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Optimization of design and operating parameters on the year round performance of a multi-stage evacuated solar desalination system using transient mathematical analysis

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Abstract
The available fresh water resources on the earth are limited. About 79% of water available on the earth is salty, only one percent is fresh and the rest 20% is brackish. Desalination of brackish or saline water is a good method to obtain fresh water. Conventional desalination systems are energy intensive. Solar desalination is a cost effective method to obtain potable water because of freely available clean and green energy source. In this paper, a transient mathematical model was developed for the multi-stage evacuated solar desalination system to achieve the optimum system configuration for the maximum year round performance and distillate yield. The effect of various design and operating parameters on the thermal characteristics and performance of the system were analyzed. It was found that an optimum configuration of four stages with 100mm gap between them when supplied with a mass flow rate of 55kg/m^2/day would result in best performance throughout the year. The maximum and minimum yields of 28.044 kg/m^2/day and 13.335 kg/m^2/day for fresh water at a distillate efficiency of 50.989% and 24.245% and overall thermal efficiency of 81.171% and 40.362% are found in the months of March and December respectively owing to the climatic conditions. The yield decreases to 18.614 kg/m^2/day and 9.791 kg/m^2/day for brine solution at a distillate efficiency of 33.844% and 17.802% and overall thermal efficiency of 53.876% and 29.635% for March and December respectively The maximum yield of 53.211 kg/m^2/day is found in March at an operating pressure of 0.03 bar. The multi-stage evacuated solar desalination system is economically viable and can meet the needs of rural and urban communities to necessitate 10 to 30 kg per day of fresh water.

Keywords: Desalination; Evacuated; Multi-stage; Solar still; Transient analysis.

1. Introduction
Water is one of the most important ingredients present on the earth. All our day to day activities agricultural, industrial and domestic directly or indirectly depend on the usage of water. The amount of water is nearly constant since the start of life on the earth. Sea water is the major source of water which corresponds to about 97.5% while the remaining 2.5% is constituted by underground and surface waters of which 80% is frozen in glaziers. Thus, only 0.5% of total water available is found in rivers, lakes and aquifers which are the major sources of fresh water. The combined effect of the continuous increase in the world population, changes in life style, increase in ground water salinity and infrequent rainfall

together with the increasing industrial and agricultural activities all over the world contributes to the depletion and pollution of fresh water resources. Desalination of salt water through conventional techniques often requires significant amounts of energy to separate the salts from the water. Such energy can be provided as heat, in the case of thermal processes, or as mechanical or electrical energy, as in the case of membrane processes. Further, processes like Electro Dialysis is always limited to the treatment of low salinity brackish water while Reverse Osmosis require more substantial pretreatment in order to meet the required standards due to the sensitivity of membranes to fouling problems. It has been estimated by that the production of 1000 m^3 per day of freshwater requires 10,000 tons of oil per year [1]. Considering the energy costs of recent years and likely rising trend, it is very important to look for alternative energy powering sources for the economic production of distillate yield. This can be achieved by coupling desalination technologies to renewable energy resources. Among the renewable energy sources, solar energy is one of the best sources having zero emission and zero fuel cost that can be used for desalination. Solar desalination seems to be the green energy method to produce potable water, specifically for remote and rural places. It is one of the most important and technically viable applications of solar energy. The process of getting fresh water from saline water can be done easily and economically by solar desalination.

The solar still, in many respects, is an ideal source of fresh water for both drinking and agriculture. The simple solar still of the basin type is the oldest method and improvements in its design have been made to increase its efficiency [2]. Numerous experimental and numerical investigations on basic types of solar still have been reported in the literature by [3-5]. The disadvantage of basin solar stills includes their relatively low performance due to excessive heat losses to the ambient, resulting in the lower thermal efficiency. It is evident from [6] that the maximum thermal efficiency of basin solar stills is usually around 25%, with an average distillate output capacity of 1.5-3.0 kg/m^2/day. Also basin stills requires the need for regular flushing of accumulated salts. Efforts have been made to re-utilize the released latent heat by having more than one stage for occurrence of evaporation and condensation processes in the still. As a result, double-basin still [7], diffusion still [8, 9] and multiple-effect still [10] have emerged. It has been reported that the performance of diffusion stills and multiple-effect stills is much better than that of conventional basin-type solar stills being 35% or more but the cost and complexity are correspondingly higher.

The productivity of any type of solar still whether it may be simple basin-type solar still, double-basin solar still, diffusion-type solar still or multiple-effect solar still will be determined by the temperature difference between the water in the basin and inner surface glass cover. In a passive solar still, the solar radiation is received directly by the basin water and is the only source of energy for raising the water temperature and consequently, the evaporation leading to a lower productivity. Later, in order to overcome the above problem, many active solar stills have been developed by supplying extra thermal energy to the basin through an external mode. Many researchs have been carried out on the active solar desalination systems the first being reported by [11]. They found that, the daily distillate production of a coupled single basin still with flat plate collector is 24% higher than that of an uncoupled one. The parametric study of passive and active solar stills integrated with a flat plate collector is presented by [12]. The results of the thermal model for the active solar still coupled to one flat plate collector show that the daily yield values are 3.08 l.

The requirement of higher yield of distilled water from active and passive solar stills is a real challenge for researchers around the world and necessitates the development of more advanced concepts of solar stills, focusing on multi-stage and evacuated solar stills coupled to solar thermal collectors. The experimental and analytical investigation of the multi-stage solar still, which consists of a stacked array of distillation trays of w-shaped bottom that acts as a condenser for the tray below has been investigated by [6]. The two main conclusions of their work are that the multi-stage desalination of seawater is reliable, and the undesirable flow of steam that bypasses the condenser is quite harmful to the overall performance of the still. A computer simulation model is presented by [13, 14] for studying the steady-state and transient performance of a multi-stage stacked tray solar still. A numerical modeling of a multi-stage solar still with an expansion nozzle and heat recovery for steady state conditions was carried out by [15]. Design and evaluation of the novel solar desalination system for higher performance is done by [16]. The advantage of multi-stage evacuated solar desalination system coupled with flat plate collector was reported by [17, 18]. The results show that the total daily yield was found to be about three times of the maximum yield of the basin-type solar still. Experimental investigation on the performance of a multi-stage water desalination still connected to a heat pipe evacuated tube solar collector was perfomed

[19]. The results of tests demonstrate that the system produces about 9 kg/day of fresh water and has a solar collector efficiency of about 68%. The multistage solar desalination system with heat recovery was developed by [20]. The results show that, the system produces about 15– 18 l/m^2/day, which is 5–6 times higher than simple still. Study of the year round transient analysis on Multi-stage evacuated solar desalination system was done by [21] and the results show that the system produces a maximum distillate yield of 16.4 kg/m^2/day at an average efficiency of 45%.
From the above literature review, it is clear that multi-stage evacuated solar still with heat recovery was proven to be of better performance for the requirement of higher distillate yield. Due to the dearth of research in the field of multi-stage evacuated solar desalination system, the present paper describes the mathematical model to optimize the system configuration for maximum distillate yield by considering the effect of various design and operating parameters on the performance and thermal characteristics of the system.

2. Description of the multi-stage evacuated solar desalination system

The Multi-stage evacuated solar desalination system is a combination of evaporative-condenser unit and flat plate collectors. The system is supplied heat additionally through flat plate collectors thus making it active to enhance the distillate yield. Each evaporative-condenser unit is a combination of bottom and top trays which acts as evaporator and condenser surfaces. One such unit is called as a stage. The multi-stage desalination system consists of N_s number of such stages stacked one over the other. The condenser surface of bottom stages acts as the evaporator surface for the stages above. The system consists of two flat plate collectors connected either in series or parallel combination to the multi-stage desalination unit as shown in Figure 1(a) and Figure 1(b) respectively. In a series combination, the outlet from the saline tank is given as inlet to the first collector. The outlet of first collector will be inlet to the second collector and the outlet of the second collector will be inlet to the next and so on up to the N_c^{th} collector. Thus, the outlet temperature of the last collector is taken as the oulet temperature of the series combination. In a parallel combination, the outlet from the saline tank is distributed as inlet to all the collectors through a common header and the outlet from all of them are connected separately through another common header. Thus, net cummulative outlet temperature of all the collectors is taken as outlet temperature of the parallel combination. Each flat plate collector has an area of 1.35m^2 inclined at an angle equal to latitude of Chennai (13^o) facing towards due south for the maximum year round performance. Each evaporator and condenser tray has an area of 1m^2 inclined at an angle of 16^o.

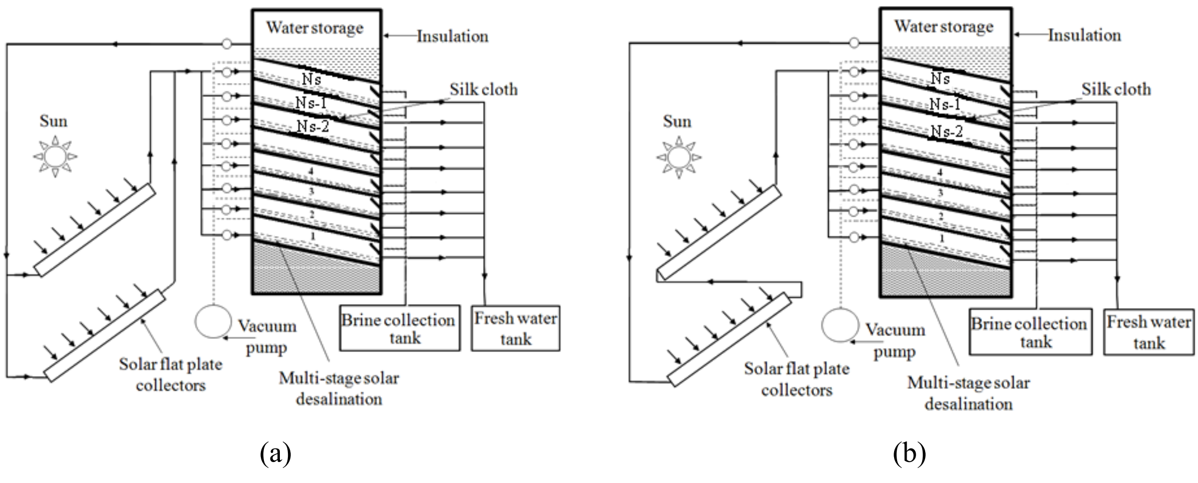


Figure 1. Coupling of Multi-stage evacuated solar desalination system to flat plate collectors; (a) Parallel combination of collectors, (b) Series combination of collectors

At the top of the last stage, there is a water tank of 150 liters capacity which stores the saline water. The saline water from the tank flows through the combination of flat plate collectors and thus gets heated. The heated saline water enters each stage of the desalination system with a controlled mass flow rate using flow control valves. The evaporator surface of each stage is covered with a porous silk cloth so that the incoming saline water gets spread throughout the tray, thus ensuring maximum evaporation owing to minimum thickness of water. The evaporated water in the first stage gets condensed on the bottom side of the top tray thus releasing the latent heat of condensation to the second stage. Thus, the second stage is additionally heated by this latent heat apart from the incoming hot water, thus leading to more evaporation and thus condensation. Thus, top stages yields higher distillate compared to bottom stages. The condensed water due to gravity falls into the collection trough provided beneath the condenser surface. The condensed fresh water and left over drain from each stage is collected separately into two different tanks. The experimental set up and inside view of a four stage evacuated solar desalination system at solar research laboratory, IIT Madras is shown in Figure 2(a) and Figure 2(b) respectively.

(a) (b)

Figure 2. Multi-stage evacuated solar desalination system; (a) Experimental Set up, (b) Inside View of the system

3. Mathematical modeling

3.1 Solar flat plate collector

The heat losses from the solar flat plate collector to the surrounding are important in the study of collector performance. The heat lost to the surroundings from the absorber plate through the glass cover by conduction, convection and radiation is calculated using energy balance equations. These heat losses from the flat plate collector are shown in the Figure 3. The detailed thermal analysis of flat plate collector is carried out by considering heat losses from the collector following the procedure given in [22, 23] to determine the outlet temperature for different climatic conditions.

For a single flat plate collector

$$T_{fo} = \left(\frac{S}{U_l} + T_a\right)\left\{1 - \exp\left\{-\frac{A_c U_l F'}{\dot{m}_c C_p}\right\}\right\} + T_{fi}\exp\left\{-\frac{A_c U_l F'}{\dot{m}_c C_p}\right\} \tag{1}$$

where T_{fo} is collector outlet temperature (K), S is incident flux absorbed by the absorber plate (W/m^2), U_l is overall heat loss coefficient (W/m^2 K), A_c is collector area (m^2), F' is collector efficiency factor, $\dot{m}_c$ is mass flow rate of fluid through the collector (kg/s), C_p is specific heat capacity (J/kg K), T_{fi} is collector inlet temperature (K).

For series combination of flat plate collectors

For a system of collectors connected in series, the outlet fluid temperature from the N_c^{th} collector can be expressed in terms of the inlet temperature of the first collector as

$$T_{foN_c} = \left(\frac{S}{U_l} + T_a \right) \left\{ 1 - \exp\left\{ -\frac{N_c A_c U_l F'}{\dot{m}_c C_p} \right\} \right\} + T_{fi} \exp\left\{ -\frac{N_c A_c U_l F'}{\dot{m}_c C_p} \right\} \quad (2)$$

where T_{foNc} is fluid outlet temperature from N_c^{th} collector (K), T_a is temperature of surrounding air (K), N_c is number of collectors.

For parallel combination of collectors

Assuming the outlet from the saline tank is equally split into N_c collectors, the fluid outlet temperature from the N_c^{th} collector in parallel combination can be expressed in terms of the inlet temperature of the first collector by dividing the mass flow rate term in equation (2) with the number of collectors.

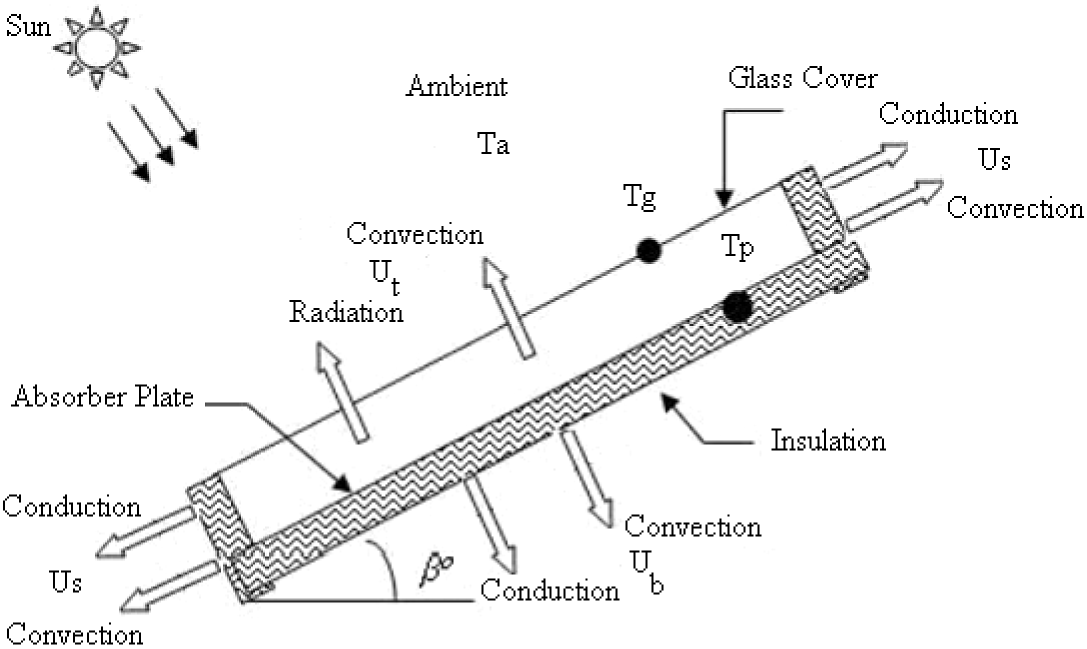


Figure 3. Detailed heat losses from the absorber plate of a flat plate collector

3.2 Multi-Stage evacuated solar desalination system

In multi-stage desalination system, due to low temperature difference between the adjacent stages and also because of the absence of non-condensable gases heat transfer by radiation and natural convection are limited. Thus, heat transfer between the hot saline water bed and the condensation surface in every stage is mainly conveyed by evaporation and condensation process [18]. The temperature of water and yield in the still can be obtained by applying energy balance for various stages of desalination system.

For Stage-1

The energy balance equation for the first stage is given as:

$$\dot{m}_1 c_{ps1} T_{fo} - \left(\dot{m}_1 - \dot{m}_{e1} \right) c_{ps1} T_{1o} - \dot{m}_{e1} h^*_{fg1} = M_{w1} c_{ps1} \frac{dT_1}{dtime} \quad (3)$$

where $\dot{m}_1$ is inlet mass flow rate of salt water to first stage (kg/s), C_{ps1} is specific heat capacity of salt water in the first stage (J/kg K), $\dot{m}_{e1}$ is mass flow rate of distillate outlet from the first stage (kg/s), T_{1o} is mass flow rate of drain outlet from the first stage (kg/s), h^*_{fg1} is refined latent heat of water at the condenser surface of first stage (J/kg), M_{w1} is mass of salt water in the first stage (kg), T_1 is first stage water temperature (K), time is time (s).

For Stages-2 to N_s

The energy balance equation for second stage to N_s stage is given as:

$$\dot{m}_{e_{i-1}} h^*_{fg_{i-1}} + \dot{m}_{e_{i-1}} c_{pw_{i-1}} \left(T_{i-1} - T_i\right) + \dot{m}_{si} c_{psi} T_{fo} - \left(\dot{m}_i - \dot{m}_{e_i}\right) c_{ps_i} T_{io} - \dot{m}_{e_i} h^*_{fg_i} = M_{wi} c_{ps_i} \frac{dT_i}{dtime} \quad (4)$$

Where $m_{\dot{e}_{i-1}}$ is mass flow rate of distillate outlet from the previous stage (kg/s), $h^*_{fg_{i-1}}$ is refined latent heat of water at the condenser surface of the previous stage (J/kg), $C_{pw_{i-1}}$ is specific heat capacity of fresh water in the previous stage (J/kg K), T_{i-1} is previous stage water temperature (K), T_i is ith stage water temperature (K), $\dot{m}_{si}$ is inlet mass flow rate of salt water to the ith stage (kg/s), C_{psi} is specific heat capacity of salt water in the ith stage (J/kg K), m_i is inlet mass flow rate of salt water to the previous stage (kg/s), $\dot{m}_{ei}$ is mass flow rate of distillate outlet from the ith stage (kg/s), T_{io} is mass flow rate of drain outlet from the ith stage (kg/s), h^*_{fgi} is refined latent heat of water at the condenser surface of the ith stage (J/kg), M_{wi} is mass of salt water in the ith stage (kg), T_i is ith stage water temperature (K).

The refined latent heat of vaporization of water for each stage used in equation (3) and equation (4) can be determined by the following expression proposed by [24] as

For i=1 to N_s-1

$$h^*_{fgi} = h_{fgi} + 0.68 \times c_{pw_i} \left(T_i - T_{i+1}\right) \quad (5)$$

where h_{fgi} is latent heat of vaporization of water at the condenser surface of the ith stage (J/kg), C_{pwi} is specific heat capacity of fresh water in the ith stage (J/kg K), T_{i+1} is (i+1)th stage water temperature (K).

For N_s^{th} stage

$$h^*_{fgNs} = h_{fgNs} + 0.68 \times c_{pw_{Ns}} \left(T_{Ns} - T_a\right) \quad (6)$$

Where h^*_{fgNS} is refined latent heat of vaporization of water at the condenser surface of last stage (J/kg), h_{fgNs} is latent heat of vaporization of water at the condenser surface of the last stage (J/kg), C_{pwNs} is the specific heat capacity of fresh water in the last stage (J/kg K), T_{Ns} is the last stage water temperature (K).

The latent heat of vaporization of water for each stage which can be determined by the following expression proposed by [25] as

$$h_{fgi} = 1000 \times \left[3161.5 - 2.4074\left(t_{av} + 273\right)\right] \quad (7)$$

where t_{avi} is average temperature of ith stage (^oC) (i.e., average temperature of water at evaporator surface and condenser surface of ith stage)

For i=1 to N_s-1

$t_{av}=(t_i+t_{i+1})/2$ (8)

For N_s^{th} stage

$t_{av}=(t_{Ns}+t_a)/2$ (9)

where t_i, t_{i+1}, t_{Ns}, t_a denote the temperatures as above mentioned in ^oC.

The specific heat capacity of water for each stage used in equation (3) to equation (6) can be computed by the following formula as a function of liquid-air interface temperature inside the stage as suggested by [26]

$$c_{pwi} = 1000 \times \left[4.2101 - 0.0022 t_i + 5 \times 10^{-5} t^2_i - 3 \times 10^{-7} t^3_i \right] \tag{10}$$

The specific heat of salt water at constant pressure for each stage used in equation (3) and equation (4) can be determined using the correlation taken from [27]. The following correlation gives the variation of c_{ps} with water salinity and temperature.

$$c_{ps} = \left(A + B t_{av} + C t_{av}{}^2 + D t_{av}{}^3 \right) \tag{11}$$

where the variables A, B, C and D are evaluated as a function of water salinity as follows:

$$A = 4206.8 - 6.6197 s + 1.2288 \times 10^{-2} s^2 \tag{12}$$

$$B = -1.1262 + 5.4178 \times 10^2 s - 2.2719 \times 10^{-4} s^2 \tag{13}$$

$$C = 1.2026 \times 10^{-2} - 5.3566 \times 10^{-4} s + 1.8906 \times 10^{-6} s^2 \tag{14}$$

$$D = 6.8777 \times 10^{-7} + 1.517 \times 10^{-6} s - 4.4268 \times 10^{-9} s^2 \tag{15}$$

where s is water salinity in gm/kg.

In a multi-stage evacuated solar desalination system, the transport phenomenon is highly complicated. Inside each stage of the still, there is interrelated combined heat and mass transfer phenomena owing to the presence of complex temperature and concentration dependent thermo-physical properties of humid air. As ordinary Grashof number determines the natural convection heat transfer due to temperature differential alone, the complicated phenomenon of combined heat and mass transfer inside multi-stage still leads to the definition of modified Grashof number given by [28] as

$$Gr_i^* = \frac{g \beta_i rho^2{}_{mi} L^3 \Delta T_i^*}{\mu^2{}_{mi}} \tag{16}$$

where Gr^*_i is the modified Grashof number for the i^{th} stage, β_i is thermal expansion coefficient for the i^{th} stage (K^{-1}), rho_{mi} mixture density for the i^{th} stage (kg/m^3), L is gap between the stages (m), ΔT^*_i is the modified temperature difference for i^{th} stage (K), μ_{mi} is mixture dynamic viscosity for the i^{th} stage (Ns/m^2).

For i=1 to N_s-1

$\beta_i=(T_{i+1})^{-1}$ (17)

$$\Delta T_i^* = \left(T_i - T_{i+1} \right) + \frac{\left(P_{v,i+1} - P_{v,i} \right)\left(M_v - M_a \right) T_i}{M_a P_o + P_{v,i} \left(M_v - M_a \right)} \tag{18}$$

where $P_{v,i+1}$ is saturation vapour pressure for the (i+1)th stage (N/m^2), $P_{v,i}$ is saturation vapor pressure for the ith stage (N/m^2), M_v is molar mass of water vapor in the ith stage (kg/K mol), M_a is the molar mass of dry air in the ith stage (kg/K mol), P_o is total pressure inside the evaporative-condenser unit of the ith stage (N/m^2).

For N_s^{th} stage

$$\beta_{Ns+1}=(T_a)^{-1} \tag{19}$$

where β_{Ns+1} is thermal expansion coefficient for the Nsth stage condenser surface (K^{-1})

$$\Delta T_{Ns}{}^{*} = \left(T_{Ns} - T_a\right) + \frac{\left(P_{v,Ns+1} - P_{v,Ns}\right)\left(M_v - M_a\right)T_{Ns}}{M_a P_o + P_{v,Ns}\left(M_v - M_a\right)} \tag{20}$$

where ΔT^{*}_{Ns} is the modified temperature difference for last (K), $P_{v,Ns+1}$ is saturation vapour pressure for the last stage condenser surface (N/m^2), $P_{v,Ns}$ is saturation vapor pressure for the last stage (N/m^2).

The convective heat transfer coefficient in an enclosed space is calculated from the following familiar correlation proposed by [29]

$$Nu=C(GrPr)^n \tag{21}$$

where Nu is Nusselt number, Gr is Grashof number, Pr is Prandl number.

Assuming the values of constants C and n to be 0.2 and 0.26 respectively which can be applied in a fairly wide range of Rayleigh number ($3.5\text{x}10^3<Ra<10^6$), the McAdams relation modifies to each stage of a multi-stage evacuated solar desalination system as

$$N_{u_i} = \frac{h_{cv_i} L}{k_{m_i}} = 0.2\left(Gr_i^{*} Pr_i\right)^{0.26} \tag{22}$$

where Nu_I is Nusselt number for the ith stage, h_{cvi} is convective heat tarnsfer coefficient for ith stage (W/m^2 K), k_{mi} is mixture thermal conductivity for the ith stage (W/m K).
where

$$\Pr_i = \frac{\nu_{m_i}}{\alpha_{m_i}} \tag{23}$$

where ν_{mi} is mixture kinematic viscosity for the first stage (m^2/s), α_{mi} is mixture thermal diffusivity (m^2/s).

Thus, using equation (16) to equation (23), the convective heat transfer coefficient for each stage is given by by the following expression

For i=1 to N_s-1

$$h_{cvi} = 0.2 k_{mi} L^{3n-1}\left(\frac{g \cdot rho_{mi} \cdot \beta_i}{\mu_{mi}\alpha_{mi}}\right)\left[\frac{\left(T_i - T_{i+1}\right) + T_i\left(P_{v,i} - P_{v,i+1}\right)\left(M_a - M_v\right)}{M_a P_o - P_{v,i}\left(M_a - M_v\right)}\right]^{0.26} \tag{24}$$

For N_s^{th} stage

$$h_{cvNs} = 0.2k_{mNs}L^{3n-1}\left(\frac{g \cdot rho_{mNs} \cdot \beta_{Ns}}{\mu_{mNs}\alpha_{mNs}}\right)\left[\frac{(T_{Ns}-T_a)+T_{Ns}(P_{v,Ns}-P_{v,Ns+1})(M_a-M_v)}{M_aP_o-P_{v,Ns}(M_a-M_v)}\right]^{0.26} \tag{25}$$

Thus, using equation (24) and equation (25), the distillate mass outflow from each stage of a multi-stage evacuated solar desalination system is given by the following expression by [30] as

For i=1 to N_s-1

$$\dot{m}_{ei} = \frac{h_{cvi}}{(rho_{mi}.c_{pmi})}.\frac{P_o}{P_{AM,i}}.\frac{M_v}{R}.\left(\frac{P_{v,i}}{T_i}-\frac{P_{v,i+1}}{T_{i+1}}\right).Le_i^{-2/3} \tag{26}$$

where $P_{AM,i}$ is arithmetic mean pressure for the ith stage (N/m^2), Le_i is Lewis number for the ith stage, R is gas constant(J/kg mol K).

For N_s^{th} stage

$$\dot{m}_{eNs} = \frac{h_{cvNs}}{(rho_{mNs}.c_{pmNs})}.\frac{P_o}{P_{AM,Ns}}.\frac{M_v}{R}.\left(\frac{P_{v,Ns}}{T_{Ns}}-\frac{P_{v,Ns+1}}{T_a}\right).Le_{Ns}^{-2/3} \tag{27}$$

where

$$P_{AM,i} = P_o - \frac{P_{v,i}-P_{v,i+1}}{2} \tag{28}$$

$$Le_i = \frac{\alpha_{mi}}{D_i} \tag{29}$$

where D_i is diffusion coefficient inside ith stage (m^2/s).

Diffusion coefficient from water vapor to dry air inside each stage can be calculated by using the following expression proposed by [30] as

$$D_i = 1.820034881\times10^{-5} + 1.324098731\times10^{-7}t_{av} + 1.978458093\times10^{-10}t_{av}^{2} \tag{30}$$

The saturation pressure of water vapor inside each stage can be expressed by the following formula proposed by [28] as

$$P_{v_i} = 1.131439334 - 3.750393331\times10^{-2}t_{av} + 5.591559189\times10^{-3}t_{av}^{2}$$
$$-6.220459433\times10^{-5}t_{av}^{3} + 1.10581611\times10^{-6}t_{av}^{4} \tag{31}$$

The difference in evaporation from saline water and fresh water is because of chemical salt concentration. The evaporation rate can be linked to the salinity by introducing water molar fraction X_{H_2o} as an effective variable in a salt solution. Thus, the saturated vapor pressure above salt water inside each stage can be calculated using the following expression

$$P_{v_{si}} = P_{v_i} X_{H20} \tag{32}$$

where X_{H_2o} is given by [31] as

$$X_{H_2o} = \left(\frac{C_{mH_2o}}{C_{mH_2o} + \sum_{i=1}^{N_d} C_{m(Salt)_i}} \right) \tag{33}$$

where C_m is the molality of the solute which is the concentration of solution given as moles per 1000 grams of solvent (moles/kg).

Hourly supplied mass flow rate to the i[th] stage (kg/h) can be expressed as

$$M_i = \int_0^{time} \dot{m}_i dtime \tag{34}$$

Daily supplied mass flow to the i[th] stage (kg/day) can be expressed as

$$M_{d_i} = \int_{time=1}^{12} M_i dtime \tag{35}$$

Daily supplied mass flow rate to the multi-stage evacuated solar desalination system (kg/day) can be expressed as

$$M_{d_{ms}} = \sum_{i=1}^{N_s} M_{d_i} \tag{36}$$

Hourly distillate yield from the i[th] stage (kg/h) can be expressed as

$$M_{ei} = \int_0^{time} \dot{m}_{ei} dtime \tag{37}$$

Daily distillate yield from the i[th] stage (kg/day) can be expressed as

$$M_{ed_i} = \int_{time=1}^{12} M_{ei} dtime \tag{38}$$

Daily distillate yield from the multi-stage evacuated solar desalination system can be calculated using the following expression as

$$M_{ed_{ms}} = \sum_{i=1}^{N_s} M_{ed_i} \tag{39}$$

Cumulative distillate efficiency for each stage (%) is defined as the ratio of total cumulative daily distillate yield from each stage to that of the total supplied mass flow rate to that stage through out the day. It can thus be calculated by the following expression

$$\eta_{dis_i} = \frac{M_{ed_i}}{M_{d_i}} \tag{40}$$

Cumulative distillate efficiency for the multi-stage evacuated solar desalination system (%) is defined as the ratio of total cumulative daily distillate yield from all the stages to that of the total supplied mass flow rate to all the stages throughout the day. It can thus be calculated by the following expression

$$\eta_{dis_{ms}} = \frac{M_{ed_{ms}}}{M_{d_{ms}}} \tag{41}$$

Overall thermal efficiency for each stage (%) is defined as the ratio of total heat content output from the stage by the cumulative daily distillate yield of that stage to that of the total heat content supplied to that stage through out the day. For the first stage, the total heat content input is only through flat plate collectors. Whereas, for the second to N_s stages, there is an additional heat input through latent heat of condensation. The outlet temperature from the flat plate collectors, latent heat and refined latent heat of vaporization of water from each stage and specific heat capacity of water from each stage are averaged over the day. Thus, the overall thermal efficiency can be calculated by the following expression

For the first stage (i=1)

$$\eta_{oth_i} = \frac{M_{ed_i} h_{fgi_{av}}}{M_{d_i} c_{psi_{av}} T_{fo_{av}}} \tag{42}$$

For i=2 to N_s

$$\eta_{oth_i} = \frac{M_{ed_i} h_{fgi_{av}}}{M_{d_i} c_{psi_{av}} T_{fo_{av}} + M_{d_{i-1}} \left[h^*_{fgi-1_{av}} + c_{pwi-1_{av}} \left(T_{i-1_{av}} - T_{i_{av}} \right) \right]} \tag{43}$$

The various variables used in above equations are already mentioned above but they are evaluated at average conditions of evaporator and condenser surfaces.

Overall thermal efficiency for the multi-stage evacuated solar desalination system (%) is defined as the ratio of total heat content output from all the stages by the cumulative daily distillate yield of all the stages to that of the total heat content supplied to system throughout the day. For the entire system the total heat content input is only through flat plate collectors. The latent heat of vaporization of water and specific heat of water is averaged over the entire system. For simplicity purpose to avoid tedious calculation, their values are assumed to be fixed as there is no much variation with temperature. Thus, the overall thermal efficiency can be calculated by the following expression

$$\eta_{oth_{ms}} = \frac{M_{ed_{ms}} h_{fg}}{M_{d_{ms}} c_{ps} T_{fo_{av}}} \tag{44}$$

The various thermophysical properties of humid air mixture (dry air-water vapor) inside each stage of a multi-stage evacuated solar desalination system used in equation (16), equation (22) to equation (27) and equation (29) can be evaluated by the expressions given by [28].

4. Modeling procedure

Two separate programs are written for calculating outlet temperature from flat plate collectors and distillate yield from desalination system. The outlet temperature from the flat plate collectors is calculated for every hour for twelve hour operating period from equationn (1) and equation (2). This temperature is given as input to the multi-stage desalination program. The main program of the multi-stage desalination system is used to solve the differential equation (3) and equation (4) for every second of twelve operating hours to predict individual stage water temperature. At every call of the main program, the sub programs solves the energy balance equations for all the stages, calculates all the required thermophysical properties, the convective heat transfer coefficient from equation (24) and equation (25) and the mass of water evaporated from the equation (26) and equation (27). The main function takes the output from all these subroutines as input arguments to calculate the distillate yield from all the stages after every hour and cumulative distillate yield at the end of the day. The code is written in MATLAB 7.7 and it can be run in other lower and higher MATLAB versions.

By taking the values of C=0.2 and n=0.26 in convective heat transfer coefficient and by using the formula proposed by [28] for modified Grashof number and by using the formula proposed by [30] for distillate mass flow, the proposed model accurately predicts the distillate yield for multi-stage evacuated solar desalination system operating at high temperatures. Further, this model overcomes the drawbacks of basic Dunkle's model which has been used by many authors even today. The advantages of the present model to that of Dunkle's model is that it is valid at higher operating temperatures more than 50^oC, it takes into account the thermo physical properties of humid air, the partial vapor pressure at the water surface and condensing surface is not neglected compared to the total barometric pressure present inside the still, takes into consideration the influence of the average distance between the water surface and condensing surface. Thus, the model can be treated to be the most generalized expression and can able to predict the distillate yield more accurately.

The distillate yield is computed with the same water and glass temperatures for V-shaped multi-tray desalination system as per the dimensions of [32]. Figure 4 and Figure 5 shows a very good agreement between the present model and their experimental results.

Also there is a good agreement that was observed for the distillate yield between the present model and the experimental results for single slope active solar still as per the dimensions of [33] as shown in Figure 6.

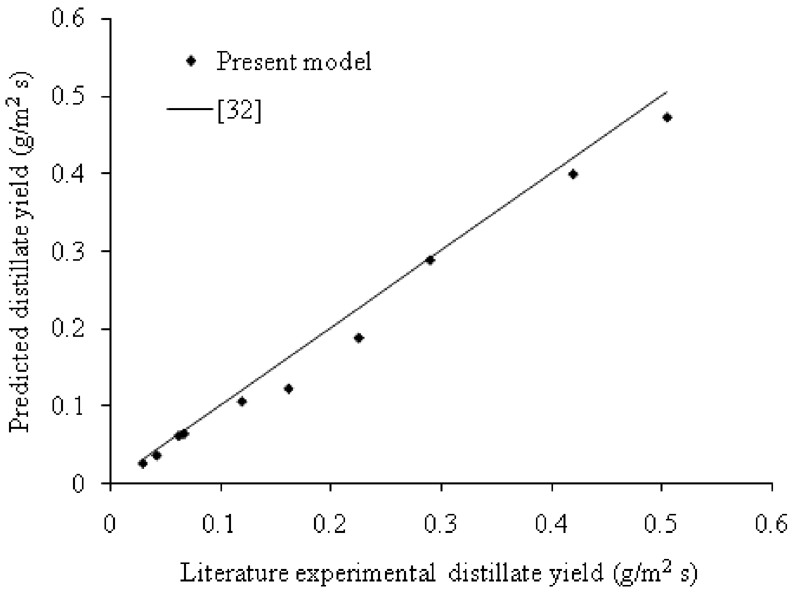


Figure 4. Parity plot showing the Comparison of distillate yield for a single tray still with height 0.06m and area $0.690x0.705m^2$

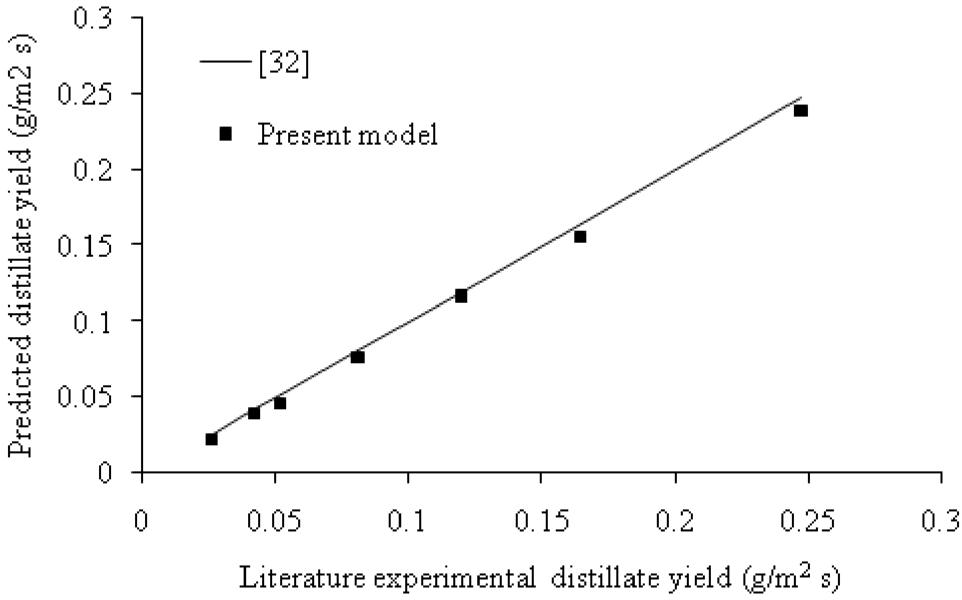


Figure 5. Parity plot showing the Comparison of distillate yield for the second tray of two stacked tray still with heights 0.06m and 0.07m and area 0.690x0.705m^2

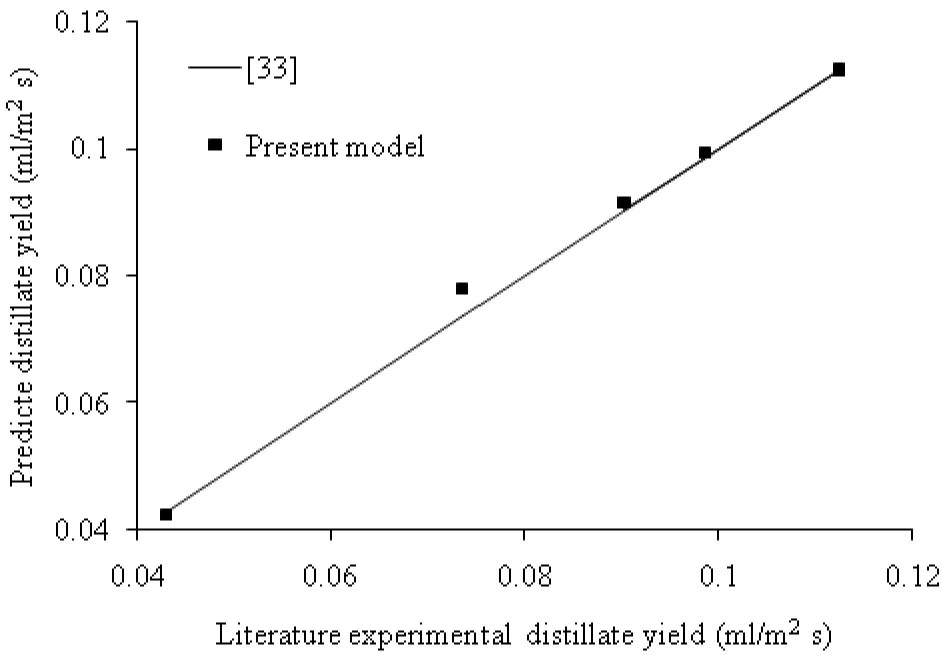


Figure 6. Parity plot showing the Comparison of distillate yield for the active solar still with area of 2 m^2 and height 0.155 m

Further more in order to validate the proposed model, it has been evaluated with the recent literature by [19]. The stage temperatures predicted by the present model is in good agreement with their experimental data. In addition, the model is also validated with their theoretical distillate yield, and there was a very good agreement that was observed. The parity plot of distillate yield is Figure 7.

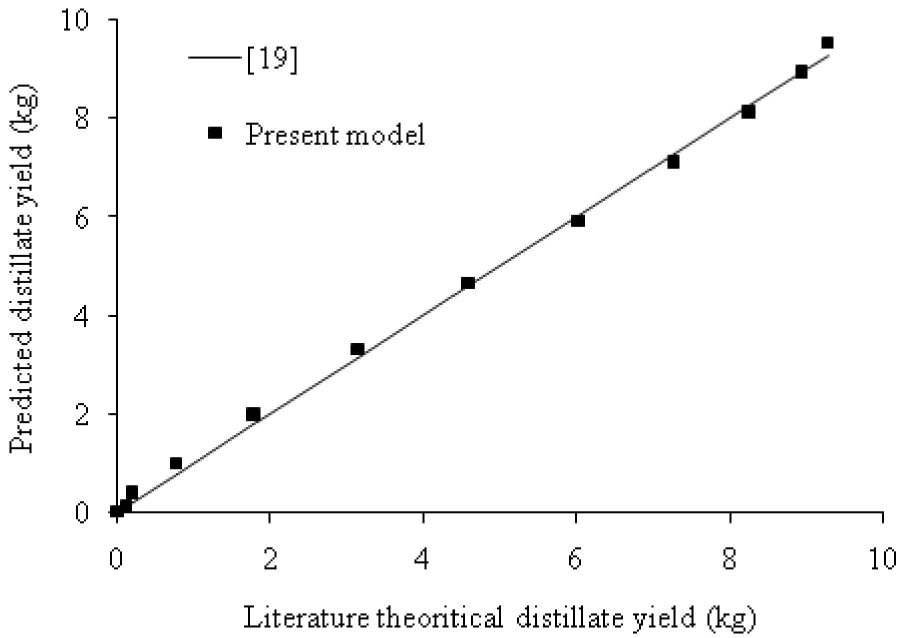


Figure 7. Parity plot showing the comparison of present model with that of [19] for cumulative distillate yield

5. Results and discussion

There are many design and operating parameters which affect the performance characteristics and distillate yield of the multi-stage evacuated desalination system. These parameters and their effects on the flat plate collector and multi-stage desalination system performance are discussed in detail in this section.

5.1 Variation of global solar radiation and ambient temperature

The year round global solar radiation and ambient temperature data for Chennai is taken from [34]. Figure 8 shows the variation of global solar radiation and the ambient temperature for the months of January to June. Figure 9 shows the variation of global solar radiation and the ambient temperature for the months of July to December. The maximum radiation occurs in the month of March of 955.56 W/m^2 at 13:00 and minimum in December of 705.56 W/m^2 at 12:00. Whereas ambient temperature is maximum of 36.1^{o}C at 13:00 in the month of May and minimum ambient temperature of 27.9^{o}C occurs in December at 13:00.

5.2 Effect of number of stages on the distillate yield

Firstly, the analysis is done by fixing certain mass flow rate of 150 kg/day through the collector which are kept in parallel combination. For 150 kg/day, the outlet temperature from the flat plate collector is computed and is fed into the stages of the desalination unit where the gap between the stages is fixed to be 250 mm. The preliminary year round analysis is done for fresh water feeding into the evaporative-condenser unit which is operating at atmospheric pressure. Now, the effect of variation of number of stages on the cumulative distillate yield is computed and it is plotted in Figure 10. It is found that with the increase in number of stages, the temperature difference between the stages decreases because of which there is no improvement in the distillate yield. The optimum number of stages is found to be four for the maximum year round performance.

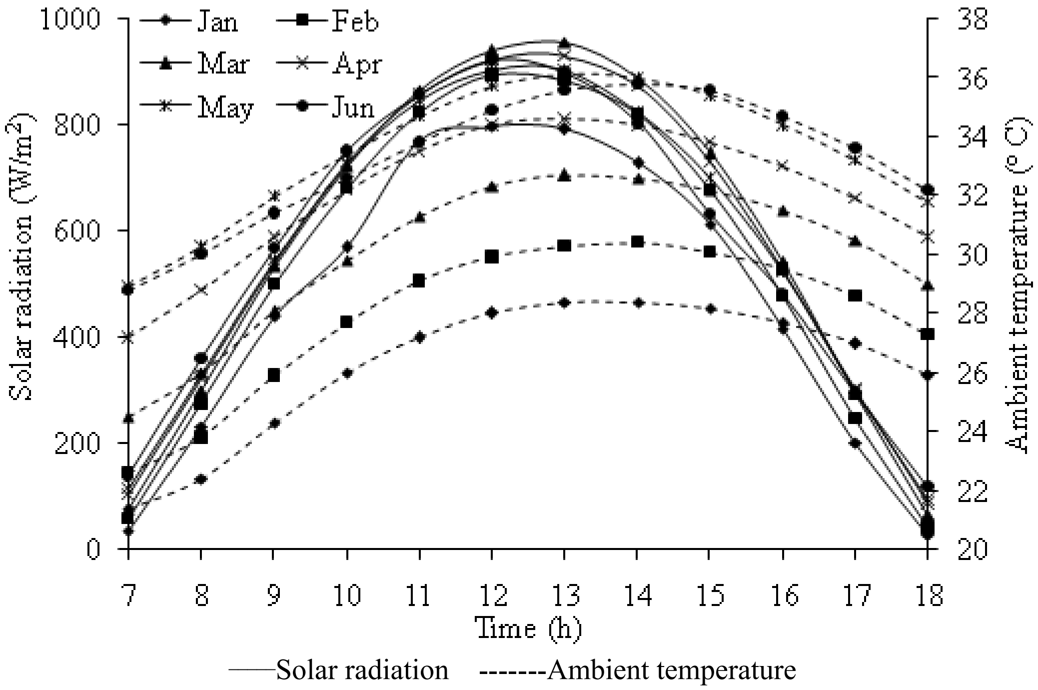


Figure 8. Mean monthly hourly variation of global solar radiation and ambient temperature at Chennai for January to June

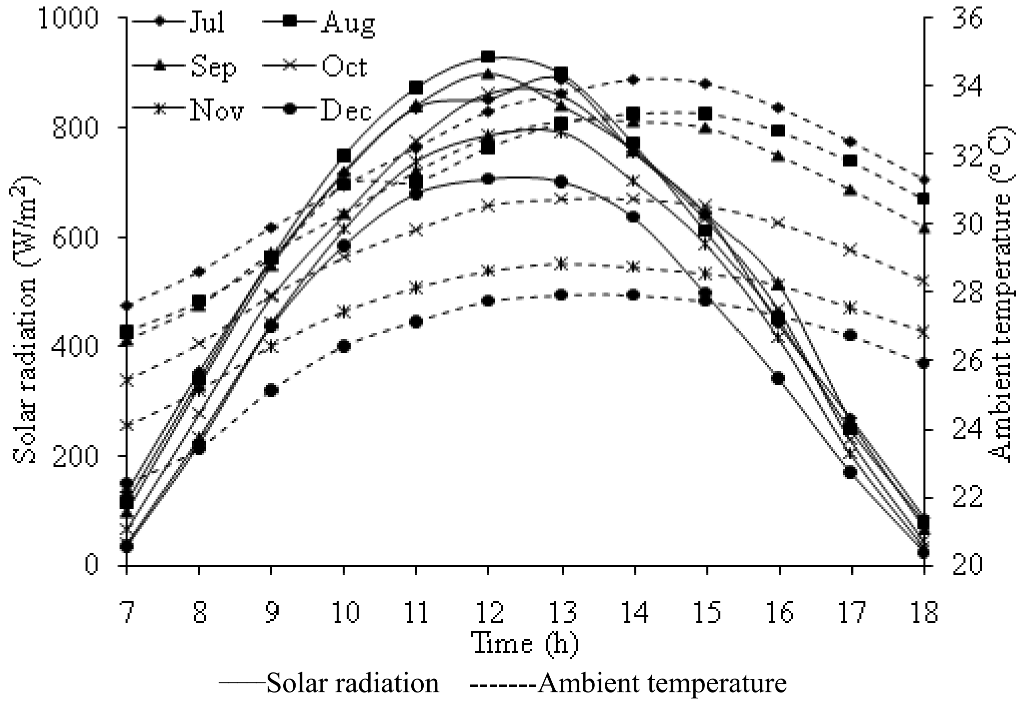


Figure 9. Mean monthly hourly variation of global solar radiation and ambient temperature at Chennai for July to December

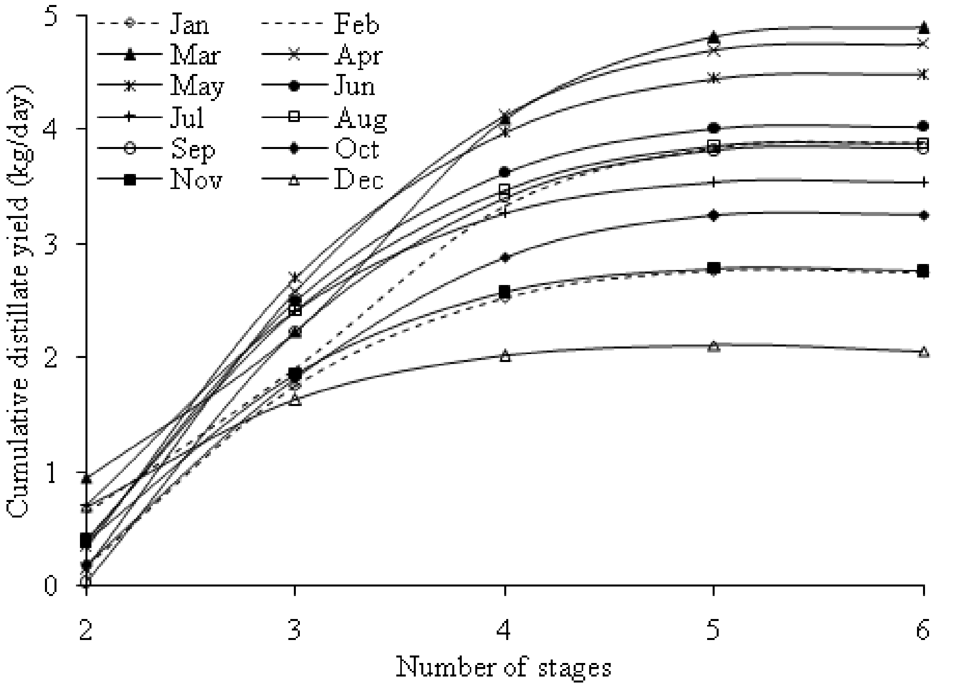


Figure 10. Effect of number of stages on the cumulative distillate yield

5.3 Effect of mass flow rate on the distillate yield

In order to study the effect of mass flow rate on the distillate yield, the flat plate collector analysis is performed with different mass flow rates and the outlet temperature is computed which is then given to all the four stages as the initial guess and the same mass flow rate is equally distributed to all the stages. The effect of mass flow rate on the distillate yield is shown in the Figure 11. Initially as the mass flow rate decreases from 150 kg/m^2/day to 55 kg/m^2/day, thickness of water layer in the stages decreases thus it enhances evaporation and condensation phenomena leading to more stage water temperature and hence increase in the distillate yield. But, further decrease in mass flow rate from 55 kg/m^2/day to 30 kg/m^2/day, the temperature in the stages decreases thus leading to a decrease in distillate yield.

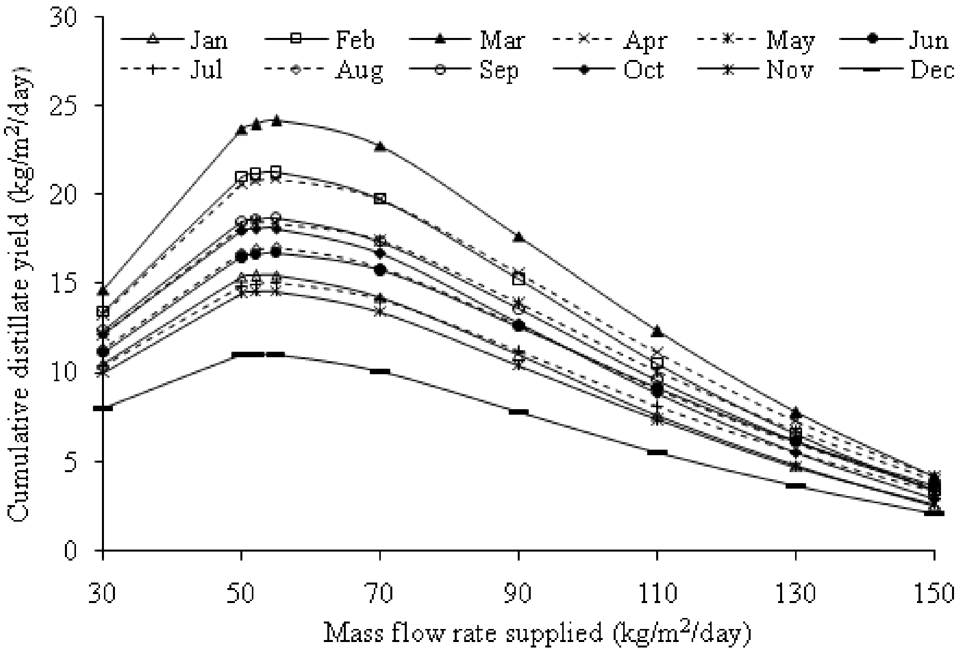


Figure 11. Effect of mass flow rate on the distillate yield

5.4 Effect of gap between the trays on the distillate yield

The year round analysis is performed on the desalination system with optimum 4 stages and mass flow rate 55 kg/m^2/day for fresh water by varying the gap between the trays. It is found in the Figure 12 that by decreasing the gap between the trays, the distillate increases due to increase in the temperature difference between the stages which is due to reduction in the vapour leakage. As practically it is not feasible to keep very small distance between the trays, the optimum gap is fixed as 100mm. Thus, further analysis is carried for the mass flow rate of 55 kg/m^2/day and 100mm gap between the trays operating under atmospheric pressure for 4 stage desalination system.

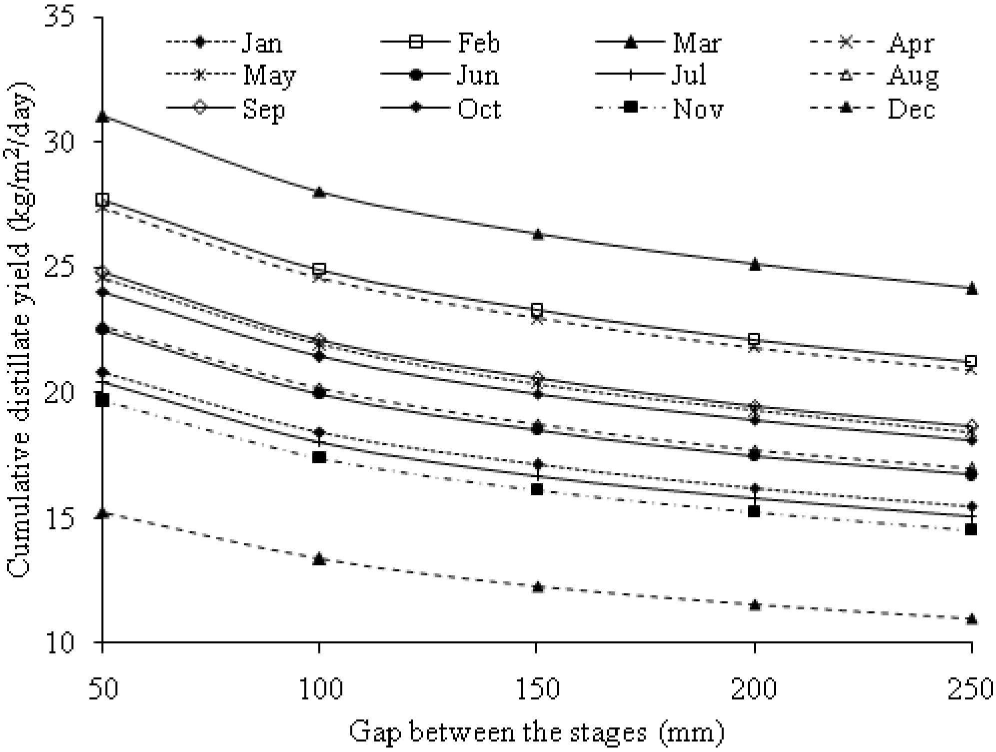


Figure 12. Effect of gap between the trays on the distillate yield

5.5 Effect of salinity on the distillate yield, distillate efficiency and overall thermal efficiency

The year round variation of cumulative distillate yield, distillate efficiency and overall thermal efficiency of fresh water, brackish water, saline water and brine solution is shown in the Figure 13 to Figure 15 respectively. It is found that by increasing the salt content in the solution, the distillate yield decreases. With the increase in salinity, the evaporation of water decreases due to increase in ion activity and the reduction of thermodynamically spontaneous change of a liquid phase into a vapour phase. Increasing the water salinity increases the boiling point elevation, which reduces the temperature of the evaporated water and its vapour pressure. The maximum yield for fresh water is 28.044 kg/m^2/day in March and it is decreased to 25.721 kg/m^2/day for brackish water, 22.553 kg/m^2/day for saline water and 18.614 kg/m^2/day for brine solution. While for the month of December, the distillate yield is minimum of 13.335 kg/m^2/day for fresh water and it decreased to 12.543 kg/m^2/day for brackish water, 11.382 kg/m^2/day for saline water and 9.791 kg/m^2/day for brine solution. The maximum distillate efficiency for fresh water is 50.989% in March and it is decreased to 46.765% for brackish water, 40.46% for saline water and 33.844% for brine solution. While for the month of December, the distillate yield is minimum of 24.245% for fresh water and it decreased to 22.805% for brackish water, 20.694% for saline water and 17.802% for brine solution. The maximum distillate efficiency for fresh water is 81.171% in March and it is decreased to 74.447% for brackish water, 65.278% for saline water and 53.876% for brine solution. While for the month of December, the distillate yield is minimum of 40.362% for fresh water and it decreased to 37.964% for brackish water, 34.452% for saline water and 29.635% for brine solution.

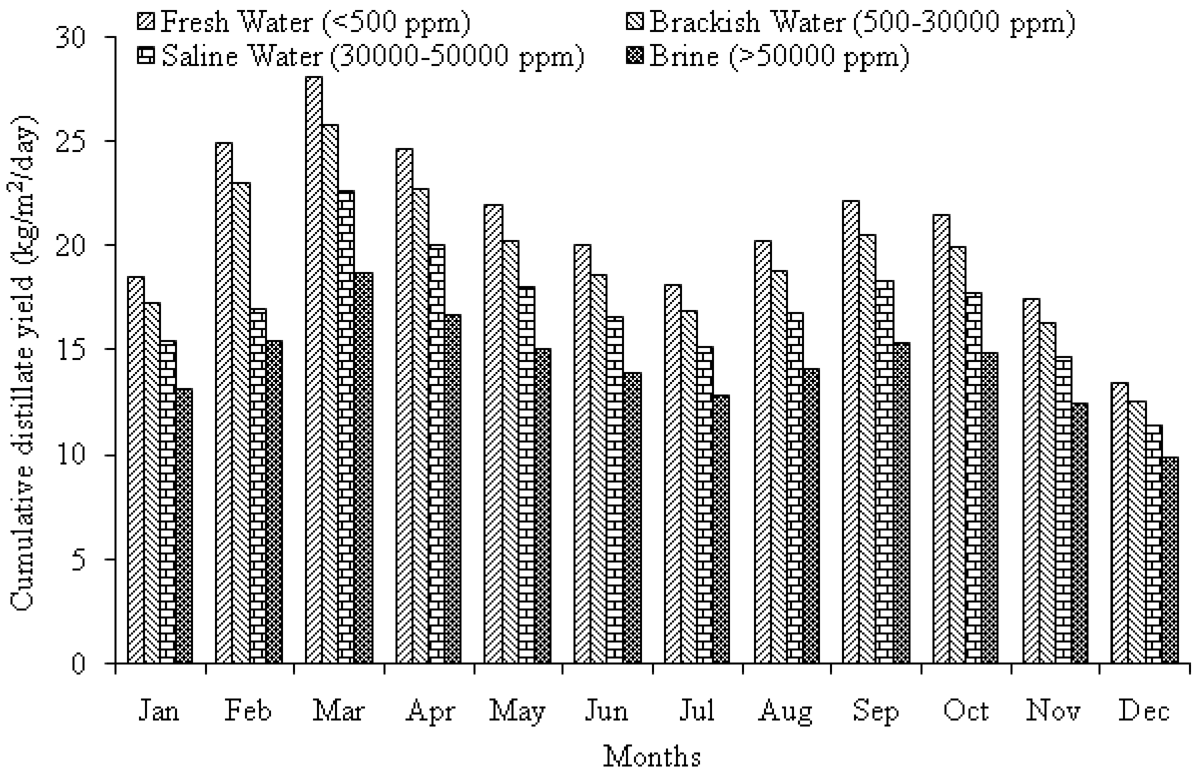


Figure 13. Year round variation of distillate yield with salinity

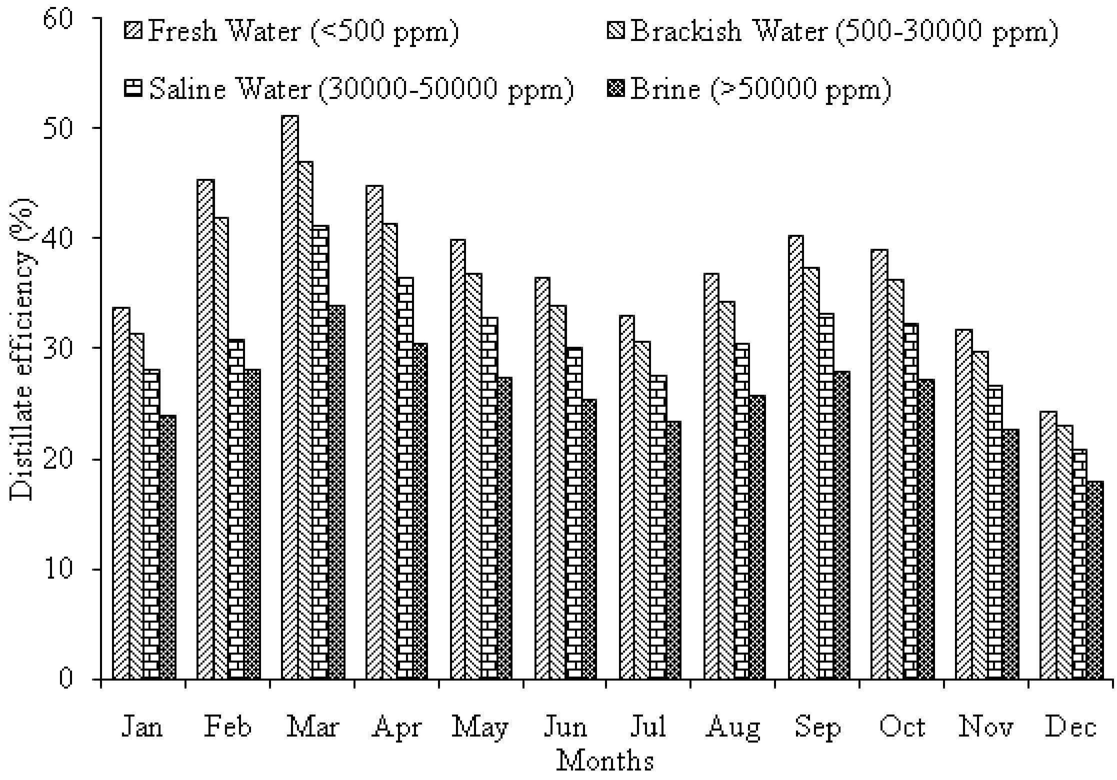


Figure 14. Year round variation of distillate efficiency with salinity

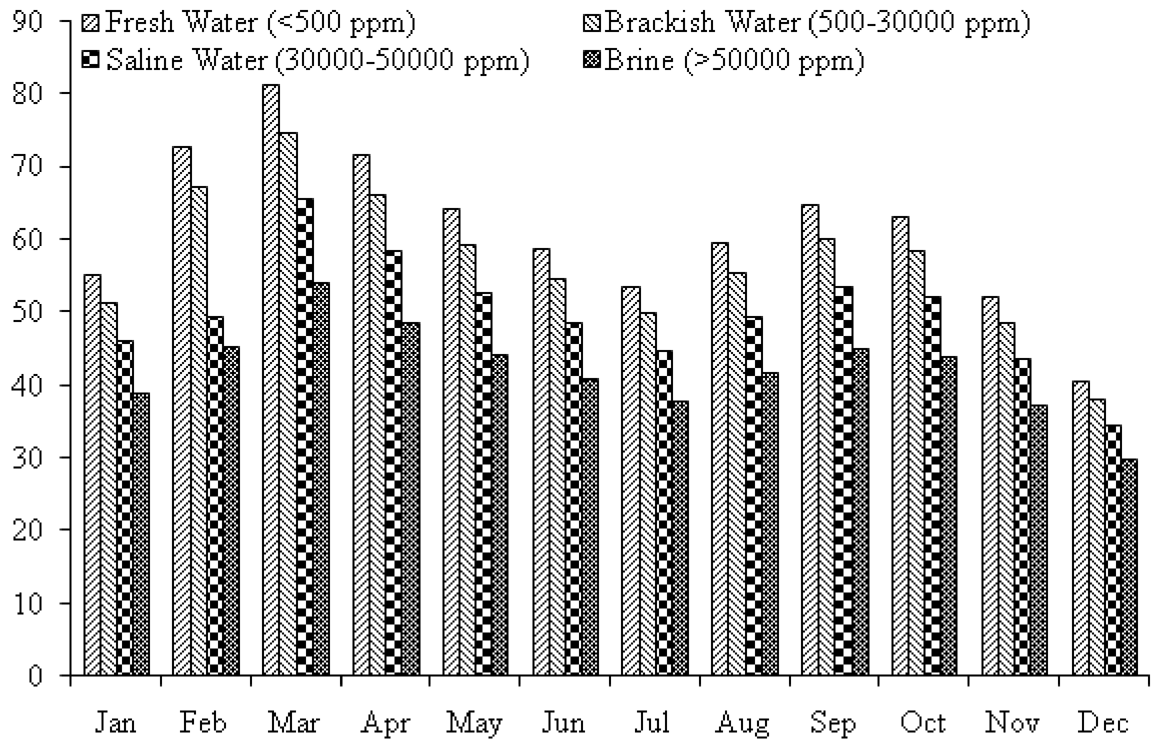


Figure 15. Year round variation of overall thermal efficiency with salinity

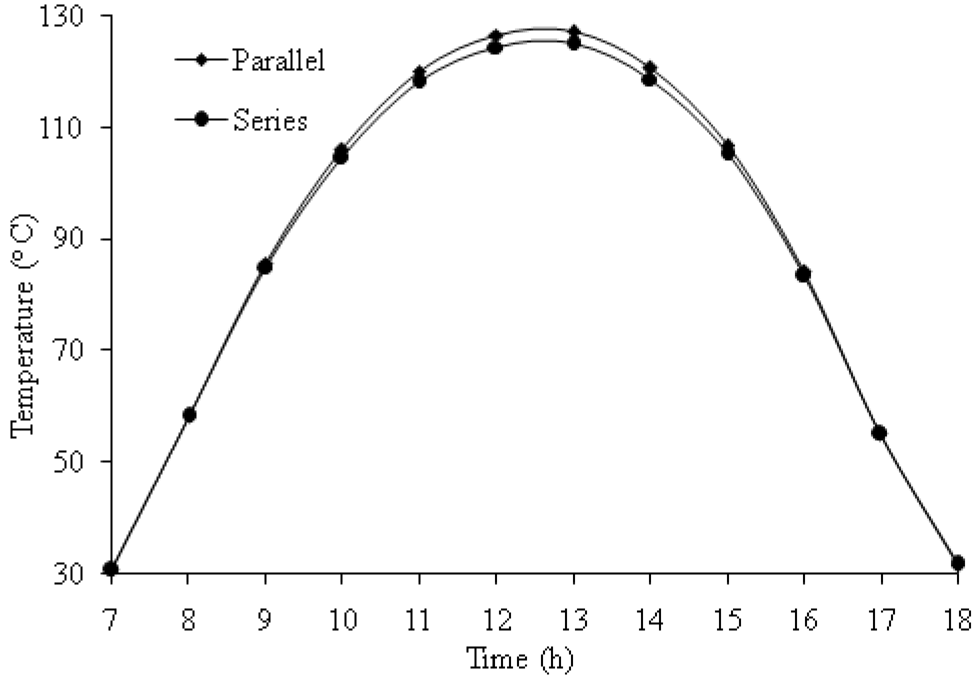
Based on the previous analysis, it is found that for the month of March, the distillate yield, distillate efficiency and overall thermal efficiency are maximum for all the water bodies. Thus, the further analysis considering the effect of series and parallel combination of flat plate collectors, global radiation, wind velocity, evaporative-condenser internal pressure has been performed only for the month of March.

5.6 Effect of series and parallel combination of flat plate collectors

The combination of flat plate collectors in both series and parallel are considered and its effect on the outlet temperature of the collector combination and distillate yield are computed. From Figure 16, it is very obvious that due to less temperature output from the collector, the distillate yield in series combination is less compared to parallel combination. In series combination of collectors, the outlet temperature of first collector is inlet to the next collector leading to more heat losses from the second collector and thus the oulet temperature of the collector combination is less. Whereas in parallel combination the inlet to both the collectors is ambient thus heat losses will be less, additionally the mass flow rate supplied is distributed equally among the two collectors leading to increase in collector outlet temperature. The maximum outlet temperature from series combination is found to be 124.287^{o}C, while from parallel combination it is 127.132^{o}C at 13:00. Thus, the further analysis is carried out only for month of march when collectors are connected in parallel and the desalination system is supplied with fresh water.

5.7 Variation of cumulative distillate yield and stage temperature with time

For fresh water, the yield from all the stages is computed at every hour and the hourly individual yield is summed up and the variation in cumulative distillate yield at every hour is calculated and it is shown in Figure 17. The cummulative yield after two hours is the sum of the hourly yield at first hour and second hour. In this way, the cummulative yield is found out throughout the day for all the stages. Further, the cumulative yield from all the stages are added to get the total cumulative distillate yield from the multi-stage desalination system. Even after 13:00 beyond which the solar radiation drops, the cumulative yield increases because of the existence of stage temperature difference, which is due to hot collector outlet temperature but the increament is less. But, at the end of the day because of insufficient heat source to the first stage which is due to less outlet temperature from the flat plate collector combination (almost equal to ambient), the evaporation of water in the stage decreases leading to decrease in latent heat of condensation which leads to decrease in temperature difference between the stages. Thus, there is no increment in cummulative distillate yield and it attains almost steady state. The cumulative distillate yield at the end of the day for the individual stages are 0.846 kg/m^2/day for first stage, 4.168 kg/m^2/day for second stage, 9.454 kg/m^2/day for third stage and 13.576 kg/m^2/day for fourth stage respectively. The overall cummulative distillate yield at the day for the multi-stage solar desalination system is found to be 28.044 kg/m^2/day. The variation of temperature in the stages with time is computed and is shown in Figure 18.



Fifure 16. Effect of series and parallel combination of flat plate collectors on the outlet temperature for the month of march

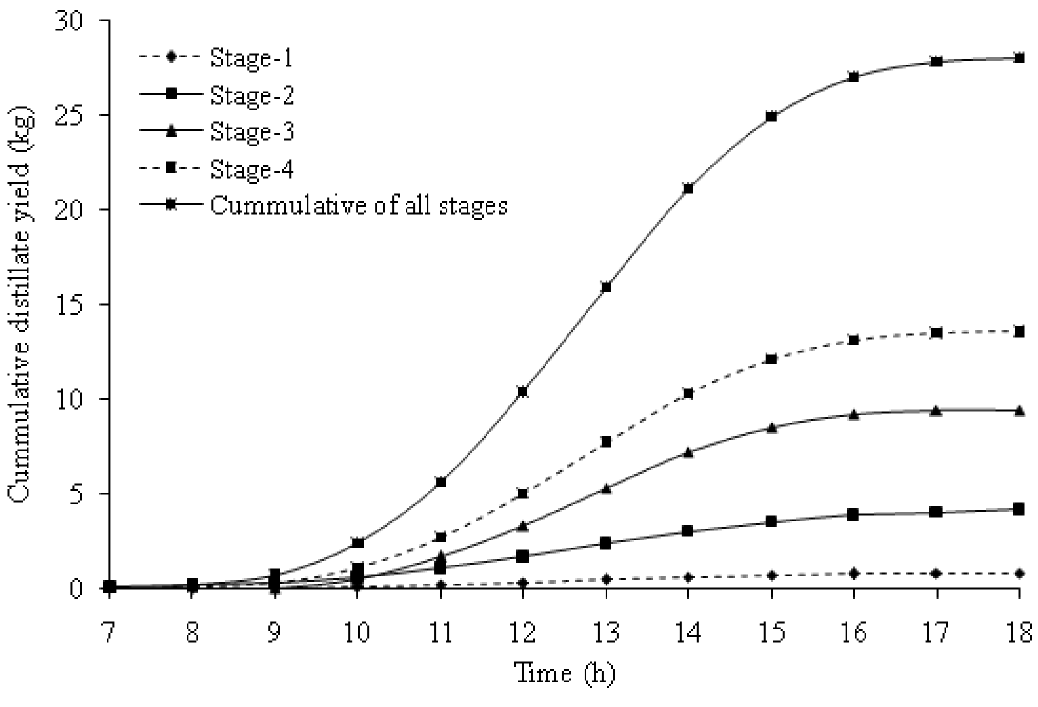


Figure 17. Variation of cummulative distillate yield with time

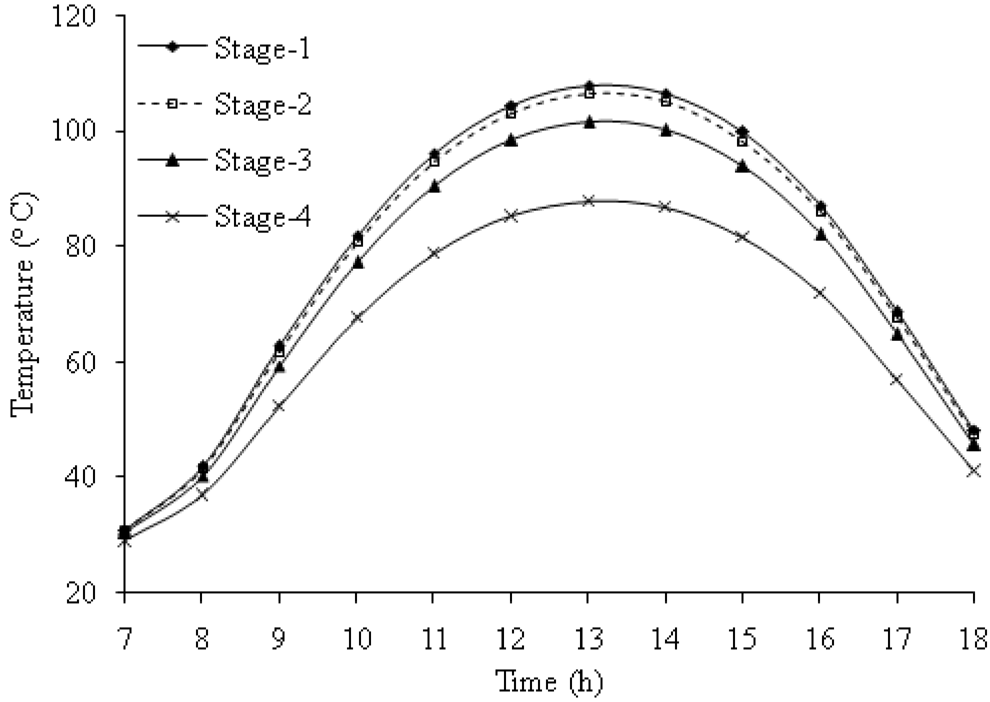


Figure 18. Hourly variation of temperature in the stages

5.8 Effect of temperature difference between the stages on the distillate yield

The temperature difference and hourly distillate yield for all the stages are computed. Figure 19 shows the effect of temperature difference between the evaporating and condensing surfaces on the hourly distillate yield for the first stage. When the temperature difference between the evaporating and condensing surfaces increases, the distillate yield increases owing to higher evporation and thus higher condensation. It is found that the maximum hourly distillate yield for the first stage is 0.143 kg/m^2/h for a temperature difference of 1.51^{o}C between the condensing and evaporating surface at 13:00.

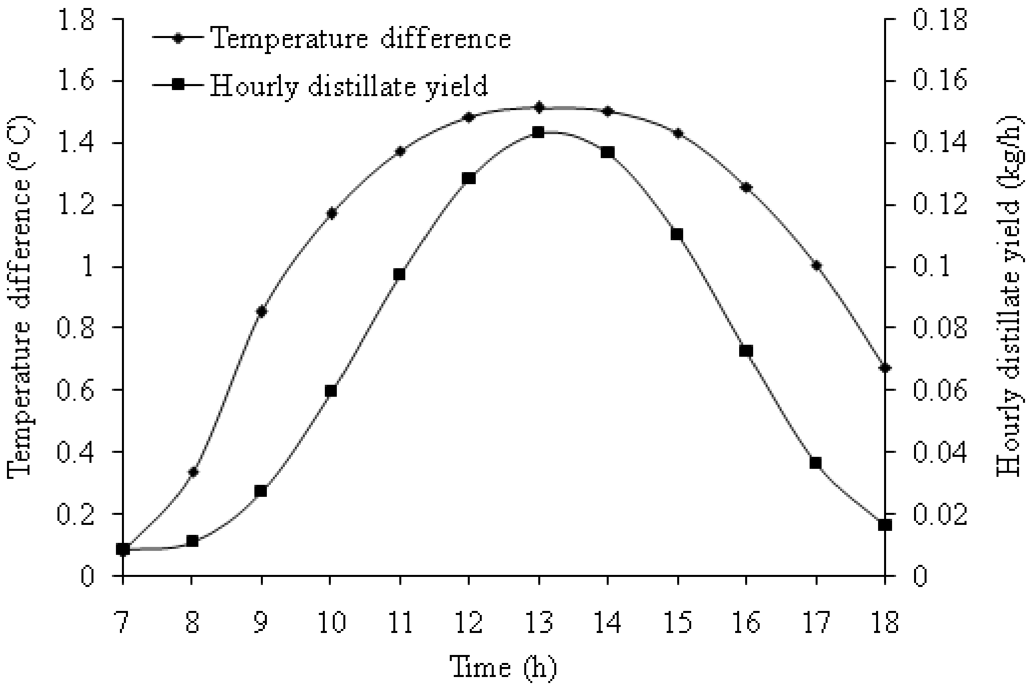


Figure 19. Effect of temperature difference between the evaporator and condenser surfaces on the hourly distillate for the first stage

5.9 Effect of global solar radiation on the distillate yield

The effect of global solar radiation on the hourly distillate yield is analysed for the fresh water. The variation is shown in Figure 20. The hourly distillate yield and global solar radiation are directly related. The maximum hourly distillate yield is found to be 8.281 kg/m^2/h at 13:00 where the global solar radiation is maximum of 955.556 kg/m^2/day.

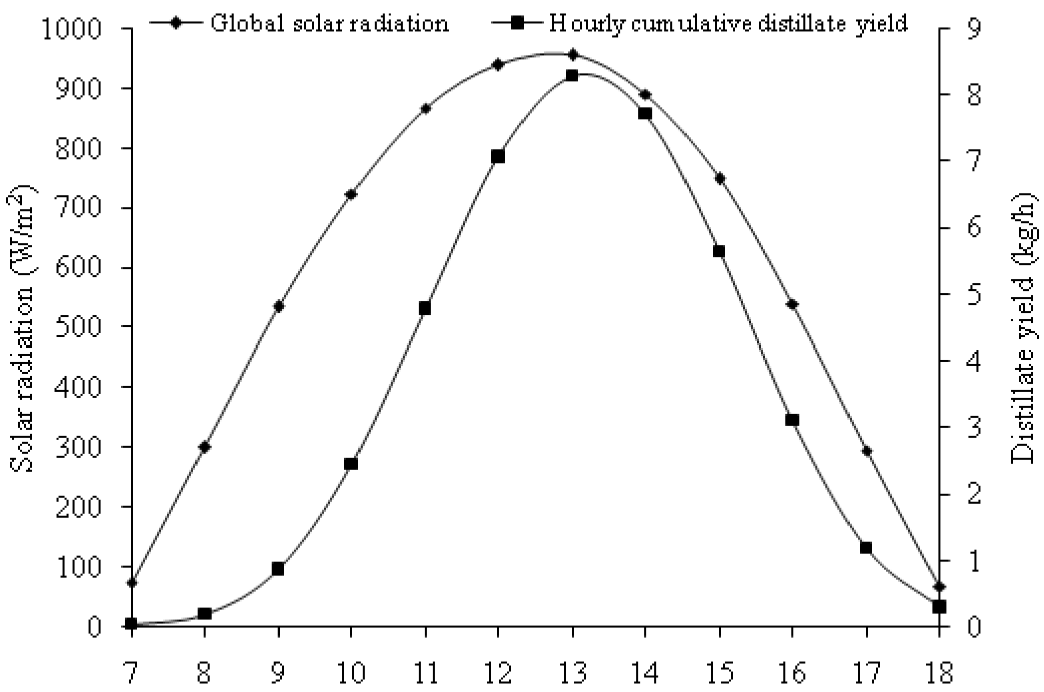


Figure 20. Effect of Global solar radiation on the distillate yield

5.10 Effect of wind velocity on the distillate yield

The effect of wind velocity on the distillate yield is computed and the variation is shown in Figure 21. It is found that the distillate yield increases when the wind velocity decreases because of less heat losses from the flat plate collector leading to higher temperature input to the first stage and thus high stage temperature which leads to high temperature between the stages. Increase in temperature difference between the stages leads to increase in evaporation and condensation leading to increase in distillate yield. The maximum yield is found to be 8.281 kg/m^2/h at a wind velocity of 3.25 m/s at 13:00.

5.11 Effect of pressure on the distillate yield

The internal pressure of evaporative-condenser unit is varied and its effect on distillate yield is shown in Figure 22. With the decrease in pressure, distillate yield increases due to increase in temperature difference between the stages. By further decrease in pressure, the temperature difference between the stages decreases due to enhanced evaporation happening in all the stages simultaneously leading to a decrease in distillate yield. At very high vacuum pressure, all the supplied water gets evaporated immediately from all the stages and thus condensation phenomena will not happen. Infact, it is seen that by decrease in pressure beyond certain limit, the top stages are attaining higher temperature than the stages below, thus stopping condensation phenomena to occur leading sudden drop in distillate yield. It is found that the distillate yield and distillate efficiency increases from 28.044 kg/m^2/day and 50.989% at atmospheric pressure to 53.211 kg/m^2/day and 96.747% respectively at 0.03 bar pressure for fresh water. Whereas for brackish water, the yield and efficiency increasd from 24.344 kg/m^2/day and 42.444 % at atmospheric pressure to 42.042 kg/m^2/day and 76.44% at 0.02 bar respectively. For saline water, it is found that yield and efficiency increases from 19.352 kg/m^2/day and 35.185% to 40.256 kg/m^2/day and 73.193% by decreasing the pressure from atmospheric to 0.02 bar respectively. In case of brine solution, the yield and efficiency increased from 13.247 kg/m^{2}day and 24.085 % at atmospheric pressure to 33.051 kg/m^2/day and 60.093% at 0.02 bar respectively.

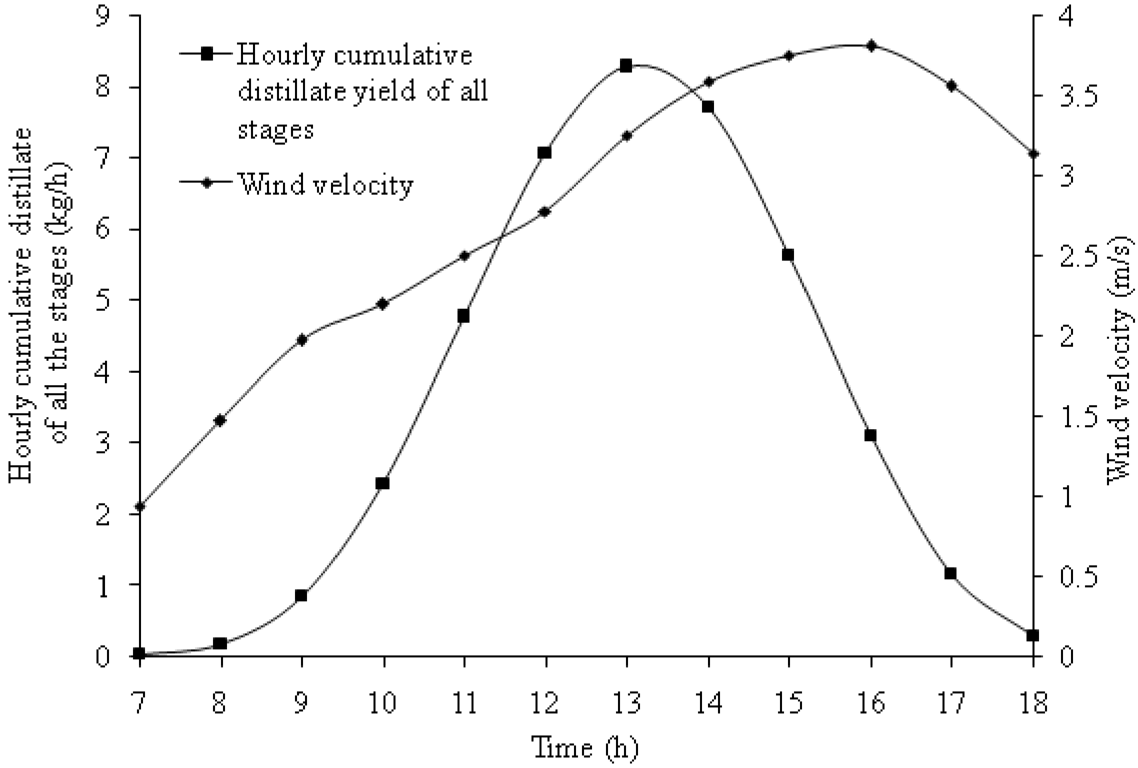


Figure 21. Effect of wind velocity on the distillate yield

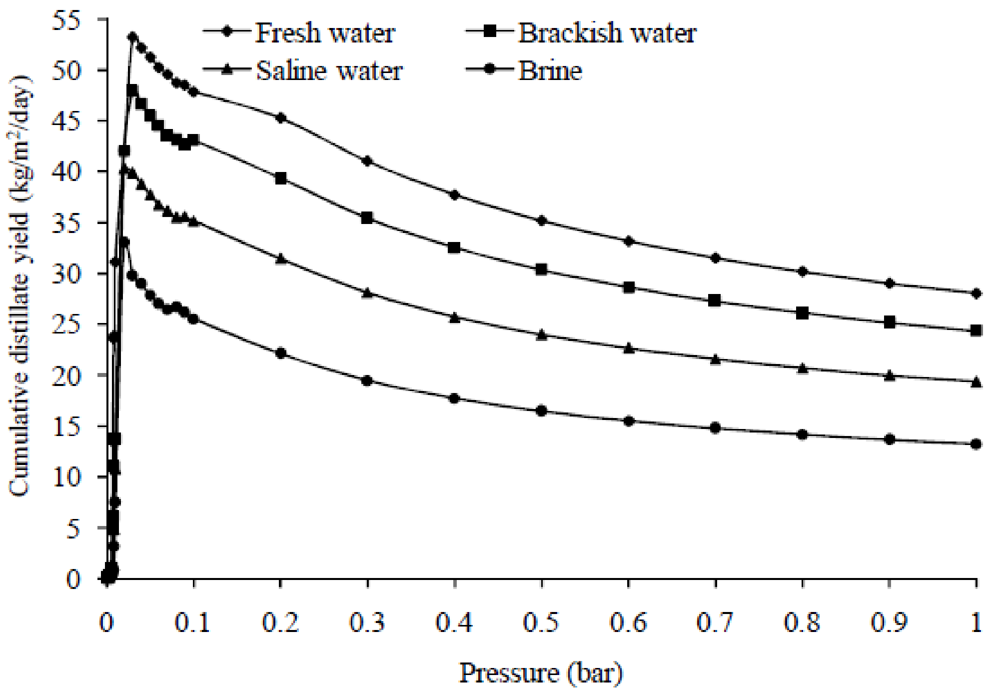


Figure 22. Effect of evaporative-condenser pressure on the distillate yield

6. Conclusion

A transient mathematical model was developed for the flat plate collector and the multi-stage evacuated solar desalination system to evaluate the optimum design configuration and system performance throughout the year. The model is validated with the lierature and a good agreement was observed. The optimum number of stages and the supplied mass flow rate for the system were found to be four and 55kg/m^2/day irrespective of the climatic conditions i.e., for all the months. Highest distillate yield was found in the month of March because of the higher global solar radiation compared to other months and lowest distillate was found for December owing to lower climatic conditions. The maximum yield of 28.044 kg/m^2/day is found in March for fresh water at a distillate efficiency of 50.989% and an overall thermal efficiency of 81.171%. With increase in salinity, the yield decreases to 18.614 kg/m^2/day for brine solution at a distillate efficiency of 33.844% and an overall thermal efficiency of 53.876%. While the minimum yield, disillate efficiency and overall thermal efficiency are found in December of 13.335 kg/m^2/day, 24.245% and 40.362% for fresh water, whereas the yield, distillate efficiency and overall thermal efficiency decreases to 9.791 kg/m^2/day, 17.802% and 29.635% respectively for brine solution. Parallel combination of collectors has been found to be better compared to series combination because in later, the heat losses will be more leading to lower outlet temperature and thus leads in lower distillate yield. With the decrease in wind velocity, the collector outlet temperature and the distillate yield from the desalination system were increased. With the increase in temperature difference between the stages, the distillate yield increases owing to the increase in evaporation and condensation phenomena. The effect of pressure was found to be very significant on the distillate yield. It was found that for the month of March, the distillate yield increases from 28.044 kg/m^2/day at atmospheric pressure to 53.211 kg/m^2/day at 0.03 bar pressure for fresh water. For brackish water, the yield increasd from 24.344 kg/m^2/day at atmospheric pressure to 42.042 kg/m^2/day at 0.02 bar. For saline water, it is found that yield increases from 19.352 kg/m^2/day to 40.256 kg/m^2/day by decreasing the pressure from atmospheric to 0.02 bar. For brine solution, the yield increased from 13.247 kg/m^{2}day to 33.051 kg/m^2/day at 0.02 bar. The optimum design conditions gave a maximum yield of 28.044 kg/m^{2}day and a minimum of 13.335 kg/m^{2}day. The multi-stage solar desalination system can meet the fresh water needs of rural and urban communities to necessitate 10 to 30 kg per day.

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