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Thermodynamic analysis of a single and two-stage solar assisted air-cooled flash evaporation desalination system for small-scale applications

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ABSTRACT

Thermodynamic analysis of a single and two-stage air-cooled desalination system assisted by solar energy is presented. The proposed single and two-stage system is simulated for various operating parameters such as incident solar radiation, pressure in the flash vessel and temperature of the feed water. The results of the analysis show that the amount of distillate yield obtained in the single-stage system in a year ranges from 2.77 to 3.61 kg/h, while the yield of the two-stage system ranges from 4.38 to 6.03 kg/h. The improvement in yield of the two-stage system is found to be about 36–40% higher than that of the single-stage system. The ambient air temperature has a significant impact on the performance of the air-cooled condenser used in the system.

Keywords: Air-cooled; Flash evaporation; Solar desalination; Two-stage; Vacuum

1. Introduction

The fresh water availability on this planet earth has been consistent since the origin of life. However, the scarcity of clean water with acceptable standards is a pressing problem today, and it is expected to intensify in the years to come. Man-made activities like excessive deforestation, rapid modernization and increase in population have lead to the non-uniform distribution of rainfall and severe changes in the weather patterns. The available fresh water sources like lakes, rivers and underground water supply are not able to meet the demand for potable water. Hence, the advent of new alternatives and technologies has taken centre stage in almost all the countries to solve this serious crisis.

Desalination is a feasible alternate in which the saline water available in abundance in the oceans is converted into potable water. Solar thermal desalination, which replicates the natural water cycle, is an energy intensive process. The integration of solar energy in the process of converting seawater to fresh water is one of the most promising applications to resolve the water crisis. The free availability and insignificant operating cost of solar-based desalination units make them best suited for small-scale production, especially in remote arid areas and islands, where solar insolation is good and the supply of conventional energy is scarce [1].

However, intensive research has been carried out over the past 30 years enabling the large-scale solar-based systems to be a feasible source of fresh water in industries and market places. But, a consistent effort is the need of the hour in the development of the

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solar-based desalination technologies for small-scale applications in rural and remote arid areas [2].

2. Literature background

Many researchers around the globe have attempted to develop desalting unit for small-scale domestic purposes utilizing the waste heat or other forms of thermal energy. Over the past 20 years, the development of such systems has not progressed beyond the demonstration status. The developments in small-scale systems that are financially and commercially viable are yet to be a reality.

Experimental investigation to study the feasibility of using non-conventional energy sources in a vacuum desalination system to produce potable water has been reported in the literature [1]. Utilizing the waste heat from a low-pressure steam outlet, the system yielded a maximum distillate of 1.46 l/h. Experiments have been conducted to analyse an innovative desalination system with passive vacuum, utilizing the low-grade solar heat [3]. The effect of withdrawal rate and depth of water in the evaporator on the distillate yield were found to be very small, whereas the effect of heat source temperature was found to be significant. Further study on the same system [4] shows that the output reached 6.5 kg/d/m^2 of evaporator area. The experiments conducted on a low-pressure vaporization system [5] using barometric vacuum produced distillate in the range of 3–4% of the inlet brine at an injection pressure of 0.1 MPa using swirl nozzles. Another single-stage solar desalination system [6] developed yielded maximum distillate of 8.5 l/d with a solar collector area of 2 m^2.

The technical feasibility of a solar-powered barometric desalination system [7] has been analysed, in which the vacuum produced in the vaporizer was due to the elevation of the vaporizer above mean sea level. It was estimated that a solar panel with an area of 4.73 m^2 would be sufficient to provide 30 L of distillate per day, which is considered as the minimum requirement of one person. The study [8] on modelling and experimentation of a small-scale solar desalination based on barometric vacuum using a flat plate collector of area 4 m^2 with an efficiency of 50% provided 14–17 kg of distillate per day. This fresh water is sufficient for the basic water needs of an average family in the areas facing severe drinking water problems. The investigations [9] on the performance of a small water desalination system based on solar energy and flash evaporation process yielded 4.2–5.0 and 5.44–7.0 kg/d/m^2 of distillate during the month of June and July, respectively. The studies [10], on a pilot plant with Natural Vacuum Desalination technology, show that this system can supply distilled water throughout the year at the rate of 1.32–10.79 l/h. An absorption system [11] using water–lithium bromide solution as working fluid shows that it is possible to generate distillate at a rate of 4.1 kg/h utilizing the heat rejected from the absorption system. Another low-pressure evaporation fresh water generation system [12] which uses an ejector to create vacuum in the evaporator was able to generate maximum distillate of 0.04 l/h at a feed water temperature of 80°C.

The theoretical analysis [13] of a single-stage and two-stage solar driven flash desalination system based on passive vacuum generation utilizing the solar input from the collector area of 1 m^2 has also been reported. It is found that the single-stage system produced 5.54 kg of distillate in 7.83 h (0.7 l/h) while the two-stage system produced 8.66 kg of distillate in 7.7 h (1.12 l/h). The feasibility studies [14] on a two-stage low-temperature desalination process show an average distillate production rate of 11.34 l/h from first stage and 9.6 l/h from second stage while the feed water is injected at 64°C at the rate of 2,100 l/h. The theoretical simulation and experimental investigation [15] carried out under the climatic conditions in Middle East produced a fresh water output of 17.5 kg/m^2/d utilizing the solar energy collected by an evacuated tube solar collector of 2 m^2 area. A recent study on the use of nanofluid-based solar collector on a novel integrated flashing desalination system [16] generated fresh water up to 7.7 l/m^2/d.

It is observed from the review of literature that the low-temperature small-scale desalination systems that have been analysed are based on water-cooled systems. No attempt has been made to utilize air as a cooling medium for the condenser. Besides, only a few attempts have been made to develop a two-stage desalination system for fresh water generation. It is also inferred from the literature that utilization of vacuum pump for producing low pressure in the evaporator is also limited. Hence, the present research work focuses on the development of a small-scale air-cooled single and two-stage desalination system assisted by solar energy that could meet the fresh water needs in domestic and rural areas.

3. Novelty of the proposed system

The proposed system utilizes a vacuum generation pump and an air-cooled condenser that condenses the distillate generated from the single-stage and two-stage desalination systems. Previous study [14] suggests that it is feasible to design an air-cooled condenser to reduce pumping requirements in small-scale domestic low-temperature desalination systems.

Moreover, the free availability of clean air even in places where cooling water of reasonable quality is not available for the condenser is a solution where cleanliness and hygiene are to be taken care of to avoid waterborne diseases. Barometric vacuum systems studied earlier require a vacuum pump to maintain the pressure in the evaporator after the commencement of flashing, due to the accumulation of non-condensable gases and leakage of atmospheric air into the evaporator. Hence, the use of a mechanical vacuum pump to generate the required vacuum has the advantage of compactness, as the barometric height need not be maintained between the components. The two-stage system offers high distillate yield as compared to the single stage and occupies less space. Moreover, the low-temperature desalination systems are characterized by higher thermodynamic efficiencies, lower specific energy consumptions and lower scaling rates.

4. Estimation of available solar energy

The development of any solar energy conversion system first necessitates the calculation of the available solar radiation at the particular location. Therefore, the available solar radiation is computed theoretically for the location Coimbatore (Latitude 11°N, Longitude 76°E), Tamilnadu, India. A Matlab program is developed for the calculation of available solar radiation inclined at an angle equal to the latitude of the location and the maximum water temperature that can be obtained using standard correlations [17]. In this simulation, clear sky conditions are assumed with the collector facing south with an angle of inclination equal to that of the latitude for maximum absorption of solar energy. The isotropic diffuse model has been used to calculate the monthly average daily solar radiation. The collector is exposed to the solar radiation for an average of 7 h in a day and used to heat 100 l of water from an initial temperature of 30°C.

The monthly average daily radiation H on a horizontal surface is:

$$H = H_o\left\{a + b\frac{n}{N}\right\} \tag{1}$$

The monthly average daily radiation H_T on a tilted surface is given by:

$$H_T = \frac{H_b}{H}R_b + \frac{H_d}{H}\left(\frac{1+\cos\beta}{2}\right) + \rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{2}$$

The ratio of beam radiation to radiation on horizontal surface (R_b) is given by:

$$R_b = \frac{\sin(\varphi-\beta)\sin\delta + \cos(\varphi-\beta)\cos\delta\cos\omega}{\sin\varphi\sin\delta + \cos\delta\cos\omega} \tag{3}$$

The extra terrestrial radiation is computed as

$$H_o = \frac{24\times 3600\times \mathrm{Gsc}}{\pi}(Z)\times\{(\mathrm{X})+(Y)\} \tag{4}$$

where $Z = 1 + 0.033\cos\frac{360\times n}{365}$
$X = (\cos\delta\cos\varphi\sin\omega)$ and
$Y = (\frac{\pi\omega}{180}\sin\varphi\sin\delta)$

The declination δ and the sunset hour angle ω_s are calculated as:

$$\delta = 23.45\sin\left(360\times\frac{284+n}{365}\right) \tag{5}$$

$$\omega_s = \cos^{-1}[-\tan(\varphi)\tan(\delta)] \tag{6}$$

The monthly average daily radiation H_T has been calculated for all the months of a year, and the corresponding maximum water temperature is obtained. This is the temperature at which water is flashed in the flash vessel. The monthly average solar radiation and the average monthly maximum temperature of water that can be obtained using this radiation are shown in Fig. 3.

5. Working principle of the proposed system

The schematic arrangement of the single-stage solar driven air-cooled desalination system under analysis is shown in Fig. 1.

The single-stage system consists of a flat plate collector, flash vessel, vacuum pump and an air-cooled condenser. A flat plate collector is used to absorb the solar radiation and heat the brine water to its maximum temperature. The flash vessel is the core of the system where the inlet water heated using the solar energy is evaporated at low pressure. The hot water is sprayed through nozzles into the flash vessel, which is maintained at a low pressure with the help of a vacuum pump. The water vapour passes through the air-cooled condenser for condensation while the rejected brine is re-circulated to the hot water tank.

The schematic arrangement of the proposed two-stage solar driven air-cooled desalination system under analysis is shown in Fig. 2.

The two-stage desalination system consists of two flash vessels, an air-cooled condenser and a vacuum

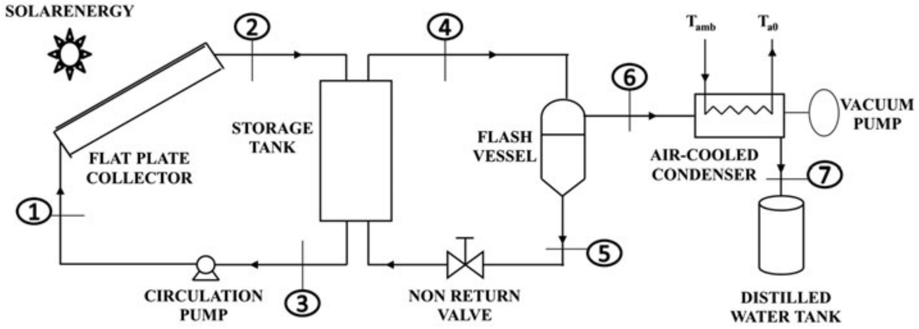

Fig. 1. Schematic arrangement of the single-stage desalination system.

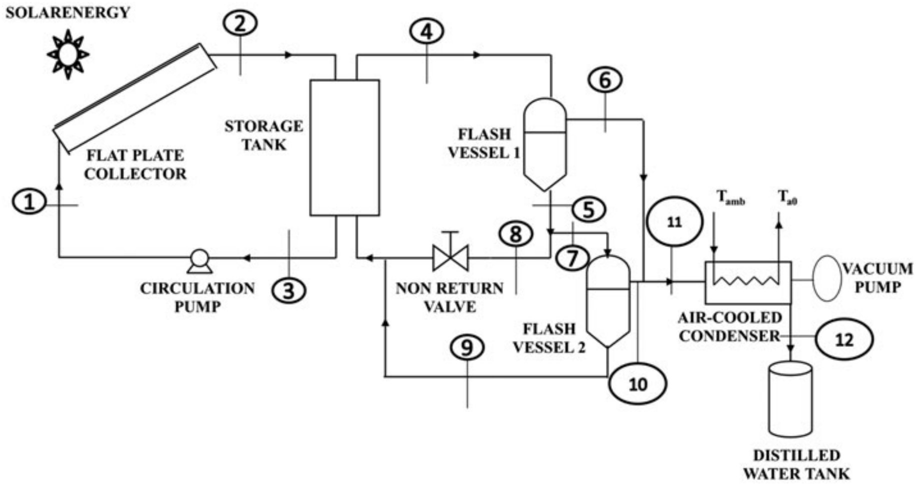

Fig. 2. Schematic arrangement of the two-stage desalination system.

pump for achieving low pressures in the flash vessels. The hot brine is flashed in the flash vessel 1, and the evaporated distillate is passed to the air-cooled condenser for condensation. A portion of the reject brine from the flash vessel 1, which is still at a reasonable high temperature, is flashed into the flash vessel 2. The flash vessel 2 is maintained at a pressure little lower than the vessel 1. The vapour formed in the vessel 2 is condensed by the common air-cooled condenser and the distillate obtained.

6. Thermodynamic analysis

The following assumptions have been made in the thermodynamic analysis of single and two-stage system.

(a) The heat loss from the flat plate collector, flash vessel and condenser is assumed to be negligible.
(b) The effectiveness of the flash vessel and condenser is assumed to be 100%.
(c) The brine coming out from the first stage is used as the input to the second stage with a constant temperature drop of 10°C for all conditions.
(d) The low pressure in both the flash vessels produced by a single vacuum pump is assumed to be respectively constant at the pre-set value throughout the flashing process.
(e) The pressure in flash vessel 1 and 2 is assumed to be 0.1 and 0.12 bar during the first analysis and 0.08 and 0.1 bar during the second analysis, respectively.
(f) The effect of non-condensable gases released from the water droplets is assumed to be negligible while the nozzle injects water in the flash vessel at constant temperature and diameter.

The mass and energy balance equations in the analysis are as follows:

6.1. Single-stage desalination system

The mass and energy balance for the solar flat plate collector is given by:

$$m_1 = m_2 \tag{7}$$

It is assumed that all the heat absorbed from the solar energy by the flat plate collector is utilized in raising the temperature of the inlet water. The useful energy absorbed by the solar flat plate collector is:

$$Q_u = H_T \times A_{\text{col}} \times \eta_{\text{col}} \tag{8}$$

Referring to Eqs. (7) and (8), the amount of temperature gained by the water passing through the flat plate solar collector is given by Eq. (9):

$$\Delta T = (T_{w2-}T_{w1}) = \frac{H_T \times A_{\text{col}} \times \eta_{\text{col}}}{m_1 \times \text{Cp}_w} \tag{9}$$

The mass balance of the insulated storage tank is given by:

$$m_2 + m_5 = m_3 + m_4 \tag{10}$$

The outlet water at a temperature of T_{wo} is pumped into the flash vessel at reduced pressure through a swirl nozzle, which atomizes the water droplets. The evaporation of water droplets in the flash vessel is driven by the pressure difference between the saturation pressure corresponding to the surface temperature (P_{sat}) and the ambient pressure (P_{amb}). Corresponding to the pressure in the flash vessel, the mass of water evaporated can be calculated using a simple mass balance Eq. (5).

$$\frac{m_6}{m_4} = \frac{\text{Cp}_{\text{w}}(T_{w2} - T_{\text{sat}})}{h_{\text{fg}_{(\text{T}_{\text{sat}})}}} \tag{11}$$

The mass balance in the flash vessel is given by:

$$m_6 = m_4 - m_5 = m_7 \tag{12}$$

Assuming the inlet water flashed into the flash vessel has a salinity of X_5 the salinity of the vapour generated is obtained as:

$$X_6 = \left[\frac{m_5}{m_6 + m_5}\right] X_5 \tag{13}$$

The temperature of vapour reaching the condenser is determined from the Eq. (14) as:

$$T_6 = T_5 - \text{ BPE} \tag{14}$$

The heat load of the condenser is given by:

$$Q_c = m_6 h_{\text{fg}} = m_a \text{Cp}_a (T_{a0} - T_{\text{amb}})$$

The performance of the proposed system can be estimated by using any one of the performance metrics like gained output ratio or performance ratio (PR) [18]. In this study, PR is used to access the performance of the system. The PR of the solar assisted system is calculated as:

$$\text{PR} = \frac{\text{Heat used for evaporation}}{\text{Energy incident on collector}} = \frac{m_6\, h_{\text{fg}}}{H_T\, A_{\text{col}}\, \eta_{\text{col}}} \tag{16}$$

6.2. Two-stage desalination system

The analysis is performed for various pressures in the flash chamber and a range of inlet water temperatures. The pressure ranges considered during the analysis are furnished below:

Case 1: Pressure in flash vessel (stage 1) as 0.1 bar while the pressure in flash vessel 2 (stage 2) as 0.08 bar.

Case 2: Pressure in flash vessel (stage 1) as 0.12 bar while the pressure in flash vessel 2 (stage 2) as 0.1 bar.

The mass and energy balance equations used for the single-stage system are applied to the two-stage system besides the other equations mentioned below.

The mass balance for the flash vessel 2 of the two-stage desalination system is given by:

$$m_5 = m_7 + m_8 \tag{17}$$

where $m_7 = m_9 + m_{10}$ Also,

$$m_{11} = m_6 + m_{10} = m_{12} \tag{18}$$

The mass of vapour evaporated at the second flash vessel is obtained by using the Eq. (19).

$$\frac{m_{10}}{m_7} = \frac{\text{Cp}_w(T_{w7} - T_{\text{sat}})}{hfg_{@(T_{\text{sat}})}} \tag{19}$$

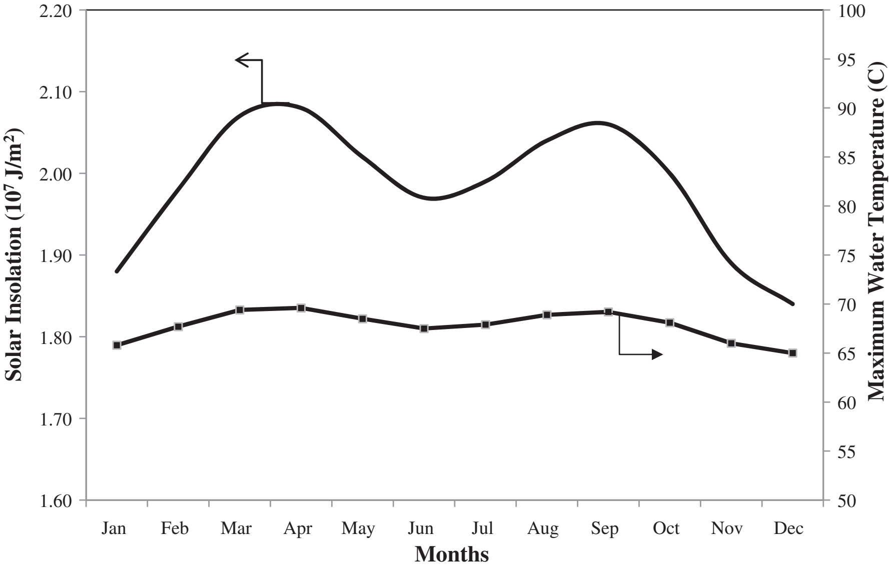

Fig. 3. Variation of estimated solar radiation and water temperature for various months.

The condenser load of the two-stage desalination system is given by:

$$Q_c = m_{11}h_{\mathrm{fg}} = m_a\mathrm{Cp}_a(T_{a0} - T_{\mathrm{amb}}) \tag{20}$$

The influence of the ambient air temperature on the mass of vapour condensed in the air-cooled condenser is studied by calculating the outlet air temperature for an assumed effectiveness say 0.7 of the condenser.

$$\varepsilon = \frac{Q_{\mathrm{actual}}}{Q_{\max}} = \frac{T_{a0} - T_{\mathrm{amb}}}{T_{11} - T_{\mathrm{amb}}} \tag{21}$$

The mass of vapour condensed at various ambient temperatures is calculated using the equation:

$$m_{12} = \frac{3600 \times m_a\mathrm{Cp}_a(T_{a0} - T_{\mathrm{amb}})}{h_{\mathrm{fg}}} \tag{22}$$

7. Results and discussion

Thermodynamic analysis of a single-stage and two-stage system is carried out for various parameters like solar radiation, inlet temperature of water and pressure in the flash vessel.

The theoretical amount of the monthly average solar radiation available for the location Coimbatore,

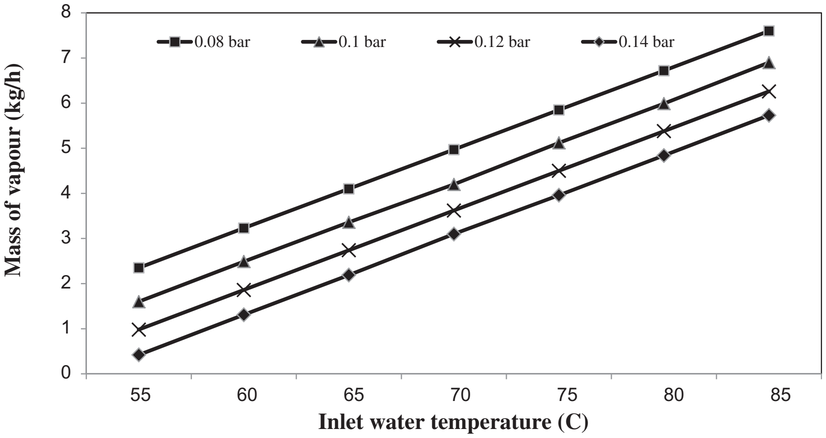

Fig. 4. Variation in the amount of vapour produced for various inlet water temperatures.

India (Latitudes 11˚N and Longitude 76˚E), was simulated for all the months of a year. The estimated monthly average solar radiation and the corresponding maximum water temperature in a year are shown in Fig. 3. It is observed that the solar radiation reached a maximum of $2.02\times107\,\text{J/m}^2$ and minimum of $1.84\times10^7\,\text{J/m}^2$ during April and December, respectively. During the same time period, the maximum and minimum water temperatures obtained are 89.43 and 82.57˚C, respectively. The temperature of hot water obtained primarily depends on the amount of available solar radiation. It can be observed that the amount of vapour produced increases with decrease in pressure in the flash vessel and with increase in the feed water temperature.

Fig. 4 shows the variation of the water vapour produced with respect to various inlet water temperatures. The feed water is flashed at various pressure conditions (0.06–0.14 bar) in the flash vessel. The amount of vapour produced increases with increase in the temperature of inlet water. For a 5˚C increase in inlet water temperature, the amount of vapour produced increases about 15–32% for the pressure between 0.06 and 0.14 bar. For the simulated inlet water temperature ranging from 55 to 85˚C, the amount of vapour produced varies from 3.27 kg/h at 0.06 bar to 5.73 kg/h at 0.14 bar. Thus, evaporation is sensitive to the level of vacuum in the

Table 1
Mass of vapour produced and the condenser load for various input parameters

P_e PR in the flash chamber (bar)	T_w Temperature of flashing (˚C)	m_v Mass of vapour generated (kg/h)	Q_C Condenser heat load (kW)
0.06	55	3.27	2.19
	60	4.14	2.7
	65	5	3.35
	70	5.88	3.95
	75	6.75	4.53
	80	7.6	5.1
	85	8.49	5.7
0.08	55	2.35	1.6
	60	3.23	2.16
	65	4.1	2.74
	70	4.97	3.32
	75	5.85	3.9
	80	6.72	4.28
	85	7.6	5.07
0.1	55	1.6	1.06
	60	2.49	1.65
	65	3.36	2.23
	70	4.2	2.79
	75	5.12	3.4
	80	5.99	3.98
	85	6.9	4.59
0.12	55	0.98	0.65
	60	1.86	1.23
	65	2.74	1.81
	70	3.62	2.4
	75	4.5	2.98
	80	5.38	3.56
	85	6.26	4.14
0.14	55	0.42	0.27
	60	1.31	0.86
	65	2.19	1.44
	70	3.1	2.04
	75	3.96	2.6
	80	4.84	3.19
	85	5.73	3.78

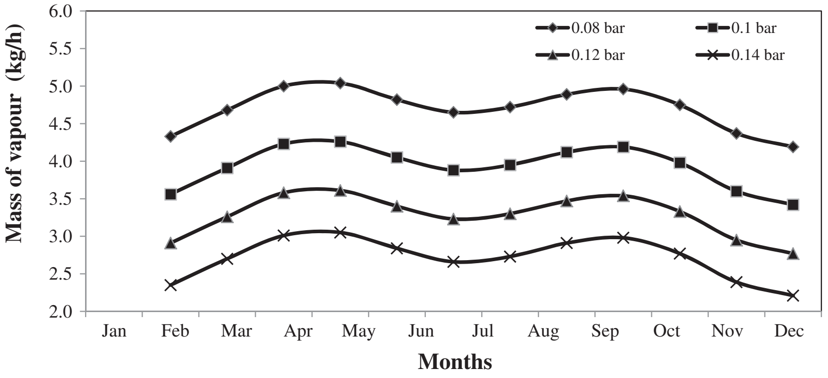

Fig. 5. Variation in the amount of vapour produced for various months in a year.

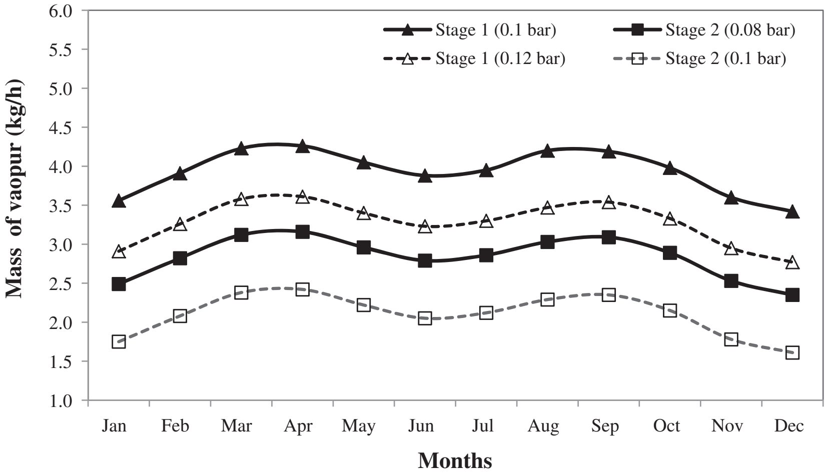

Fig. 6. Variation in the amount of vapour produced for various months in a year in a two-stage system.

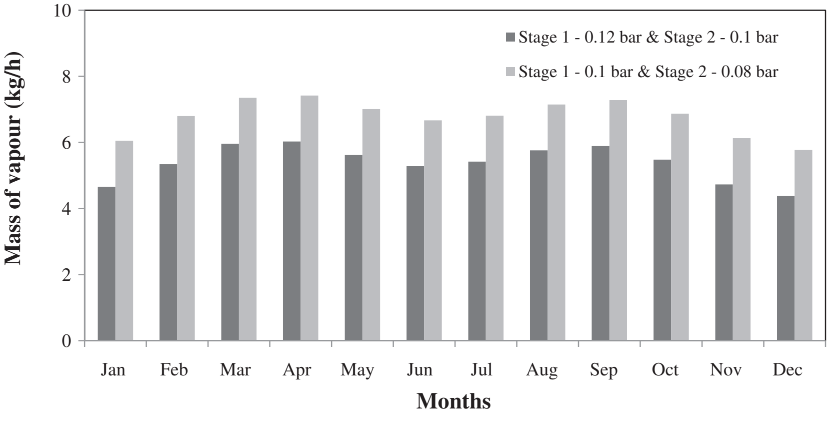

Fig. 7. Variation in total vapour produced for various months in a year in a two-stage system.

flash vessel, and the rate of evaporation rapidly decreases as the pressure in the vaporizer increases. Also, as the temperature of the water droplet increases, the degree of evaporation increases. The mass of vapour generated at various pressures and temperatures is shown in Table 1.

The variation in the amount of water vapour produced with the months in a year is shown in

Fig. 5. The mass of vapour produced is found to be maximum during April and minimum during December over the analysed pressure range. For every 5˚C rise in the inlet water temperature, the vapour produced increases by about 17 and 27% at 0.08 and 0.12 bar, respectively.

Fig. 6 shows the variation in the mass of vapour generated for all the months in a year for both the cases of the two-stage system. The amount of vapour produced in stage 1 is found to be higher than that of the stage 2 in both the cases. This is due to the high amount of superheat carried by the inlet water above the saturation temperature corresponding to the pressure in the pressure vessel. The vapour generation in stage 2 can be improved by reducing the heat losses between the stages.

The distribution of total vapour produced in the two-stage system for two different pressure conditions is presented in Fig. 7. It is observed that the system performance is better when operated at lower pressure. The amount of vapour generated varies between 7.35 and 5.96 kg/h when the pressure in stage 1 and 2 is 0.1 and 0.08, respectively. Similarly, an output about 5.77–4.38 kg/h is obtained when the two-stage system is operated at the pressure of 0.12 and 0.1 in the stage 1 and 2, respectively.

Fig. 8 shows the comparison of the amount of vapour produced in the single and two-stage system. The amount of vapour generated in the two-stage system when stage 1 is operated at 0.12 bar and stage 2 at 0.1 bar is compared with the performance of the single-stage system when it is operated at a pressure of

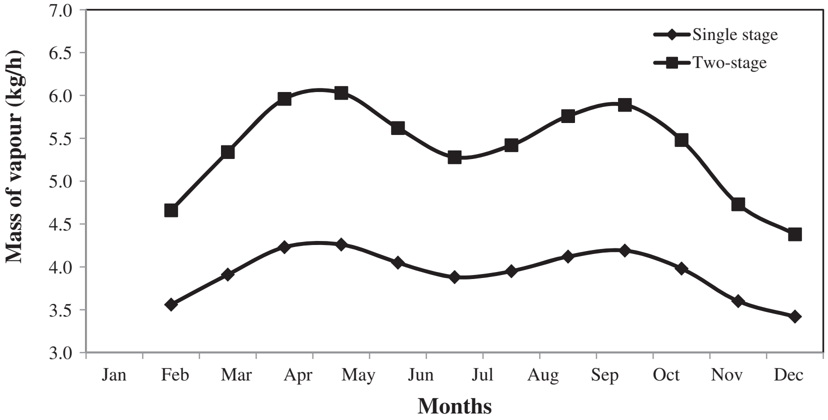

Fig. 8. Comparison of total vapour produced for all the months in a year.

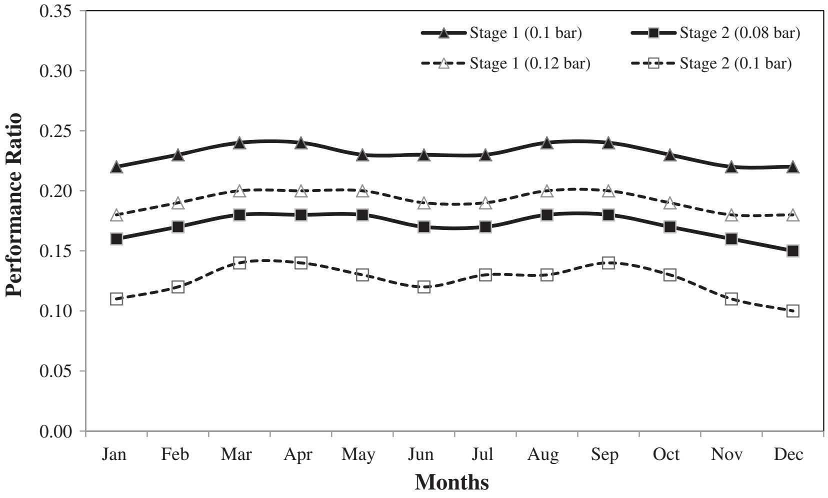

Fig. 9. Variation of PR over the months in a two-stage system.

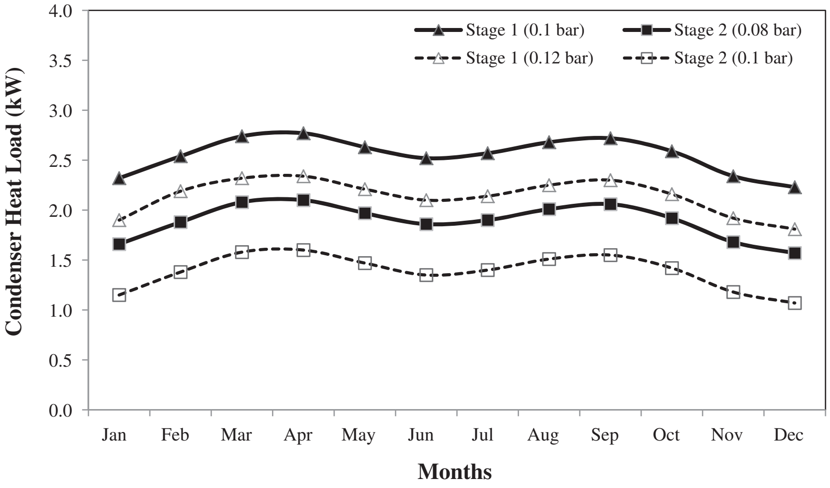

Fig. 10. Variation of condenser heat load for all the months in a two-stage system.

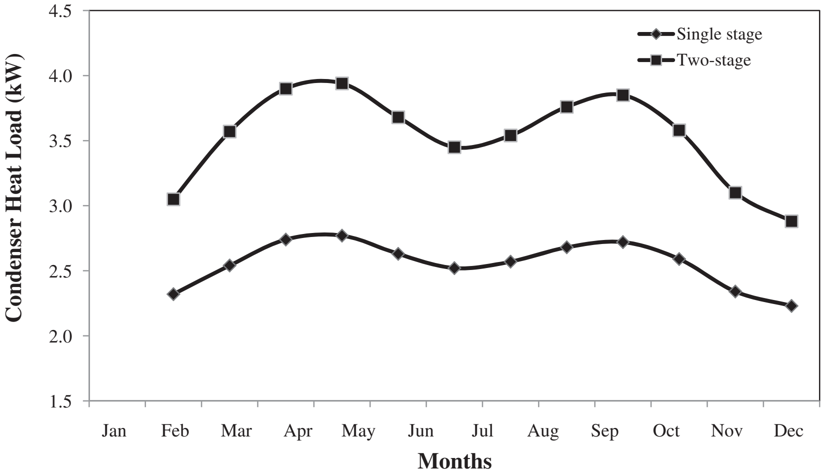

Fig. 11. Variation of condenser heat load in a year for a single and two-stage system.

0.1 bar for all the months in a year. The amount of vapour produced in the two-stage system is around 30% more than the single-stage system.

The variation of the PR of the two-stage system with months is shown in Fig. 9. The PR of the stage 1 at 0.12 bar is around 0.19 while that of the stage 2 operating at 0.08 bar is found to be 0.17. Similarly the PR of stage 1 operating at 0.1 bar is found to be around 41% more than that of stage 2 operating at the same pressure.

Fig. 10 shows the variation in the condenser heat loads of the two-stage system. Comparison of the condenser heat loads for a single and two-stage system is shown in Fig. 11. The average heat removed by the condenser in the single-stage system at 0.1 bar is around 2.55 kW. The heat removed by the condenser in the two-stage system where the stage 1 pressure is 0.12 and stage 2 is 0.1 is found to be 3.5 kW. Hence, air-cooled condensers can be effectively used to condense the vapour in the two-stage system.

Fig. 12 shows the effect of ambient air temperature on the distillate yield from the system for a constant mass flow rate of air. It is imperative from the figure that the mass of vapour condensed by the air-cooled condenser decreases with the increase in the ambient air temperature as the latent heat removal decreases with the increase in ambient air temperature.

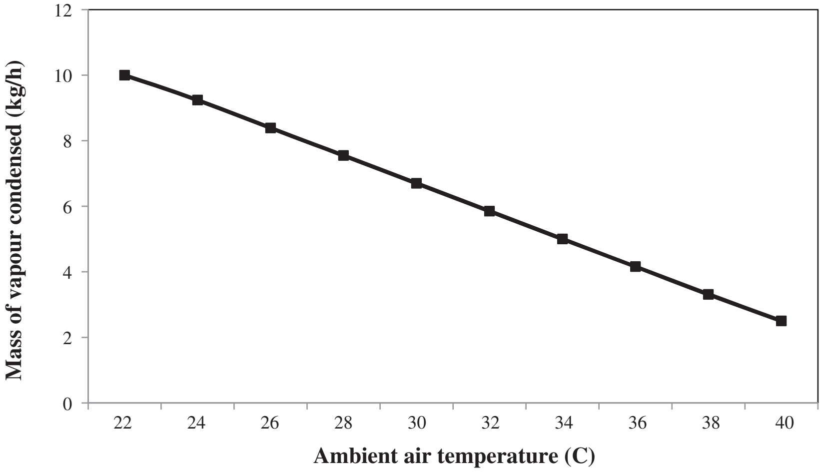

Fig. 12. Effect of ambient air temperature on distillate yield.

8. Conclusions

Thermodynamic analysis of a single stage and two-stage solar assisted desalination system is studied. Both the systems are analysed for various input parameters such as average monthly solar radiation, inlet water temperature and pressure in the flash vessel. The temperature of inlet water depends on the available solar radiation. A maximum yield of about 2.77–3.61 and 4.38–6.03 kg/h has been obtained for single and two-stage systems, respectively. The yield increases with increase in inlet feed water temperature and decrease in the pressure in the flash vessels. The performance of the system is found to be about 36–40% higher while operating as a two-stage system than that of the single-stage system. The use of air-cooled condenser to condense the vapour eliminates the necessity of a separate cooling mechanism, as in water-cooled systems. Moreover, the use of air-cooled condenser enables the system to be compact and permits the use of free air available even in places of water contamination and pollution. However, the ambient air temperature has a significant impact on the performance of the air-cooled condenser. The analysed system could be effectively used to produce fresh water for small-scale applications in rural and semi-arid areas. The operating and maintenance cost of these air-cooled systems are also less when compared to the water-cooled small-scale desalination systems.

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Nomenclature

A — area (m^2)
a', b' — regression coefficients
BPE — boiling point elevation (K)
C_p — specific heat capacity (kJ/kg)
Gsc — solar constant (W/m^2)
H — monthly average daily solar radiation (J/m^2)
h_{fg} — enthalpy of vaporization (kJ/kg)
m — mass flow rate (kg/s)
N — day length
n — day number
n' — average daily hours of bright sunshine
P — pressure
Q — heat load (kW)
C — temperature (°C)
X — salinity (PPM)

Symbols

δ — declination
ω_s — sunset hour angle
φ — latitude
η — efficiency
ρ — diffuse reflectance

Subscripts

a — air
amb — ambient
c — condenser
col — collector
e — evaporator
g — ground
o — outlet
sat — saturation
T — tilted surface
v — vapour
w — water

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