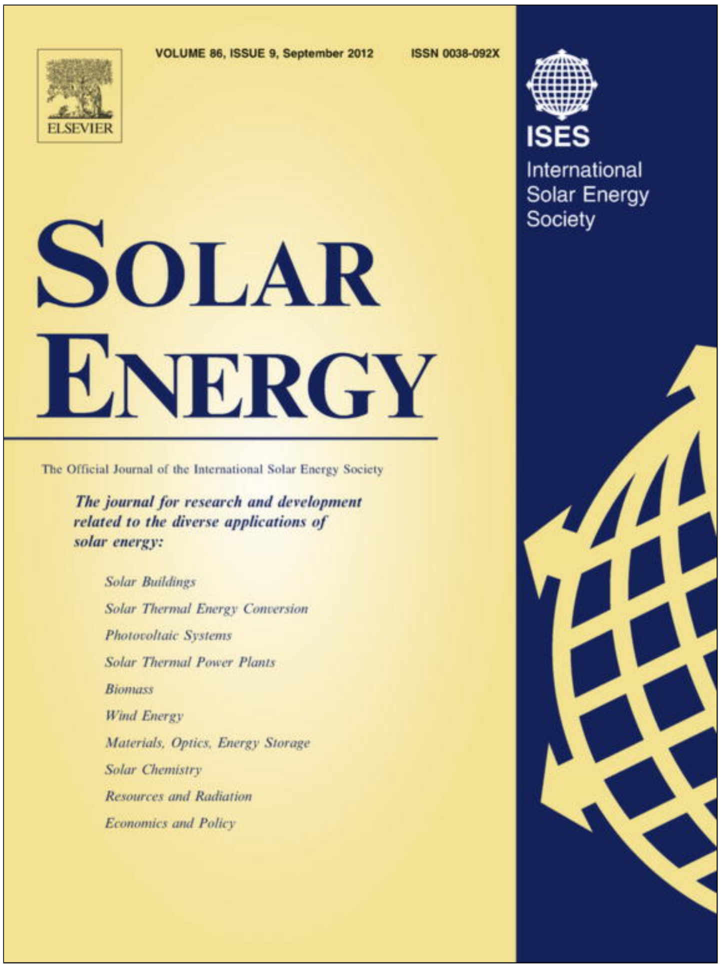
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Thermal analysis for system uses solar energy as a pressure source for reverse osmosis (RO) water desalination

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Abstract

As Natural resources are becoming limited and energy price dramatically increased, energy utilization with efficient systems is essentially required to be used in desalination technologies. The use of solar energy in desalination processes is one of the most promising applications of renewable energies. The primary focus on desalination by solar energy is suitable for use in remote areas. A proposed desalination system uses solar radiation, which concentrated by parabolic dish to heat up the working fluid in a closed space. Then the generated pressure in this space used to push salt water into RO module.

Daily production rate of fresh water quantity for suggested system compared with other solar techniques is a promising rate for each m^2 of solar radiation collecting surface. The production rate for one operation cycle could reach to 1800 L/cycle of fresh water at low water salinity (Brackish water with 5000 ppm) and 55 L/cycle at highest water salinity (sea water salinity with 42,000 ppm). The required energy needed to produce 1 kg of fresh water is also promising even when in case of using another type of energy, also operating cycle has ability of repetition according to salinity concentration through sunny hours.

Keywords: Desalination; Solar energy; Reverse osmosis (RO); Thermal desalination; Solar desalination

1. Introduction

Desalination systems are divided into two main types thermal and non-thermal. Thermal type desalination plants such as multi stage flash (MSF), vapor compression (VC), solar distillation and freeze desalination uses heat either direct heating or heat moving. Other systems are classified as non-thermal system such as reverse osmosis (RO), capacitive deionization technology (CDT). Actually cost for each method depends mainly on type of physical process of salt removal (i.e. evaporation, filtration, freezing or electrostatic potential difference). The efficiency of each type depends on the total energy required to remove the salt particles which depends on some extent on the method of operation and also on the purity of the required water.

Solar energy will play a critical role in sea water desalination. A great attention should be given to develop new techniques for improving efficiency and productivity of solar desalination systems. Solar desalination techniques can either be direct or indirect. Direct system uses solar energy to produce distilled water directly from solar distiller. Indirect system combines conventional desalination techniques such as vapor compression (VC), reverse osmosis (RO), membrane distillation (MD), and electro dialysis (ED) with solar collector as source of heat or photovoltaic as source of electricity.

An enhancement for traditional solar energy in desalination process by developing multi-stage distiller connected with an evacuated tube heat pipe solar collector. A multi-stage solar still water desalination system was designed to

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Nomenclature

A	collector area (m^2)
E	constant (radiation losses constant) $E = \delta * (A = 1\mathrm{m}^2) * 5(\mathrm{minutes}) * (60\ \mathrm{sec})$ ($\mathrm{J/K}^4$)
δ	(Boltzmann constant) $= 5.76 \times 10^{-8}$ ($\mathrm{W/m^2\ K^4}$)
I_O	solar constant 1336 ($\mathrm{W/m}^2$)
η_{ref}	Reflection efficiency for Dish concentrator surface (–)
θ	the angle of incident between the solar radiation beam and the imaginary line normal to surface (°)
φ	latitude angle (°)
δ	declination angle of the celestial sphere measured northward or southward from the celestial equator plane (°)
ω	hour angles (°)
β	Inclination angle of the collector (°)
γ	surface–azimuth angle (how far the solar collector deviates from the north–south axis (°)
n	day number according to Julian days (–)
Q_{in}	Total heat coming from the collector (W)
Q_{used}	actual energy used (W)
C_p	specific heat for metals of (J/kg K)
I	solar radiation ($\mathrm{W/m}^2$)
t_t	initial temperature of the system (°C)
T_a	ambient temperature (°C)
m_{wf}	Charge amount of working fluid (kg)
h_i	initial enthalpy of working fluid (kJ/kg k)
m_{copper}	mass of metals of working fluid housing includes boiling bubble, piping and first part of pressure tank (kg)
h_f	fluid enthalpy of working fluid at certain saturation temperature (kJ/kg k)
h_g	vapor enthalpy of the working fluid at certain saturation temperature (kJ/kg k)
v_f	fluid specific volume of working fluid at certain saturation temperature (m^3/kg)
v_g	vapor specific volume of working fluid at certain saturation temperature(m^3/kg)
v_t	specific volume of working fluid at certain saturation temperature (m^3/kg)
m_v	mass of working fluid that founded in vapor form (kg)
m_f	mass of working fluid that founded in liquid form(kg)
x	dryness fraction of the working fluid at certain saturation temperature
W	work done (J)
w	specific work done (J/kg)
P	pressure ($\mathrm{N/m}^2$)

recover latent heat from evaporation and condensation processes in multi stages (Shatat and Mahkamov, 2010). Using solar in RO system is done using photovoltaic cells, which converts solar radiation into electricity. The output electricity used to operate the salty water pump into RO module. An economic analysis for the RO and the power supply system is presented. Also system simultaneously exploits the waste heat of photovoltaic cells to desalinate water (Tzen, 1998; Mittelmen et al., 2009). Also, a scheme exploits the vapor pressure difference between fluids of different salinities and temperature to produce fresh water from seawater. In this scheme, heat is injected into sea water use solar energy to produce distillate directly in solar distiller.

2. System description

The proposed system consists of solar collector (parabolic dish concentrator type with spherical tank (boiling bubble) in its focal point), pressure tank (which, divide into two parts-separated by movable piston- first and second part) and RO module. The solar radiation has been concentrated on focal point where boiling bubble, which containing working fluid exists. With accumulation of heat during day hours the temperature and pressure increases inside boiling bubble due to working fluid evaporation in a closed space. The pressure increases till reaches to operating pressure of RO module. During this time the generated pressure in boiling bubble applied on movable piston through pipe connected to first volume of pressure tank. The movable piston pushes the salt water that fills second volume of pressure tank into RO module. The fresh water comes out from fresh water side of RO module with the movement of movable piston in pressure tank. The volume swapped by the movable piston is equal to fresh water production rate. At the end of the day piston moves come back again to original position by reducing pressure through condensing steam. The condensation process is done by allowing cooling water to flow around pressure tank.

The piping system, boiling bubble, and first part of pressure vessel form continuous volume. The formed volume (first volume) contains specified amount of working fluid (mostly pure water) which will evaporate in closed space (heat add at constant volume process) causing pressure and temperature raise. In pressure vessel the movable piston separates working fluid in first volume and salt water that fills second volume. The second volume connected to RO module through pipes with flow control valves. The piston designed to reduce heat lost from hot pressure side

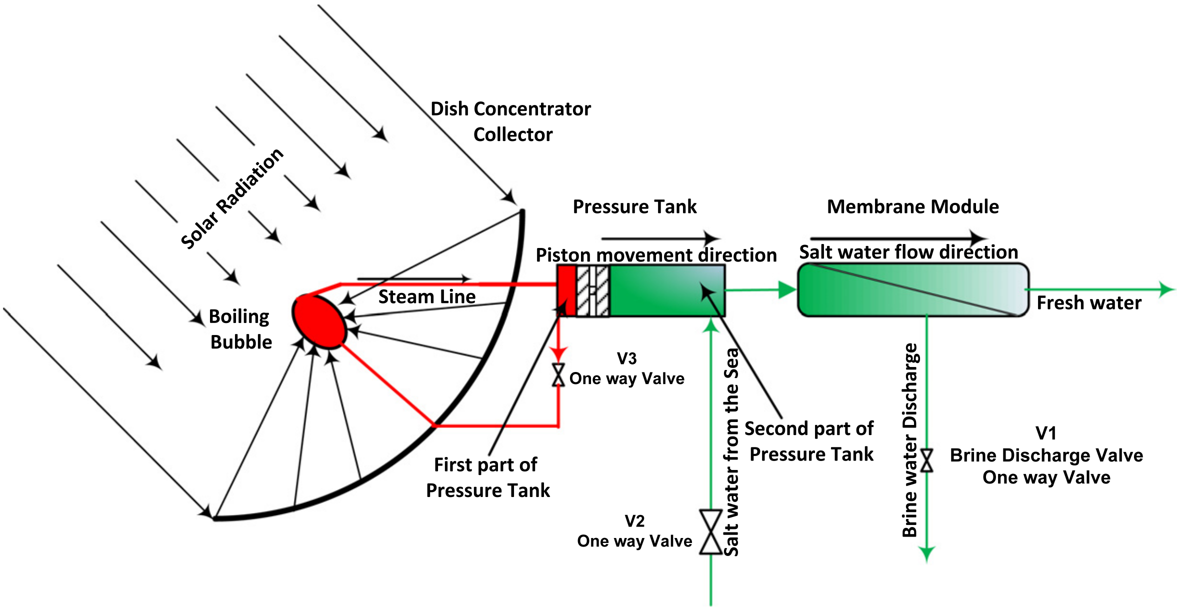

Fig. 1. System layout.

(in pressure vessel first volume) to salt water (in pressure vessel second volume). RO module is selected according to properties of salt concentration on saltwater or TDS values. Specification of RO Module determines required value of operating pressure.

Finally the system could be described as two parts. First Volume consists of boiling bubble, first part of pressure tank and piping system connected between them (see Fig. 1). It forms closed loop which always maintain the working fluid in form of liquid state at focal point inside boiling bubble. It also contains a fixed amount of working fluid. The Second volume consists of RO module, second part of pressure tank and piping system connected between them (green color in Fig. 1 at right).

3. System operation and thermal analysis

Before start of system operation cycle first volume (boiling bubble, piping system and first part of pressure tank) should evacuate from residual gases, then charged with a specified amount of working fluid. Also, the second volume should filled by salt water. The system operation cycle is divided into three stages.

3.1. Stage one

Start of operation (early morning of the day) working fluid in boiling bubble is at 25 °C and 1.0 bar. The concentrated solar radiation, that coming from the collector reflecting surface, is used to heat up boiling bubble which contains working fluid. The temperature rose from 25 °C (ambient temperature) up to 100 °C (saturation temperature of atmospheric pressure). Process form state 1 to state 2, is a process of heat add at constant pressure. See Fig. 2.

$$\begin{aligned}&(\text{Heat comming from collector})\\&\quad = (\text{Heat stored in copper Tubing system})\\&\qquad + (\text{Heat Input to working fluid to raise its}\\&\qquad\quad \text{temperature tell it reaches}100^\circ\text{C})\\&\qquad + (\text{Heat Lost from system})\end{aligned} \quad (1)$$

$$\begin{aligned}&(\text{Heat Lost from the system})\\&\quad = (\text{Radiation heat Losses})\\&\qquad + (\text{Covection heat losses})\\&\qquad + (\text{Conduction heat loses})\end{aligned} \quad (2)$$

$$\begin{aligned}&(\text{Heat Lost from the system})\\&\quad = E(T_{i+1}^4 - T_a^4) + A * h * (T_{i+1} - T_a) + K * \frac{A}{x} * (T_{i+1} - T_a)\end{aligned} \quad (3)$$

Surface area of convection is small so the convection heat lost is neglected. Also the only way for conduction between first volume and second volume is through the movable piston. Also this piston is designed to reduce conduction between its two sides. Radiation heat loss is the major losses that should take in consideration. So that heat balance equation will be in the following form.

$$\begin{aligned}(Q_{in}) &= m_{\text{copper}} * C_{p_{\text{Copper}}} * (T_{i+1} - T_i) + m_{wf}\\&\quad * C_{p_{\text{water}}}(T_{i+1} - T_i) + E\left(T_{i+1}^4 - T_a^4\right)\end{aligned} \quad (4)$$

3.2. Stage two

At start of this stage the working fluid is at 100 °C and 1.0 bar. With more radiation coming, working fluid starts to evaporate, the pressure inside first volume increases and consequently saturation temperature (heat add at constant volume) in the first volume. This stages ends when

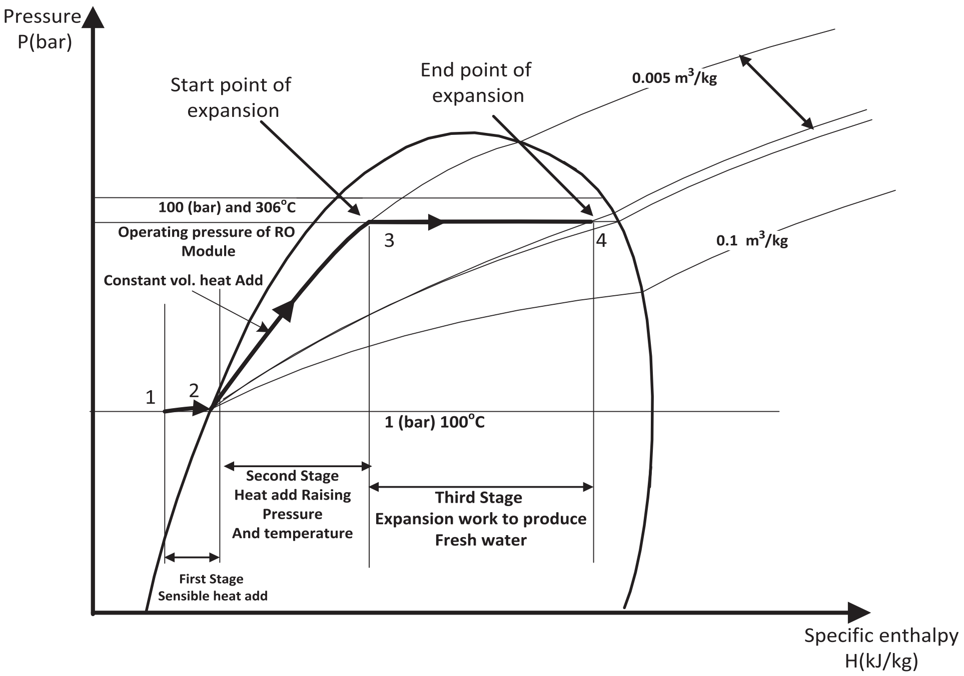

Fig. 2. Process layout on steam pressure enthalpy diagram.

pressure reaches to operating pressure of RO module. At state 2, fresh water will start to flow from throughout RO module.

$$\begin{aligned}&(\text{Heat comming from collector})\\&\quad=(\text{Heat stored in coppe Tubing system})\\&\qquad+(\text{Heat Input to working fluid(water)raising its}\\&\qquad\quad\text{temperature and pressure tell it reaches to}\\&\qquad\quad\text{operating pressure of RO module})\\&\qquad+(\text{Heat Lost from system})\end{aligned}\tag{5}$$

$$\begin{aligned}(Q_{in}) &= m_{\text{copper}} * C_{p_{\text{Copper}}} * (T_{i+1} - T_i) + m_{wf}(h_{i+1} - h_i)\\&\quad + E(T_{i+1}^4 - T_a^4)\end{aligned}\tag{6}$$

3.3. Stage three

During this stage the working fluid in first volume expands at constant pressure process (operating pressure of RO module) to produce fresh water through RO module and the energy equation will be as follow.

$$\begin{aligned}&(\text{Heat comming from the collector})\\&\quad=(\text{Heat Input evaporats working fluid(water)which}\\&\quad\quad\text{expands at constant temperature and pressure}\\&\quad\quad\text{producing freshweater through RO module})\\&\qquad+(\text{Heat Lost from the system})\end{aligned}\tag{7}$$

$$(Q_{in}) = m_{wf}(h_{i+1} - h_i) + E(T_{i+1}^4 - T_a^4)\tag{8}$$

The fresh water production rate is related to expansion rate of the working fluid in first volume which consequently related to amount of heat input to the system through solar concentrator through third stage. At the end of the day the system discharges the remaining brain salt water through the brine discharge valve. See Fig. 2.

Total quantity of fresh water produced per day is influenced by a lot of parameters like, operation day (which determine incoming solar radiation i.e. total quantity of heat input to the system), the working fluid type(latent heat and evaporation rate), specific volume of the working fluid at start of operation (i.e. mass of working fluid divided by value of the first volume, piping system and first part of pressure tank) and finally type of RO module (operating pressure which is related to salt concentration). Also the tilt angle of the collector surface affects on total heat coming to the system. The tilt angle optimization still needs large studies and should be compromised with the benefits of the system. The major conclusion stats that tilt angle in winter differ than tilt angle in summer. The tilt angles used in our calculation is stated in Table 1.

Computer program was built to calculate system performance. The program is divided into three modules. First module estimates incoming solar energy (radiation module). The energy is calculated each 5 min at different latitudes for any day of the year for any collecting surface tilt angle. Second module is for calculating working fluid saturation properties (pure water in this study). The working fluid saturation properties are estimated using correla-

Table 1
Tilt angle.

Month	Tilt angle
From 21 March up to 21 September (Summer)	$\phi - 11.75$
From 21 September up to 21 March (Winter)	$\phi + 11.75$

For latitude 30.5 (Cairo-Egypt) surface tilt angles will be 42.25 for Winter and 18.75 Summer.

tions for each property as function of working fluid saturation temperature. The third module is for system performance calculations.

4. Calculation procedure

Program calculation procedure will be done as follow. The program main input parameters are as follow. Total collecting surface are 1 m^2. Latitude for system operation is 30.5 (Cairo Egypt). Tilt angle for calculation is 42.25 and day of calculation is 21-December. The parabolic dish reflection surface efficiency is $\eta_{\text{ref}} = 90\%$.

With above constants the calculation is done with the following procedure.

Step 1: at Julian day no n = 355 (21 December) get value of I, at start time from 0:00:00

$$I = I_O * \cos(\theta) \tag{9}$$

where

$$\cos(\theta) = \sin(\delta)\sin(\emptyset)\sin(\beta) - \sin(\delta)\cos(\emptyset)\sin(\beta) \times \cos(\gamma) + \cos(\delta)\cos(\emptyset)\cos(\beta)\cos(\omega) + \cos(\delta)\sin(\emptyset)\sin(\beta)\cos(\gamma)\cos(\omega) + \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega) \tag{10}$$

$$\delta = 23.45\sin\left(\frac{360}{365}(n+284)\right) \tag{11}$$

$$\omega = 15(12 - h) \tag{12}$$

when $I > 0$ the system starts to heat up and calculation procedure is as follow.

At time of sun rise $T_i = 25$ °C

Step 2: The value of heat input through 5 min

$$Q_{in} = \eta_{\text{ref}} I * 60 * 5 \tag{13}$$

Process from point 1 to point 2, see Fig. 2 (sensible heat add)

Step 3:

$$T_{i+1} = T_i + 0.005 \tag{14}$$

The value of temperature step is related to sensible heat for solid and liquid combination because the sensible heat is very sensitive to temperature so that the step value should be low. This gives the following heat ratios for water only $(0.005 * 4200 * 1/(500 * 60 * 5)) = 0.00014$. This will be about 0.014% accuracy which will be sufficiently accurate.

Step 4: Get the value

$$m_{\text{copper}} * C_{p_{\text{copper}}} * (T_{i+1} - T_i) + m_{wf} * C_{p_{\text{water}}}(T_{i+1} - T_i) + E(T_{i+1}^4 - T_a^4) \tag{15}$$

Step 5: Check if

$$Q_{in} - (m_{\text{copper}} * C_{p_{\text{copper}}} * (T_{i+1} - T_i) + m_{wf} * C_{p_{\text{water}}}(T_{i+1} - T_i) + E(T_{i+1}^4 - T_a^4)) < 0.5 \tag{16}$$

If No Then $T_i = T_{i+1}$ and repeat process from step 3 till step 5

If yes go to *step 6*

(The difference check value in heat balance is related to the average of input heat through the day is about 500 J/s and $Q_{in} = 60 * 5 * 500$ so the value of division of $0.5/(300 * 500)$ is about 0.00000333 which mean that the accuracy of calculation is about 0.00033%. Also the value of ambient temperature should vary through the operating hours of the day but we decide that it is more valuable studying system with constant ambient temperature at low level to increase the losses i.e. the worst case study performance.)

Step 6: check $T_i < 100$ °C

If Yes Then $T_i = T_{i+1}$ and get next value of (I) for next 5 min as stated in step 1 and step 2 and repeat process from step 3 up to step 6.

If No Then $T_i = T_{i+1}$ and then go to *step 7*

Process from point 2 to point 3, see Fig. 2 (constant volume heat add)

Step 7: For $T_i = 100$ °C get value of $h_t = h_i = h_f$ at $T_i = 100$ °C

Step 8: Get next 5 min heat add to system as stated in step 1 and step 2

Step 9:

$$T_{i+1} = T_i + 0.05 \tag{17}$$

(The temperature step in Eq. (17) is related to latent heat of water. The value of latent heat is much higher than sensible heat so the value used in Eq. (17) could be greater than that used in Eq. (14). The value of temperature is not related to temperature step directly but through the latent heat of phase change. The value of temperature step 0.05 gives about 1 kJ/kg latent heat step which its ratio to total latent heat is about (1/(2256 (kJ/kg) (latent heat at 100 °C)))=0.000374 about 0.0347% accuracy.)

Step 10: get value of h_f, h_v, V_f and V_g working fluid saturation properties at T_{i+1}

Step 11:

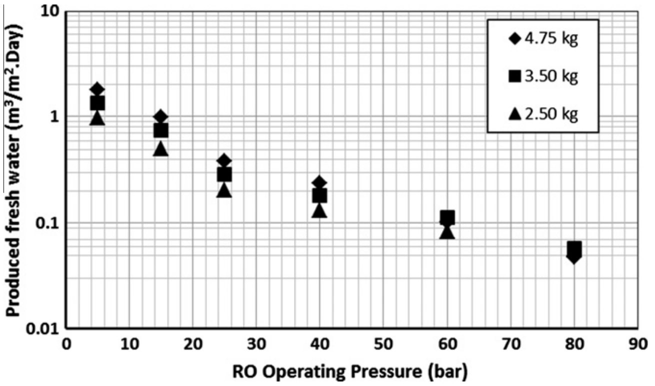

Fig. 3. Effect of RO module operating pressure on productivity at different working fluid charged amount(kg) (21 December, 1 m^2 collector area, volume 0.01 m^3, Latitude 30.5 Cairo, Egypt).

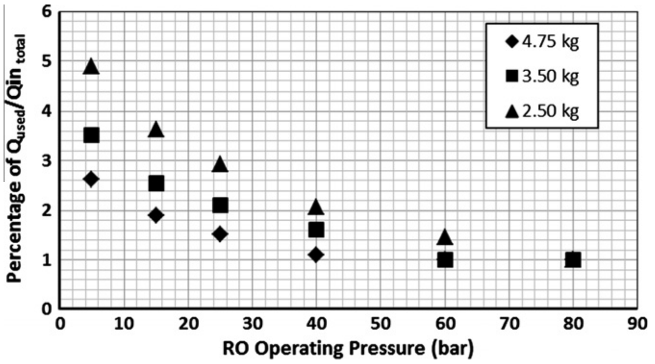

Fig. 4. Effect of operating pressure of RO module on percentage of total energy coming to system to used energy in one cycle of system operation at different working fluid charged amount(kg) (21 December, 1 m^2 collector area, volume 0.01 m^3, Latitude 30.5 Cairo, Egypt).

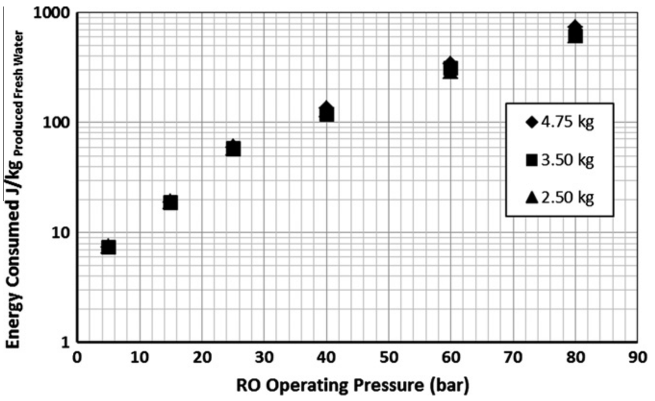

Fig. 5. Effect of operating pressure of RO module on energy consumed.(J/$kg_{\text{Produced Fresh Water}}$) at different amount of working fluid charge (kg) (at 21 December, 1 m^2 collector area, volume 0.01 m^3, Latitude 30.5 Cairo, Egypt).

$$V_t = \frac{\text{total volume of piping system and bubble of working fluid}(V_{\text{piping}})}{\text{Total mass of the working fluid}(m_{wf})} \tag{18}$$

Step 12: get

$$x = \frac{V_t - V_f}{V_g - V_f} \tag{19}$$

Then

$$h_{i+1} = (1 - x)h_f + xh_v \tag{20}$$

Step 13: check if

$$(Q_{in} - (m_{\text{copper}} * C_{p_{\text{copper}}} * (T_{i+1} - T_i) + m_{wf}(h_{i+1} - h_i) + E(T_{i+1}^4 - T_a^4))) < 0.5 \tag{21}$$

If No then $T_i = T_{i+1}$ and repeat procedure from *step 9* up to *step 13*

If yes then

Check if P_i = operating pressure of RO module or not

If No then $T_i = T_{i+1}$ and repeat procedure from *step 8* up to *step 13*

If yes then $T_i = T_{i+1}$ and get value of h_i then go to *step 14*

Process from point 2 to point 4 (constant pressure heat add (expansion process))

Step 14: Get next 5 min heat add to system as stated in step 1 and step 2

Step 15: Get value of h_f, h_v, V_f and V_g working fluid saturation properties at operating pressure of RO module.

Step 16:

$$\nabla m_v = \frac{Q_{in}}{h_v - h_l} \tag{22}$$

Step 17:

$$\nabla x = \frac{\Delta m_v}{m_{wf}} \tag{23}$$

Step 18: get

$$x = x_{i+1} + \nabla x \tag{24}$$

Step 19:

$$V_t = (1 - x)V_f + xV_g \tag{25}$$

Step 20:

$$\Delta m_{\text{fresh water}} = \rho(V_{t(i+1)} - V_{t_{(i)}}) \tag{26}$$

Then go to step 14.

At the end of the day or at the end of cycle at each operating pressure the system should come back again to its original position and start again. This will be appeared when a specified operating pressure is selected and specified design details will introduce. The system could come back again to its original position by cooling coil wrapped around the piston then allow to Cold sea water to flow through it after the end of operation cycle or by releasing the compressed vapor in pressure tank after the end of operation cycle.

Table 2
Comparison between work requirements for different water desalination methods stated in references Lara et al. (2008) and that required for suggested system.

Energy used	Multi-stage flash	Reverse osmosis	Conventional vapor compression	Theoretical high temperature vapor compression		Present work 21 December 0.01 volume 4.75 kg working fluid Charge		
				Case C	Case A	80 bar (42,000 ppm)	40 bar (22,000 ppm)	5 bar(2500 ppm)
Work (MJ/kg)	14.4	21.6–36.0	21.6–36.0	15.7	27.7	0.735	0.133	0.007

Table 3
Comparison between different water desalination methods productivity that stated in references (Qiblawey, 2008; Moghadam, 2011; Karagiannis, 2008; Charcosset, 2009; Shatat and Mahkamov, 2010; Tzen, 1998; Joyce, 2001; Hawlader, 2004; El-Dessouky, 2002; Nassar, 2007; Sen, 2008; Abdel Dayem, 2007; Lara et al., 2008; Mittelmen et al., 2009; Manolakos et al., 2009; Bemporad, 1995; Garacia-Rodriguez, 2003; Al-Hallaj et al., 2006) and that for suggested system.

Energy used	Single effect solar stills	Diffusion still (4 units)	Multiple effect basin still	Solar MEH	MSF Solar powered	Present work 21 December 0.01 volume 4.75 kg working fluid Charge		
						80 bar (42,000 ppm)	40 bar (22,000 ppm)	5 bar (2500 ppm)
Productivity (L/m^2 d)	4–5	8.7	25	13	6–60	55	200	1800

Then recharge the piston with specified charge amount of water.

The operation cycle could repeat if the system reaches to end point of cycle at suitable sunny time when the remaining sunny time allows to the cycle to be repeated completely.

5. Discussion

The system productivity is greatly influenced with RO module operating pressure. Fig. 3 represents the effect of operating pressure RO module on the productivity of the suggested system at different working fluid charge amount. More operating pressure of RO module increases more produced fresh water quantity decreases. This is because more RO pressure increases more need for energy to overcome increase in pressure.

Effect of operating pressure of RO module on percentage of total energy coming to system with respect to actual energy used at different charged amount of working fluid is shown in Fig. 4. This percentage is useful in determining ability of repeating operation cycle of the system during day hours. This due to that quantity of working fluid may completely evaporate during period of operation time. The cycle of operation could be repeated many times equal to this percentage. This means that the productivity at certain operation condition could be multiplied by this ratio. The more charged amount of working fluid increases the more ability of repeating decreases.

Energy consumed for producing one kg of fresh water is studied. See Fig. 5. The working fluid charged amount has no effect on energy consumed. With increase of RO module operating pressure the consumed energy increases due to need to overcome pressure. Table 2 shows comparison between the consumed energy for this system with other desalination systems. The comparison shows that the suggested system has a promising value for energy consumption for each kg of produced fresh water.

Table 3 shows comparison between productivity of the system and other types of system that listed in references (Qiblawey, 2008; El-Dessouky, 2002). The comparison show that system productivity compared with other systems in case of using solar energy is very promising.

6. Conclusion

Solar desalination by suggested system increases the productivity for each m^2 of solar radiation collecting surface. The productivity reaches up to 1.833 m^3/m^2 day at low operating pressure (brackish water). The productivity decreases with the increase of operating pressure where at 80 bars it becomes about 0.055 m^3/m^2 day which is suitable for sea water desalination. The suggested system gives a large quantity of production rate of fresh water with respect to other solar desalination system. And it is also suitable for remote areas at different type of water source.

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