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DESALINATION SYSTEM WITH FLASH EVAPORATION AT LOW TEMPERATURE AND ATMOSPHERIC PRESSURE

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ABSTRACT

A modified design for a desalination unit using flash evaporation at atmospheric pressure and low temperature is investigated. The evaporation chamber is introduced inside the condensing chamber. An electric heater is used for heating the brackish water. The experimental setup is used to study the effect of temperature and mass flow rate of heating brackish water, flow rate of cooling water and operating time on the productivity, energy 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 water heated. The unit starts to output freshwater after ten minutes of operation and becomes steadly about twenty minutes later. The temperature and mass flow rate of brackish water are 75 ^{o}C and 4.8 lit/min. The maximum water productivity, system efficiency, energy consumption are 2.95 lit/h, 85 % and 0.82 kWh/kg respectively. The model is expected to be used in solar energy desalination units.

تصميم نظام جديد للتحلية يعمل بطريقة التبخير الوميضى عند درجات الحرارة المنخفضة والضغط الجوى, تبين هذه الدراسة تطوير إستعمال المبادلات الحرارية في نظام تحلية درجة الحرارة المنخفضة والإستفاده منه فى التطبيقات المحلية الصغيرة وتوفير الطاقة المستخدمة لعمليات التحلية, تحدث عملية التبخير داخل غرفة التبخير الموجودة بغرفة التكثيف, يستخدم سخان كهربى أو مجمع شمسى لرفع درجة حرارة الماء المالح, صمم هذا الجهاز لدراسة تأثير (درجة حرارة دخول الماء المالح ومعدل تدفقه ومعدل تدفق ماء التبريد) على الإستهلاك الكهربى وإنتاج الماء العذب وكفاءة الجهاز, ويظهر جلياً من التجارب أن التأثير الكبير على إنتاج الماء العذب هو تأثير درجة حرارة دخول الماء المالح, ومن التجارب التى نُفذت إتضح أن احسن معدل إنتاجية وكفاءة وإستهلاك كهربى كان عند درجة حرارة دخول الماء المالح ٧٥ ٥م ومعدل تدفق له ٤,٨ لتر/ دقيقة وكانت النتائج كالآتى: إنتاج الماء العذب ٢,٩٥ لتر/ ساعة والكفاءة ٨٥ % ومعدل الإستهلاك الكهربى ٠,٨٢ كيلو وات ساعة/ كيلو جرام من الماء العذب , هذا النموذج يتوقع إستخدامه لتطوير عمليات التحلية بالطاقة الشمسية.

Keywords: *desalination system, flash evaporation, brackish water, atmospheric pressure, low temperature.*

Nomenclature

C_p	Specific heat constant pressure, kJ/kg K
E	Energy consumed kWh.
h_{fg}	Latent heat, kJ/kg.
I	Current, A
m	Mass, kg.
Q	Heat energy added, kWh
T	Average temperature, ^{o}C.
V	Voltage, V.
t	Time duration, h.

Greek symbols

η_{th}	Thermal efficiency,%.

Subscripts

h	Heater or heating.
o	Outlet

th	Thermal
P	Pump.
c	Cooling.
w	Water.
i	Inlet.

1. INTRODUCTION:

Energy and water shortage are two of the most important issues in the world today. The social and economic health of the world depends on sustainable supply of both energies and water. To solve the emerging crisis of energy and water, renewable energy technologies seem to be the key. The oceans constitute, is 97.5% of the total amount, 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]. 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.

Garg et al. [2] investigated the possibility of using humidification–dehumidification (HD) techniques in the coastal regions of India where many industries using seawater as coolant were implemented. 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. Heating the air inside the evaporation–condensation unit may be able to increase the distilled water productivity.

Ben Bacha et al. [3] suggested for higher productivity that it is better to use an external collector for the heating requirement of the multi evaporation distillation (MED) unit. In such a unit, the brackish water was preheated in the condenser and further heated through the collector before being feds to the evaporator. The hot and humid air of the evaporator was partially dehumidified in the condenser and recycled back to the humidifier.

Midilli and Ayhan [4] presented the theory, design and appropriate models of a distillation system with natural vacuum technique. Theoretical models of this system were investigated and appropriate models are selected for practical applications. Midilli and Ayhan [5] also studied natural vacuum distillation (NVD) process experimentally. The experiments were conducted at temperatures of 20 and 40 ^{o}C and water was used as the working fluid. It was found that 2.5 kWh/kg of distilled water was experimentally used in the NVD system with free mass convection while 2.6 kWh/kg distilled water in the NVD system with forced mass convection.

Gude et al. [6] developed energy-efficient and sustainable desalination system at low temperature. The system operates under near-vacuum conditions created by exploiting natural means of gravity and barometric pressure head. Theoretical studies included thermodynamic analysis were carried out. 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 Khandan and Gude [7], Gude and Nirmalakhandan [8], Gude et al. [9] and Gude et al.

[10] to include more source energy and to obtain better agreement with the measured results.

Shaobo et al. [11] presented a method of performance optimization of solar multi-stage flash (MSF) desalination process using pinch technology with a temperature range of 30 to 100 ^{o}C. Three different situations were studied by using pinch analysis in this paper. First, the distilled water was not discharged in each middle stage. Secondly, the distilled water was discharged in each stage. Thirdly, the distilled water is discharged every five stages. Pinch charts at different situations are given. At the same stage temperature difference (2 k) and pinch point temperature difference (2 k), the first situations have a higher gain output rate (GOR) about of 17.5 and the second and third have lowered GOR, around 9. However, GOR was easily influenced by abnormal stage temperature differences in the first situation and not influenced by abnormal stage temperature differences in the second and third situation.

Nafey et al. [12] constructed a solar water desalination system using flashing process. 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. A mathematical model was developed for all the system components to predict the system productivity under different and wide range of operating conditions. The test rig works better at higher top brine temperature (TBT), i.e., higher solar intensity. Reasonable rate of feeding water was about 0.0183 kg/s. The system daily productivity in the summer was about 4.2 to 7 kg/m^{2}day, and about 1.04 to 1.45 kg/m^{2}day during the winter.

El-Zahaby et al. [13] developed a new design of a stepped solar desalination system with the flushing chamber to improve the freshwater productivity. 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 productivity and performance of the system was significantly positive dependent on the inlet seawater temperature and the power consumed. In addition, El-Zahaby et al. [14] investigated 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.

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 modified 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, energy consumption and efficiency are investigated.

2. Experimental setup

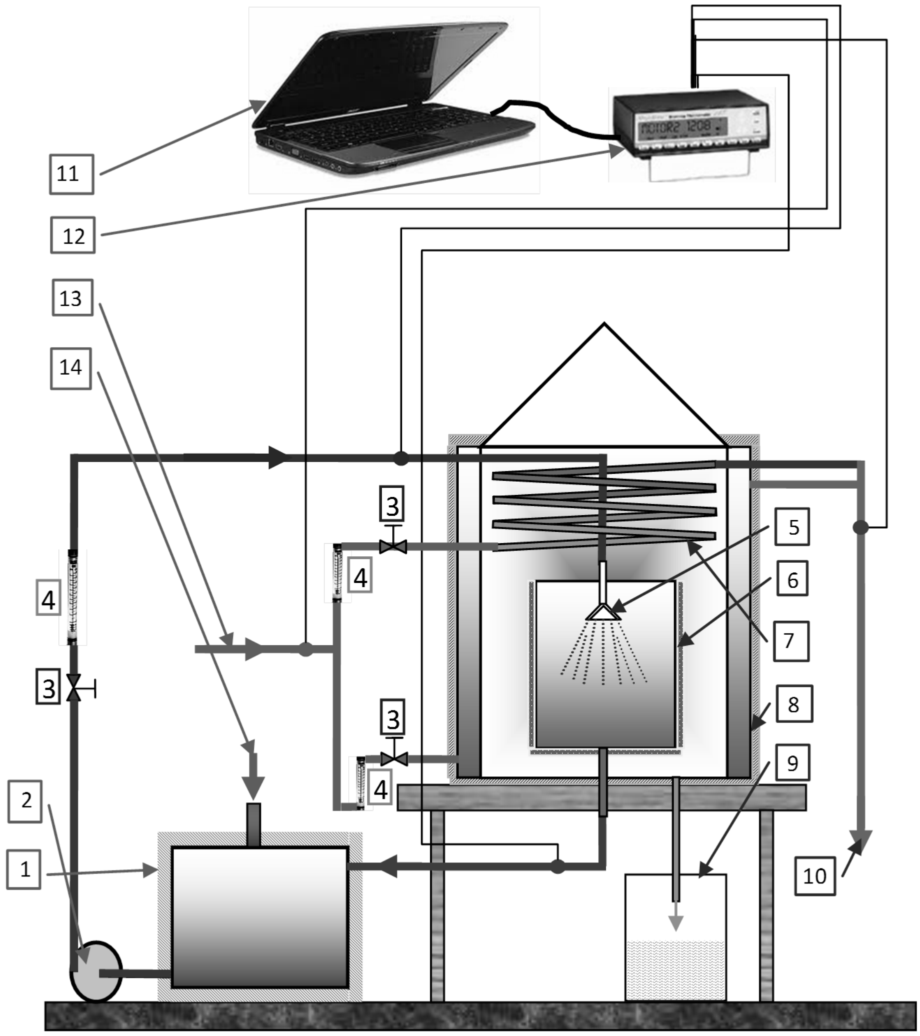
The experimental setup of desalination system is shown in Fig. 1. It includes three major parts: (a) heating water loop, (b) cold water loop, and (c) data acquisition system. Photographs of the experimental test rig and the instrumentation attached to the test section is presented in Fig. 2. The details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

2.1. Heating brackish water loop

Heating brackish water loop is shown in Fig. 1, the heater 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^2K. The heated tank contains two electric heater coils of 1.1 kW power each. A digital thermostat with an accuracy of ± 0.5°C is controlling the temperature of heating brackish water. Heating brackish water enters the pump (2) where the pressure is increased and goes to the valve (3) then flowing to the flow meter (4) which is measuring the mass flow rate. The heating water enters to sprinklers (5) which reduces the pressure and causes a spray of water. A portion of the liquid flashed off as vapor. This vapor leaves the evaporation chamber (6). It touches the cooling coil (7) and heat exchanger (8) surfaces that absorb latent heat to cool and condensation, and leaves to freshwater reservoir (9). The drain water returns to the heater tank (1). Make up water (14) is added at the same rate as water produced.

2.2. Cooling Water loop

Cooling water loop is shown in Fig. 1, where the cooling water (13) enters both the heat exchanger (8) and the cooling coil (7) at different rates. It is controlled by a regulating valve (3) and leaves (10) to drain. The heat exchanger 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^2K. 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.



1- Heater tank	5- Sprinklers	9- Fresh water tank	13- Cooling water inlet
2- Pump	6- Evaporator chamber	10- Cooling water outlet	14- Make up water
3- Valves	7- Cooling coil	11- Computer	
4- Flow meter	8- Heat exchanger tank	12- Data acquisiton unit	

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

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

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 lit/min. Five Iron–Constantan thermocouples type J with a range of -200 to 850 ^{o}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. These thermocouples are attached to a Digit-Sense 12 Channel Scanning Bench Top Thermometer (12) with scale division of 0.1 ^{o}C that was connected to a computer (11). The temperature was recorded every 60 S. The voltage and current of the electrical water heaters (6) and pump (2) 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 10 L with accuracy of ± 0.01 L.

To estimate the uncertainties in the results presented in this work, the approach described by Barford [15] is applied. 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 thermal energy and the efficiency of the desalination system respectively are ±0.27%, ± 1%, ± 0.5 %, ± 0.57 % and ± 1. 5% .

3. 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 is started 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 manually every five minutes.
6. The Voltage and current of the electrical heaters and pump are measured.
7. The following measurements are taken with time for each experiment.
   a. Hot brackish water mass flow rate.
   b. Cooling water mass flow rate of heat exchanger and cooling coil.
   c. Inlet and outlet water temperatures for each part.
   d. The Volt and Ampere of the electric heaters.

4. Performance calculation procedure

Mathematical equations 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:

$$E_t = E_p + E_h \tag{1}$$

where,

E_t is the energy consumed during the testing time, kWh.

E_p is the energy consumed by the pump during the testing time, kWh.

E_h is the energy consumed by heater during the testing time, kWh.

$$E_P = I_P \times V_P \times t_P \times \cos\phi \tag{2}$$

where,

I_p is the current of the pump, A.

V_p is the voltage of the pump, V.

t_p is the operating time of the pump, h.

$\cos\phi$ is the power factor equal unity.

$$E_h = I_h \times V_h \times t_h \times \cos\phi \tag{3}$$

where,

I_h is the current of the heater, A.

V_h is the voltage of the heater, V.

t_h is the operating time of the heater, h.

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

$$Q_{w,t} = \frac{m_{w,t}\left[h_{fg} + C_p(T_{h,i} - T_{w,o})\right]}{t} \tag{4}$$

where,

$Q_{w,t}$ is the heat energy added to the water, kW.

$m_{w,t}$ 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, ^oC.

$T_{w,o}$ is the outlet temperature of condensed freshwater, ^oC.

t is the time operating , h equal 3600 sec.

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 freshwater. The extent of energy conversion can be expressed by the following ratio, which is known as thermal efficiency.

$$\eta_{th} = \frac{Q_{w,t}}{E_t} \qquad (5)$$

where,

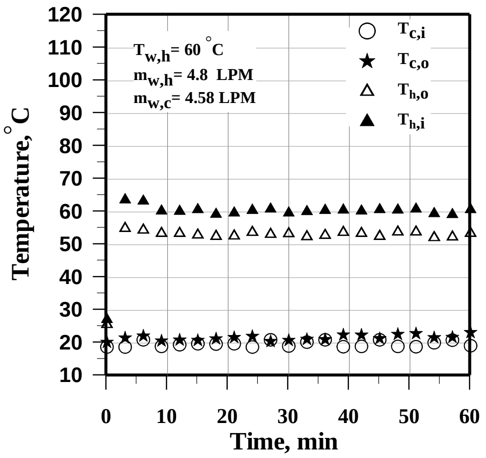
η_{th} is the thermal efficiency, %.

5. Results and discussion

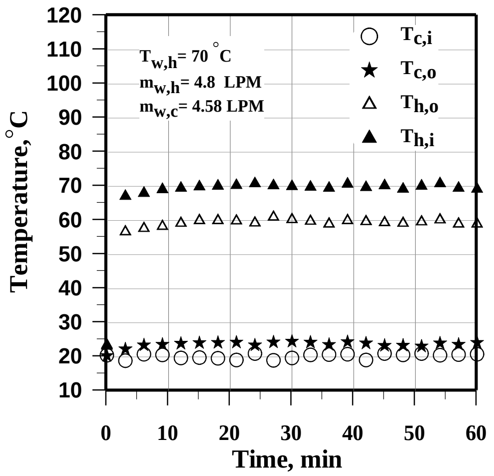
The experimental results obtained in the present work are analyzed and discussed. Results for different experiments are given in graphical form to simplify the discussion. The results are analyzed to investigate the effect of different parameters such as the inlet of brackish heating water temperature $T_{w,h}$, heating brackish water temperature mass flow rate $m_{w,h}$ and cooling water temperature mass flow rate $m_{w,c}$ on the productivity of freshwater, energy consumption and efficiency. 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 lit/min, inlet heating brackish water temperature of 60, 70 and 75 °C, and cooling water mass flow rate of 3.41, 4.58, 5.54 and 7.1 lit/min. Time operating of the pump and heater of 60 min and then shuts down while vapor inside heat exchanger tank condensate within 15 min after shutdown due to the existence of remaining vapour is still producing fresh water.

The temperature variations of the heating brackish water inlet and outlet, cooling water inlet and outlet with time at mass flow rate of heating water and different inlet heating water temperature is presented in Fig. 3 (a, b and c). The experimental data are performed for heating brackish water mass flow rate of 4.8 lit/min, cooling water mass flow rate of 4.58 lit/min and inlet heating water temperature of (60, 70 and 75^{o}C). As shown from Fig. 3, the temperature difference between heating brackish water and cooling water are 40, 50 and 55°C.

The variation of accumulated fresh water productivity with time at the different heating brackish water mass flow rates of (0.96, 2.22, 3.57, 4.8, 5.24 and 6.2 lit/min) at cooling water mass flow rate of 4.58 lit/min and different inlet heating brackish water temperatures of (60, 70 and 75 ^{o}C) is presented in Fig. 4 (a, b and c). As shown from Fig. 5, the accumulated productivity increases with increasing the heating brackish water mass flow rate. This is due to the increase evaporation rate with the heating brackish water mass flow rate. The unit starts to output freshwater after five minutes of operation and becomes steadly after ten minutes later. As shown from table 1, at an inlet heating brackish water temperature of 75 ^{o}C, mass flow rate of heating brackish and cooling water of 4.8 and 4.58 lit/min, the maximum freshwater productivity is about 2.95 kg/h at energy consumption of 0.82 kWh/kg better than reference [5,6].



(a)



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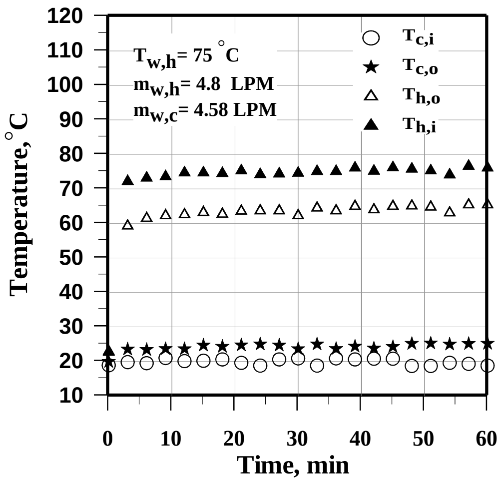
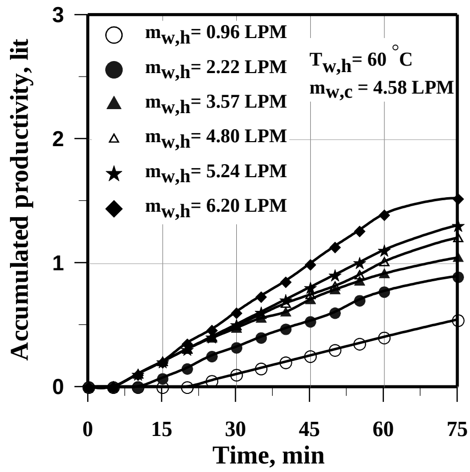
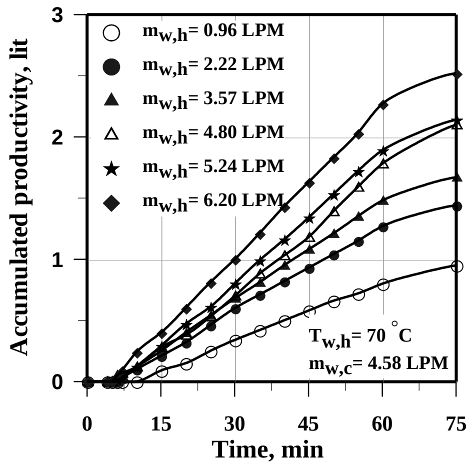


(c)

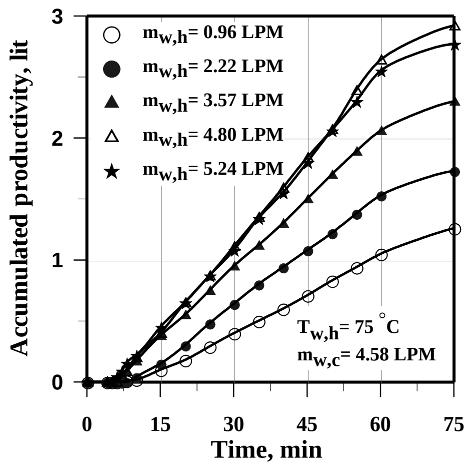
Fig. 3. The variation of the inlet and outlet temperatures of heating and cooling water with time at mass flow rate of heating and cooling water of 4.8 and 4.58 lit/min.



(a)



(b)



(c)

Fig. 4. The variation of accumulated productivity with time at different heating brackish water mass flow rates and $\dot{m}_{w,c} = 4.58$ lit/min.

The variation of accumulated productivity with time at the different cooling water mass flow rates of

(3.41, 4.58, 5.54 and 7.1 lit/min) at a heating brackish water mass flow rate of 4.8 lit/min and different inlet heating brackish water temperatures of (60, 70 and 75 ^{o}C) is presented in Fig.5 (a, b and c). As shown from Fig.5, higher cooling water flow rate is not helpful to increase the freshwater productivity. As shown from table 2, at an inlet hot water temperature of 75 ^{o}C, mass flow rate of heating brackish and cooling water of 4.8 and 4.58 lit/min, the maximum fresh water productivity is about 2.92 kg/h at energy consumption of 0.83 kWh/kg.

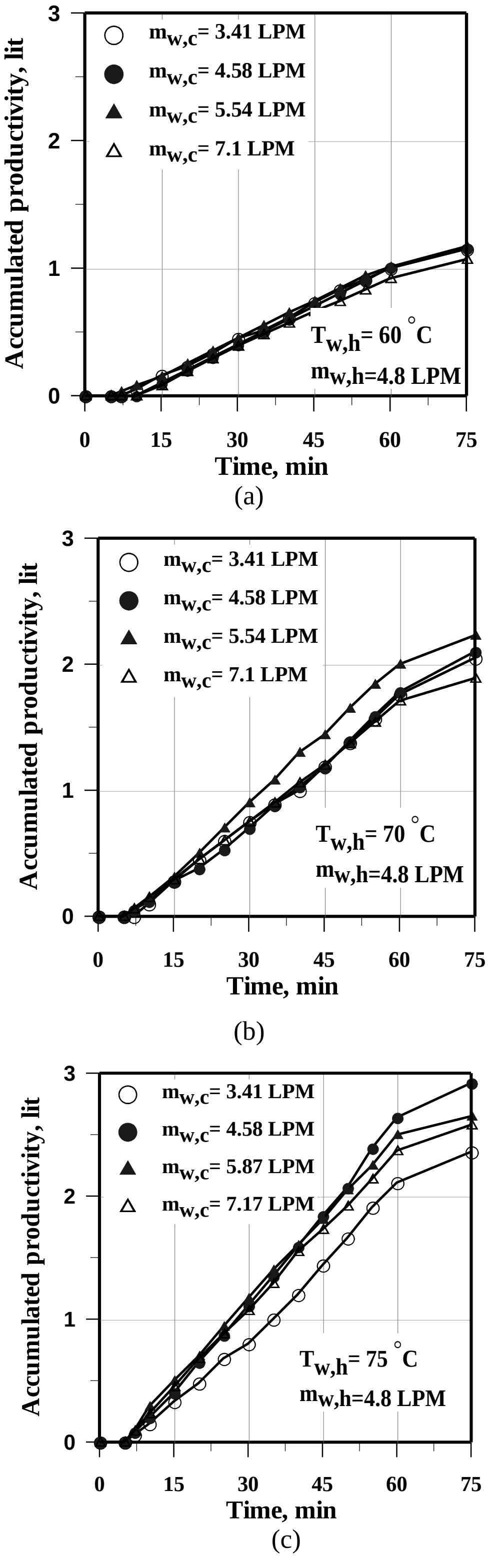


Fig. 5. The variation of accumulated productivity with time at the different cooling water mass flow rate and $\dot{m}_{w,h}$ = 4.8 LPM.

The variation of accumulated productivity with time at different inlet hot brackish water temperature (60, 70 and 75 ^{o}C) is presented in Fig. 6.

The experimental data are performed for cooling water mass flow rate of 4.58 lit/min and hot water mass flow rate of 4.8 lit/min. As shown from Fig. 6, the maximum fresh water productivity of about 1.3 lit/h is obtained in 60°C heating brackish water temperature where as 70 °C heating brackish water temperature records a productivity of 2.14 lit/h and 75 °C temperature records as 2.95 lit/h. Higher heating brackish water temperature increases the temperature difference between heating and cooling water. Hence, high fresh water productivity is obtained.

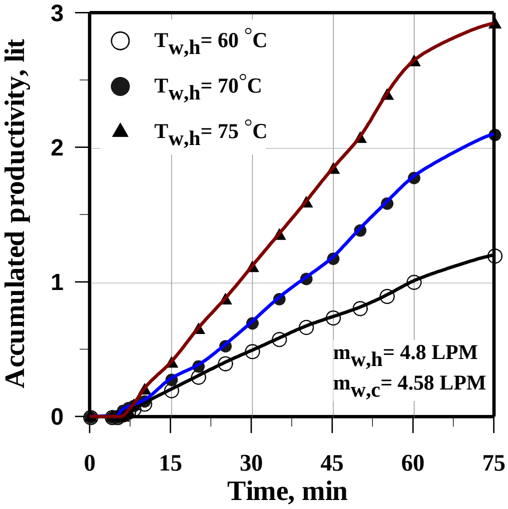


Fig.6 Variation of accumulated productivity with time at different inlet heating brackish water temperatures.

The variation of fresh water productivity with cooling water mass flow rate at different inlet heating brackish water temperatures and heating brackish water mass flow rate of 4.8 lit/min is presented in Fig. 7. As shown from Fig.7, the fresh water productivity increases to (1.2 lit/h at 60°C, 2.2 lit/h at 70°C and 2.95 lit/h at 75°C) respectively and then decrease. The maximum productivity of fresh water is about 2.95 kg/h at inlet heating brackish water temperature 75 °C and mass flow rate of cooling water of 4.58 lit/min. That is because of increasing the vapor and not enough cooling surface area.

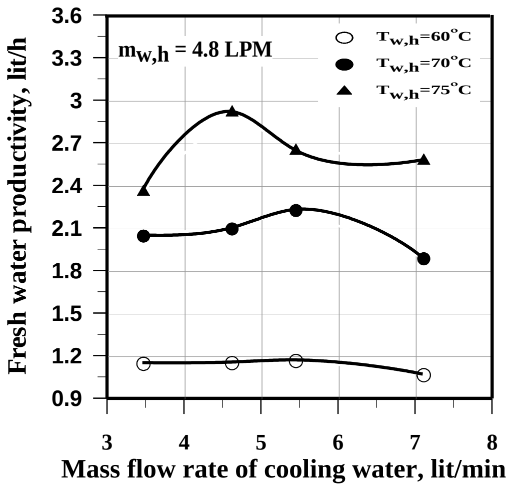


Fig.7 The variation of fresh water productivity with the cooling water mass flow rate at different inlet heating brackish water temperatures.

The variation of efficiency with the cooling water mass flow rate at different inlet heating brackish water temperature and for heating brackish water mass flow rate is 4.8 lit/min is presented from Fig.8. The efficiency increases with temperature, but at a mass flow rate of cooling water of 5.24 lit/min the efficiency increases to (61.14% at 60 °C and 79.23% at 70 °C) and then decrease. As seen from Fig.8, the maximum efficiency is about 85% at inlet heating brackish water temperature 75 °C and mass flow rate of cooling water of 4.58 lit/min.

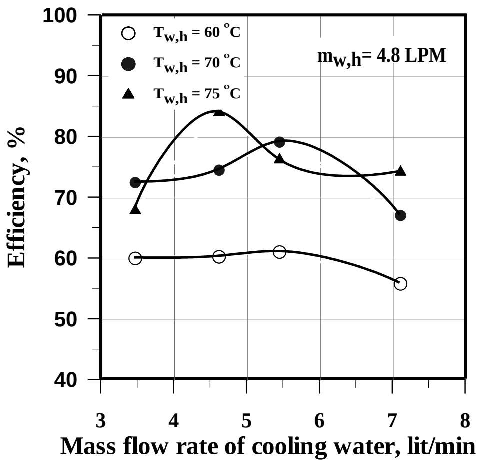


Fig.8 The variation of efficiency with cooling water mass flow rate at different inlet heating brackish water temperatures.

The variation of fresh water productivity with the ratio ($m_{w,h}/m_{w,c}$) at different inlet heating brackish water temperature and cooling water mass flow rate of 4.58 lit/min is presented in Fig.9. The fresh water productivity increases with inlet heating brackish water temperature. The maximum fresh water productivity is about 2.95 lit/h at inlet heating brackish water temperature of 75 ^oC and the ratio ($m_{w,h}/m_{w,c}$) =1.0412.

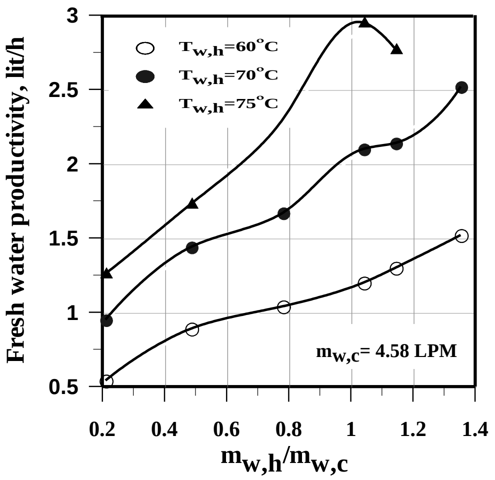


Fig. 9 The variation of fresh water productivity with the ratio ($m_{w,h}/m_{w,c}$) at different inlet heating brackish water temperatures..

The variation of efficiency with the ratio ($m_{w,h}/m_{w,c}$) at different inlet heating brackish water temperatures is presented in Fig.10. The experimental data were performed at cooling water mass flow rate of 4.58 lit/min. As shown in Fig.10, efficiency increases with inlet heating brackish water temperature and the ratio ($m_{w,h}/m_{w,c}$) but at ratio ($m_{w,h}/m_{w,c}$) of 1.0412, the efficiency increases to (75% at 70 ^oC and 85% at 75 ^oC) and then decrease. That is because of increasing the vapor and not enough cooling surface area.

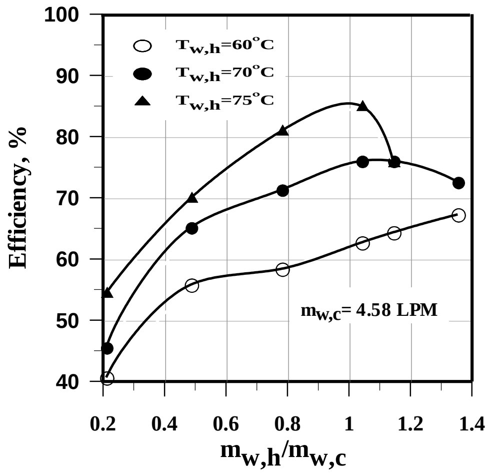


Fig.10 The variation of efficiency with the ratio ($m_{w,h}/m_{w,c}$) at different inlet heating brackish water temperatures.

6. Conclusion

The technique of evaporation and condensation at relatively low temperatures up to 75°C. The modified model is designed in this study to enhance the efficiency of the low temperature desalination system by using thermal 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 following conclusions are obtained:

- The unit starts to output freshwater after ten minutes of operation and becomes steadly about twenty later.
- The freshwater productivity, energy 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 maximum water productivity, efficiency, and energy consumption are 2.95 lit/h, 85 % and 0.82 kWh/kg at temperatures of 75 ^oC and

mass flow rate of 4.8 LPM of heating brackish water

- The $m_{w,h}/m_{w,c}$ equal 1.412 is the more compatible value with the used system configurations.
- The model is expected to be used for the development of methods of desalination by solar energy.

References

[1] J. Bendfeld, C. H. Broker, K. Menne, E. Ortjohann, L. Temme, J. Vob, P. C. M. Carvallo, Design of a PV-powered reverse osmosis plant for desalination of brackish water, Proceedings of 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna, Austria, (1998) 3075-3077.

[2] H. Garg, R.S. Adhikari, R. Kumar, Experimental design and computer simulation of multi-effect humidification (MEH)–dehumidification solar distillation, Desalination 153 (2002) 81–86.

[3] H. Ben Bacha, M. Bouzguendra, T. Damak, M.S. Abid, A.Y. Maalej, A study of a water desalination station using SMCEC technique: production optimization, Renewable Energy 21 (2000) 523–536.

[4] A. Midilli, T. Ayhan, Natural vacuum distillation technique–part I: theory and basics, Int. J Energy Res. 28 (2004) 355–371.

[5] A. Midilli, T. Ayhan, Natural vacuum distillation technique – part II: experimental investigation, Int. J Energy Res. 28 (2004) 373–389.

[6] V.G.Gude, Desalination using low grade heat sources, Pro Quest Dissertations & Theses (PQDT), New Mexico State University 2007.

[7] N.N. khandan, V. G. Gude, Desalination using low-grade heat sources, Journal of Energy Engineering 134 (2008) 95-101.

[8] V. G.Gude, N. Nirmalakhandan, Sustainable desalination using solar energy, Energy Conversion and Management 51 (2010) 2245-2251.

[9] V. G. Gude, N. N. khandan, S. Deng, Sustainable low temperature desalination: A case for renewable energy, Journal of Renewable and Sustainable Energy 3 (2011) 1-25.

[10] V. G. Gude, N. N. khandan, S. Deng, A. Maganti, Low temperature desalination using solar collectors augmented by thermal energy storage, Applied Energy 91 (2012) 466-474.

[11] H. Shaobo, Z. Zhang, Z. Huang, A. Xie, Performance optimization of solar multi-stage flash desalination process using Pinch technology, Desalination 220 (2008) 524–530.

[12] A. Nafey, M. Mohamad, S. Elhelaby, M. Sharaf, Theoretical and experimental study of a small unit for solar desalination using flashing process, Energy Convers Manage 48 (2007) 528–538.

[13] A. M. El-Zahaby, A. E. Kabeel, A. I. Bakry, S. A. El-Agouz, O. M. Hawam, Augmentation of solar still performance using flash evaporation, Desalination 257 (2010) 58–65.

[14] A. M. El-Zahaby, A. E. Kabeel, A. I. Bakry, S. A. El-Agouz, O. M. Hawam, Enhancement of solar still performance using a reciprocating spray feeding system-An experimental approach, Desalination 267 (2011) 209-216.

[15] N. C. Barford, Experimental measurements: precision, error and truth, 2nd ed. New York: John Wiley & Sons; 1990.

Table 1. Energy consumption of different heating brackish water temperature and cooling water mass flow rate at $\dot{m}_{w,c} = 4.58\ \mathrm{lit/min}$.

$\dot{m}_{w,h}$ Lit/min	$\dot{m}_{w,c} = 4.58$ lit/min		
	60 °C	**70 °C**	**75 °C**
	Power consumption kWh/kg	**Power consumption kWh/kg**	**Power consumption kWh/kg**
0.96	1.7	1.52	1.28
2.22	1.24	1.07	0.99
3.57	1.18	0.97	0.86
4.8	1.1	0.92	0.82
5.24	1.07	0.91	0.92
6.2	1.03	0.96	--------

Table 2. Energy consumption of different brackish water temperature and cooling water mass flow rate at $\dot{m}_{w,h} = 4.8$ lit/min

$\dot{m}_{w,c}$ Lit/min	$\dot{m}_{w,h} = 4.8$ lit/min		
	60 °C	**70 °C**	**75 °C**
	Power consumption kWh/kg	**Power consumption kWh/kg**	**Power consumption kWh/kg**
3.41	1.15	0.96	1.03
4.58	1.145	0.936	0.83
5.54	1.13	0.88	0.913
7.1	1.23	1.04	0.94