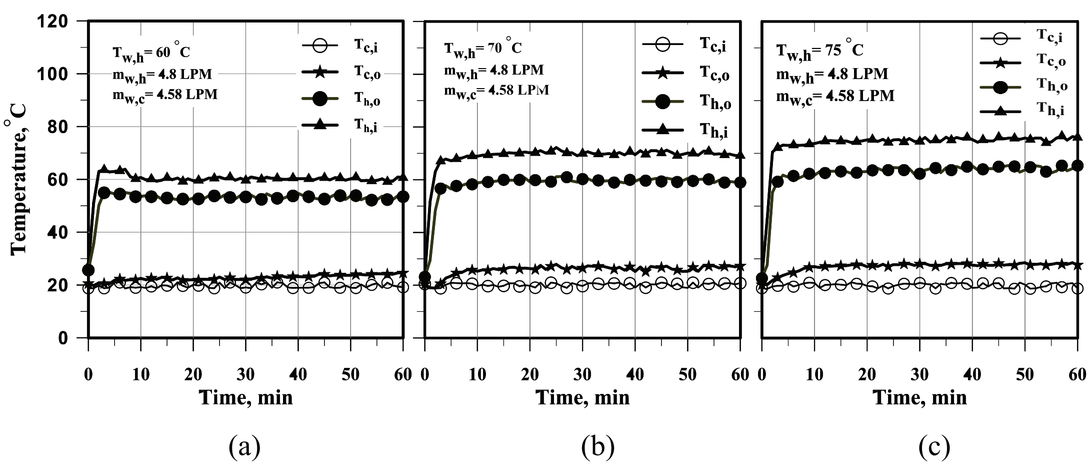


Fig. 4. The variation of the inlet and outlet temperatures of heating and cooling water with them at a mass flow rate of heating and cooling water of 5.24 and 4.58 LPM.

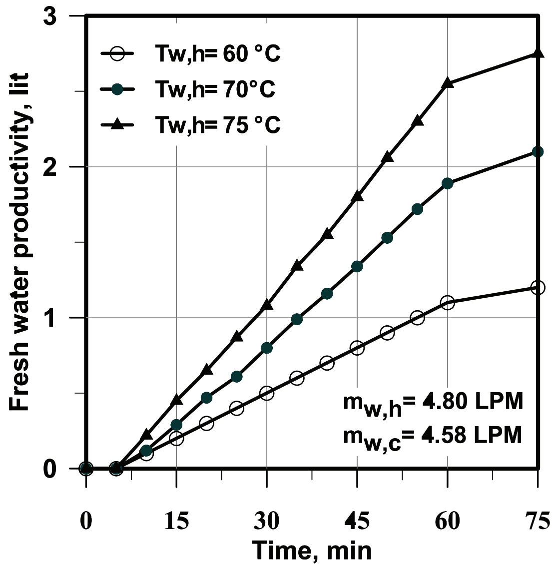


Fig. 5. Variation of freshwater productivity with time at different inlet heating brackish water temperatures.

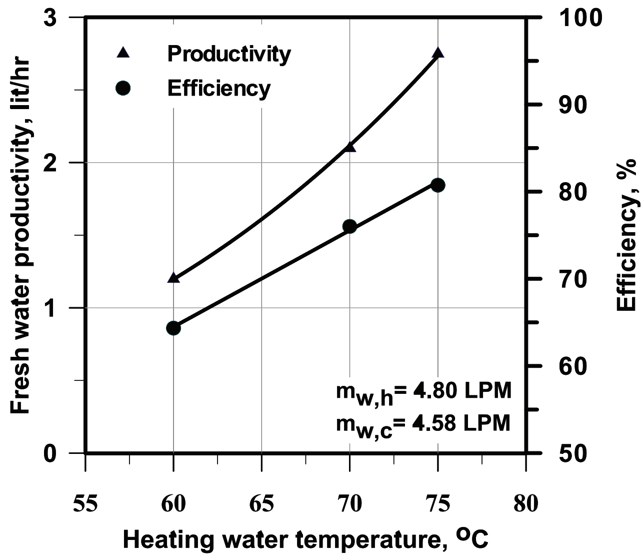


Fig. 6. Variation of freshwater productivity and efficiency with heating brackish water temperatures.

utes of operation and becomes steady state about twenty minutes later.

As shown in the mentioned Fig. 6, the water productivity and efficiency increases with the increase of heating brackish water temperatures. When $T_{w,h}$ is increased from 60 to 75°C, productivity is increased by about 113% and efficiency is increased by about 17.7%.

3.3. Influence of $m_{w,c}$ on the desalination unit

Provided heating brackish water temperature $T_{h,i}$ = 60, 70 and 75°C, heating brackish water flow rate $m_{w,h}$ = 4.8 LPM, cooling water flow rate $m_{w,c}$ = 3.46–5.44 LPM, the variation of productivity with the time is shown in Fig. 7. In addition, the influence of cooling water flow rate on the productivity and efficiency is shown in Fig. 8.

The results indicate that higher cooling water flow rate is not helpful to increase the freshwater productivity, especially under low operation heating brackish water temperature as shown in Fig. 7. However, the pump power will increase at the same time and more electrical energy is needed. Therefore, under the condition of not influencing the productivity, the cooling water flow rate should be as small as possible. Therefore, the cooling water flow rate of 4.58 LPM is used in this study. The unit starts to output freshwater after ten minutes of operation and becomes steady state about twenty minutes later.

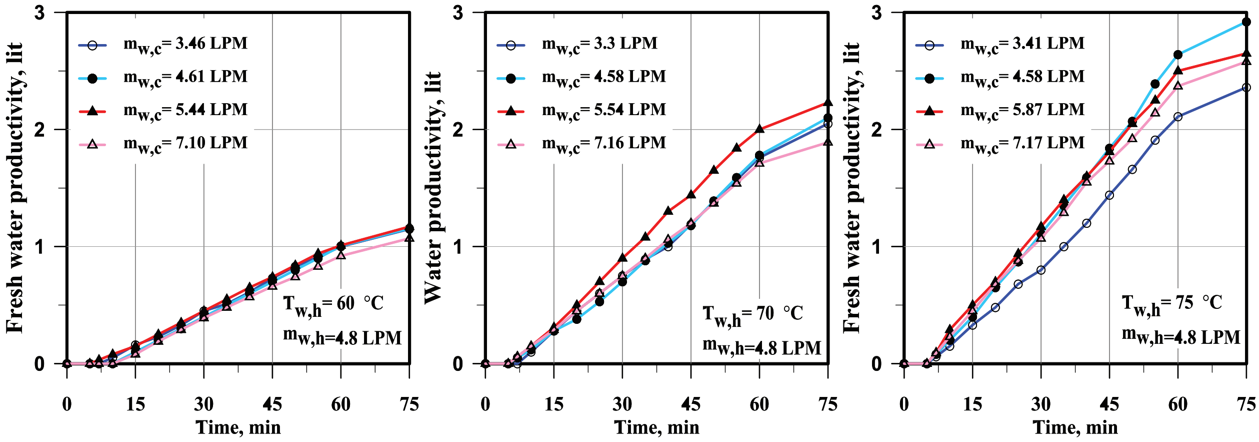
The productivity and efficiency increase with increase cooling water mass flow rate at the same $T_{w,h}$. This is due to higher cooling water mass flow rate, which increase the condensation rate. It is also observed from Fig. 8 that the productivity and efficiency is little effected by increase cooling water mass flow rate.

3.4. Influence of $m_{w,h}$ on the desalination unit

The purpose of transmitting, heating brackish water to the unit is to provide heat energy to evaporate brine. When the temperature of heating brackish water is unchanging, increasing the flow rate of heating brackish water means that more heat energy is supplied to the unit. On the other hand, when the flow rate of heating brackish water is unchanging, increasing the temperature means that more heat energy is supplied to the unit too. Increasing the flow rates of heating or cooling water is helpful to get higher productivity.

Provide heating brackish water temperature $T_{h,i}$ = 60, 70 and 75°C, cooling water flow rate $m_{w,h}$ = 4.58 LPM, heating brackish water flow rate $m_{w,h}$ = 0.96–5.24 LPM, the variation of productivity with the time is shown in Fig. 9. The experimental results show that the unit heating brackish water inlet temperature and mass flow rate are two of the important factors that influence on the freshwater productivity. The freshwater productivity grows fast with the increase temperature and mass flow rate of heating brackish water. The possible reasons is that when the flow rate is increased, the input or output of heat energy transmitted through water increases. As a result, heating or cooling driving force increases, which causes the freshwater productivity increase. At $T_{w,h}$ = 75°C, if the heating brackish water flow rates are larger than 4.8 LPM, the increase of the flow rates has no obvious effect on the freshwater productivity as shown in Fig. 9c. The unit starts to output freshwater after ten minutes of operation and becomes steady state about twenty minutes later.

The variation of productivity and efficiency with the $m_{w,h}$ and $T_{w,h}$ are shown in Fig. 10. From this figure, it can be seen that the freshwater productivity and efficiency increases with the increase heating brackish water temperature. That is because of increasing the temperature difference between heating and cooling water in which the evaporation rate is increased by increasing the temperature difference. When $m_{w,h}$ is increased from 0.96 to 5.24 LPM, productivity and efficiency are increased by about 140 and 48% at $T_{w,h}$ = 60°C while, productivity and efficiency are increased by about 134 and 45% at $T_{w,h}$ = 75°C. It is also observed from Fig. 10



(a)

Fig. 7. The variation of freshwater productivity with time at the different mass flow rate of cooling water and $\dot{m}_{w,h} = 4.58\,\text{LPM}$.

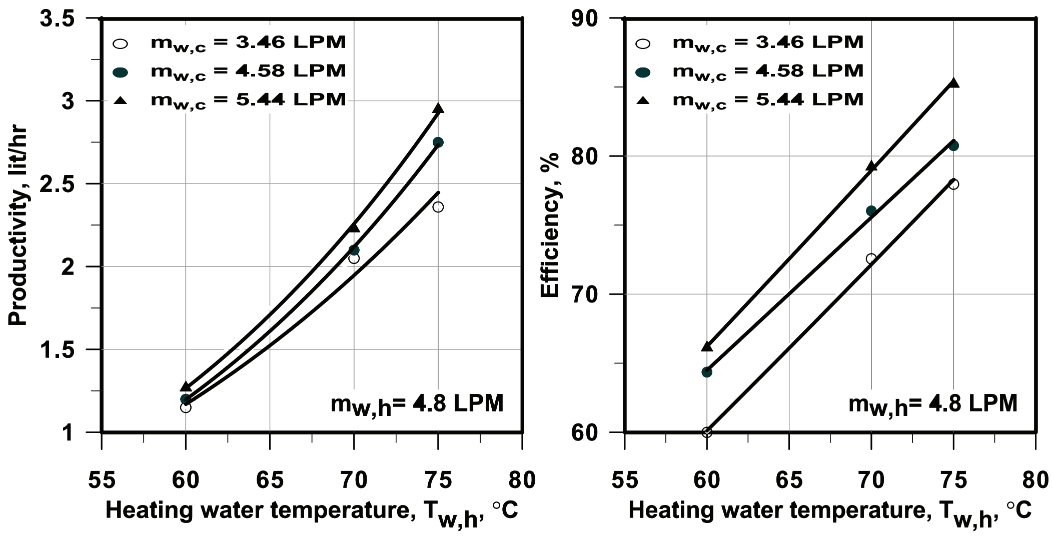
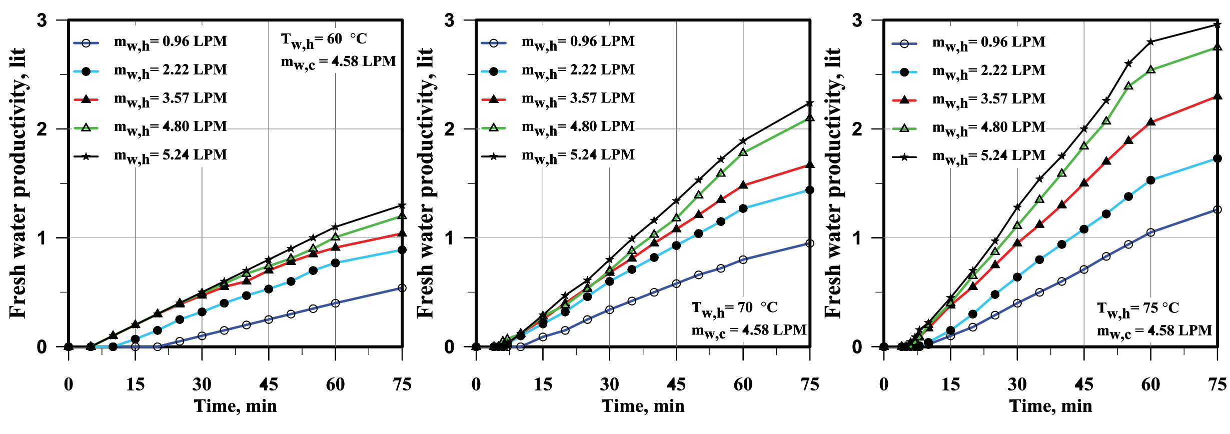


Fig. 8. The variation of productivity and efficiency with heating water temperatures at different mass flow rate of cooling water.



(a) (b) (c)

Fig. 9. The variation of freshwater productivity with time at different mass flow rates of heating brackish water.

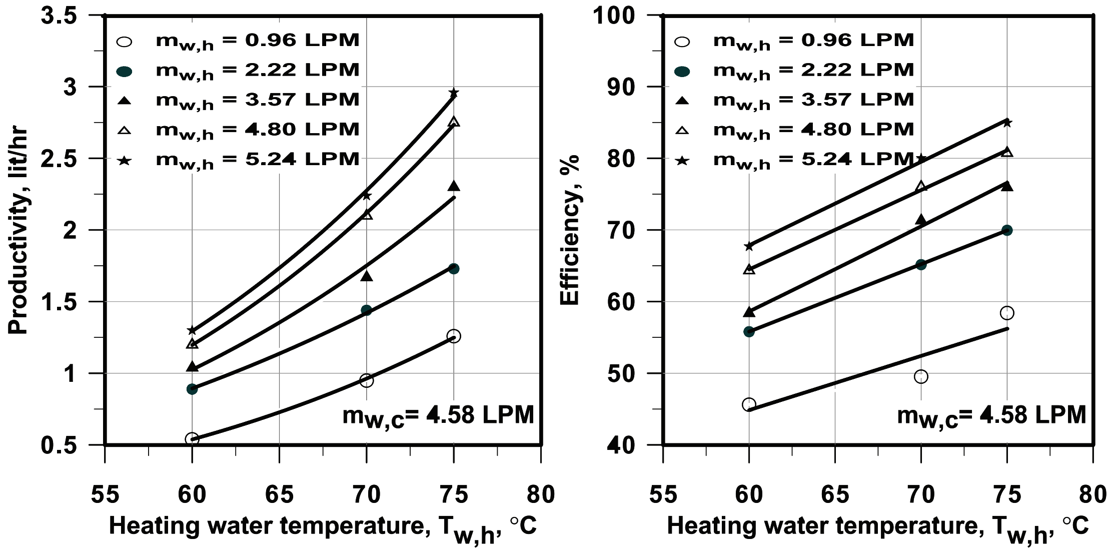


Fig. 10. The variation of productivity and efficiency with heating water temperatures at different heating brackish water temperatures.

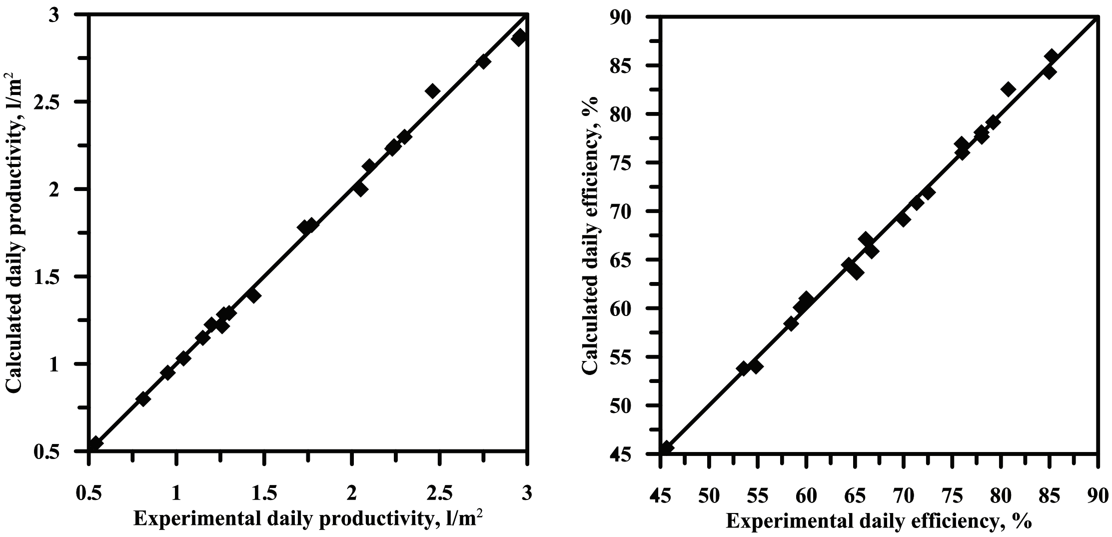


Fig. 11. Comparison of experimental and calculated results of the desalination unit.

that the productivity and efficiency is less effected by high $M_{W,h}$.

3.5. Comparisons of the calculated results and the experimental measurements

It is very important to correlate numerical results. If the design equation is general, it will be more useful in engineering applications. The general correlation of productivity and efficiency of the system as a function of water temperature, water level and airflow rate are obtained by use the Microsoft Office Excel Solver tool, which uses the Generalized Reduced Gradient (GRG) nonlinear optimization code, which was developed by Leon Lasdon, University of Texas at Austin, and Alan Waren, Cleveland State University. Fig. 11 shows that the calculated results of productivity and efficiency agrees well with the experimental results. This indicates that the correlation proposed well of productivity and efficiency. The daily productivity and efficiency of the desalination unit can be correlated with mean difference 1.733 and 0.88 % as follows:

$$\Phi = \left(T_{w,h}\right)^{a} * \left(b + m_{w,h}^{c}\right) * \left(T_{w,c}\right)^{d} * \left(e + m_{w,c}^{f}\right) \quad (5)$$

$$60 \le T_{w,h} \le 75\,°C, \quad 0.96 \le m_{w,h} \le 5.24\; LPM,$$
$$19 \le T_{w,c} \le 22\,°C, \quad 3.46 \le m_{w,c} \le 5.44\; LPM \quad (6)$$

where (*a*, *b*, *c*, *d*, *e*, and *f*) are constant of the correlations and shown in Table 1.

Table 1
The value of constants for the correlation's

Φ	Productivity, L/h	Efficiency, %
a	3.59	1.0166
b	0.8665	1.03573
c	0.752	0.38127
d	−4.364	1.0421
e	0.0484	2.87875
f	0.00323	0.17673

4. Economic analysis

The calculation methodology is based on; the salvage value of the units will be zero at the end of the amortization period. The operator and the maintenance costs are 20% of plant annual payment [19]. The product water coat is calculated from the following relation assuming 250 working days. An economic analysis of the water desalination unit was studied [20]. The total cost of the fabricated system is calculated from the sum of the cost of operation, the cost of maintenance, and the fixed charges cost. The cost of operation; it includes the energy, the operating personnel, and the handling of raw materials. The cost of maintenance; it includes the maintenance personnel, the maintenance facility cost, the test equipment, the maintenance support and handling cost, the maintenance spares and repair parts. The fixed charges cost is calculated from the present capital cost of desalination system; the capital recovery factor, the interest per year, which is assumed as 6%; n is the number of life years, which is assumed as 15 years in this analysis. Finally, the cost of distilled water per liter can be calculated by dividing the annual cost of the system by annual yield of solar still.

The total cost of the fabricated system is approximately $300. Therefore, the fixed charges cost is $41.2 and operators and the maintenance costs are $8.2 then the total cost of ownership is $49.4. The average product of water is 9 L/d. Finally, the cost of distilled water per liter is $0.022.

5. Conclusion

From the above results, it is found that the suggested process is an efficient technique of evaporation and condensation at relatively low temperatures up to 75°C or less. The new model is designed in this study to enhance the efficiency of the low temperature desalination system by using spray evaporation at atmospheric pressure. This study is developing the use of heat exchangers in the low temperature desalination system making it usable in domestic or small applications for saving- energy considerations. The results show that:

- The unit starts to output freshwater after ten minutes of operation and becomes steady state about twenty later.
- The freshwater productivity, power consumption and system efficiency is a strong effect of the inlet heating brackish water temperature and mass flow rate.
- The water productivity increases with the increase of heating water temperature and the mass flow rate.
- The productivity and efficiency is less effected by high $M_{W,h}$ and $m_{w,c}$.
- The maximum water productivity, efficiency, and power consumption are 2.95 L/h, and 85% at temperatures of 75°C and mass flow rate of 4.8 LPM of heating brackish water
- The model is expected to be used for the development of methods of desalination by solar energy.

Symbols

C_p — Specific heat constant pressure, kJ/kg K
E — Energy consumed kW h
h_{fg} — Latent heat, kJ/kg
I — Current, A
m — Mass, kg
Q — Heat energy added, kW h
T — Temperature, K
V — Voltage, V

Greek

η_{th} — Thermal efficiency, %.

Subscripts

h — heater or heating
o — outlet
th — thermal
P — pump
t — testing time, h
c — cooling
w — water
i — inlet

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