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Research paper

A novel analytical performance investigation of varying water depth in an active multi-stage basin solar still in addition to optimization of water depth in a single stage basin still

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ABSTRACT

In the present research, active solar basin stills are studied and the effect of water depth on output productivity is evaluated analytically. In order to validate the reliability of the results of the proposed model, they have been compared with the available Karimi's experimental data with an acceptable accuracy. Then, the temperature distribution of the basin, covers, the water in the basin and heat transfer coefficients between the water as well as covers in all stages are calculated. Then, the amount of fresh water as an output are derived for one and multistage units. With increasing the number of stages from one to four, the amount of fresh water was increased by 42%, 72% and 94%, respectively. In addition, the amount of yield water for the ratio of three stages to two stages and four stages to three stages was increased 20% and 13%, respectively. Moreover, in this article, a new approach is adapted based on the variation of water depth instead of considering it constant and because of this methodology, there is an optimum value for water depth, which leads to the maximum productivity. Due to the storage of energy in water as a function of water depth, with an increase in the amount of water in the basin of solar stills more than the optimum value, or even decreasing the water depth below the optimum value, one should expect to get the basin without water at the end of day. This may lead to have less fresh water in the output at the end of the day. Finally, a correlation has been provided to calculate the productivity of a single basin still based on the water depth in the basin.

1. Introduction

Clean water scarcity is a major issue in today's world of 7.7 Billion people. The strain on the water system will grow by 2050 when the world population will reach between 9.4 and 10.2 Billion, a 22 to 34% increase (Elango and Murugavel, 2015). Although three quarter of the earth is covered by water but almost 97% of saline water belongs to oceans with only a slight amount of water which is about 3% (36 million cubic meter) is potable where 70% of this is in ice form and the remaining is groundwater (Estahbanati et al., 2015). In view of the fact that saline water is the only source of water in some areas, desalination should be implemented in order to extract fresh water from the brine. Since global warming and environmental issues affecting human activity, using renewable energy in desalination units is ever increasing in recent years. Solar energy is one of the most abundant and useful sources of energy on earth. The data from the International Energy Agency (IEA) shows a rapid growth in technologies based on renewable energy and it is predicted that by 2030 around 40% of electrical energy will be generated from renewable sources (Bahgat, 2011; Shatat and Riffat, 2014). There are numerous methods of desalinations which work using solar energy (Shatat et al., 2013). Among many solar desalination units are basin stills, which are categorized into active and passive based on how the energy is transferred into the water. Numerous researches have been carried out in order to increase the efficiency of these devices. Feilizadeh et al. (2017) examined the effect of height, length, and width of a single-slope basin-type solar still on its distillate production and they showed that by increasing the height of still's walls, its efficiency decreases. Moreover, they demonstrated that by extending the still length, the side walls shadow reduces and consequently, the system efficiency increases. In addition, the optimal width to length ratio was found to be about 0.4. Estahbanati et al. (2015) worked on the effect of the number of stages on the productivity of a multi-effect active solar still experimentally in continuous and non-continuous modes. Estahbanati and his colleagues showed that with increasing the number of stages, distillate production can be predicted with a quadratic function. Moreover, adding a

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maximum of 6 and 10 additional stages can significantly increase production in continuous and non-continuous modes, respectively. They Estahbanati et al. (2015) also concluded that with more stages, the production enhancement is more in the continuous mode compared to the non-continuous mode, in a way that there is no significant difference between the performance of a single-stage device in continuous and non-continuous modes. Sharshir et al. (2020) tried to increase the performance of an inclined wick solar still (IWSS) by integrating different basin metals. Aluminum, copper, in addition to steel were used in the structure of the basin and their metal chips were sandwiched in a novel wick-metal pad. They compared the enhanced solar still with conventional inclined wick solar still (CIWSS). They revealed that using aluminum and copper basins led to increase the productivity by 34.23% and 54.26%, respectively, compared with CIWSS. The use of metal chips sandwiched between two layers of wicks (wick-metal chips pad) caused an increase in the daily production by about 27.76%, 41.54, and 65.3% for steel, aluminum, and copper, respectively. Bachchan et al. (2021) conducted different tests on the performance enhancement of a solar still by using phase change and water-absorbing materials. They found out by combining phase change materials as well as copper serpentine tubing with external heat supply to phase change material (PCM) and saline water though a parabolic trough collector arrangement provides fresh water 10.77 l/m^2 day as compared to 4.48 l/m^2 day for a conventional solar still. A new transient CFD modeling was carried out by Keshtkar et al. (2020a,b), in which they use a coupled analysis in order to find the temperature as well as the coefficients of heat transfer in a multistage basin solar still and they reached a conclusion that adding a new stage beyond 6 is not beneficial. In addition, they performed their analysis based on the variation of parameters in order to see the amount of yield for different number of stages and materials. Saravanan et al. (2021) worked on the use of kanchey marbles as sensible heat storage materials in a double slope still to increase the productivity of the still. Patel et al. (2020) examined the performance of a triple passive basin solar still by using the evacuated heat pipes with absorbers and sensible heat storage materials. They have found that implementing evacuated heat pipes improve the efficiency through increasing the temperature of the water in the lower basin. Khan et al. (2021) investigated the effect of flowing water on a performance of a hemispherical cover basin still. They concluded that by decreasing the cover temperature, the efficiency increased from 34% to 42%. Shoeibi et al. (2022) developed a CFD model for a solar still and used nanopowders in the fluid that cool the cover to alter the thermal properties; they jumped into conclusion that in addition to the amount of freshwater output, energy efficiency increased by 11.09% and 28.21%, respectively. Mishra et al. (2021) investigated the parametric analysis of an active solar still that used conical shape cover for both photovoltaic panels as well as parabolic concentrator to evaluate the output fresh water and the efficiency. Ghandourah et al. (2022) ran a test on a pyramid solar still (PSS) with corrugated absorber plate in order to increase the evaporation area and therefore enhance the yield. They estimated that the PSS produces 52.54% more fresh water than a conventional solar still because of corrugated sheet. Ho et al. (2022) examined the effects of Fresnel lens and phase change materials on the performance of a passive solar still. Their experimental results showed that by using, both lens and phase change materials, the efficiency reached 32% from 28% compared to a conventional basin still. From the present review, it is clear that many researches have been carried out in this area in order to find the effects of different parameters such as geometrical as well as water depth on productivity to increase the yield amount by manipulating these variables. However, there has been a few researches on parametric relations between the output and water depth (or mass of water in each basin). Therefore, in this article the effect of water depth in addition to number of stages on the yield enhancement are studied. A simple polynomial has been developed to find the productivity based on water depth for one stage basin solar still. The novelty of this research is due to the consideration of varying mass of the water in the basin in order to find the amount of output fresh water and the optimized depth of the water in the basin of one stage basin still.

2. Procedure of analysis

In this research, the performance of a four-stage active solar still, as shown in Fig. 1, has been investigated. The heat transfer from the water in the basin to the cover above is taken as the heat input for the next stage. This heat transfer process is again repeated for the next stages in the still. In the last stage, the water loses heat to the cover above it and eventually the heat is dissipated into the atmosphere by convection and radiation. In order to find the amount of productivity for the performance evaluation of the basin still, the data of temperature distributions of the basin, covers as well as the water in the basin and other stages are essential. Thus, the energy balance for each part of the basin is taken into account. For the heat input, a flat plate collector is used in the basin as depicted in Fig. 1. For each part of the device, an energy balance is carried out and then a system of coupled linear ordinary differential equations are solved to find the temperature of different parts of the solar still; the detail of which are given in the following subsections.

2.1. Energy balance

The absorbed heat in the collector is delivered into the water inside the basin, which is stored in the water inside the basin; next, it transferred to upper cover due to the temperature difference between the water and the cover above each stage. Obviously, in each stage, the water in trays acts as a storage material, while some of heat is transferred to the upper stage via convection, radiation and evaporation (Fig. 2). At the same time, heat is being lost to the ambient from the last cover via convection and radiation. Also, some of the heat is transferred by conduction plus convection from the water in the basin to the basin then from the basin into the atmosphere by convection as well. The governing equations in the proposed model for heat transfer coefficients are as follows Davani (2016):

2.1.1. Energy balance for water

$$\left(\frac{dE_{w,b}}{dt}\right)_{c.v} = \sum_{in} \dot{E} - \sum_{out} \dot{E} \tag{1}$$

$$\left(\frac{dE_{w,b}}{dt}\right)_{c.v} = c_w \frac{d(M_{w,1}T_{w,1})}{dt} \tag{2}$$

where in Eq. (2), $M_{w,1}$ is the amount of water in basin, c_w is the specific heat of water.

2.1.2. Energy balance for each stages

$$E_{in} = \eta Q_{col} \tag{3}$$

$$\sum_{out} E = Q_{conv,w,1-c,1} + Q_{evap,w,1-c,1} + Q_{rad,w,1-c,1} + Q_{w-b} \tag{4}$$

In Eq. (3), η is the efficiency of flat collector and Q_{col} is the amount of heat absorbed by collector.

The first three heat terms on the right-hand side of Eq. (4) are the convection, evaporation and radiation heat transfer between

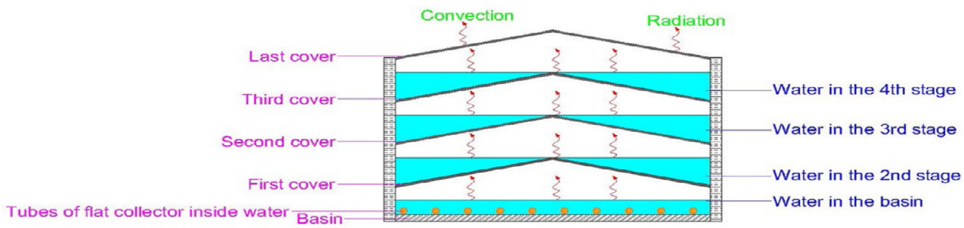

Fig. 1. Schematic of four stages active solar still.

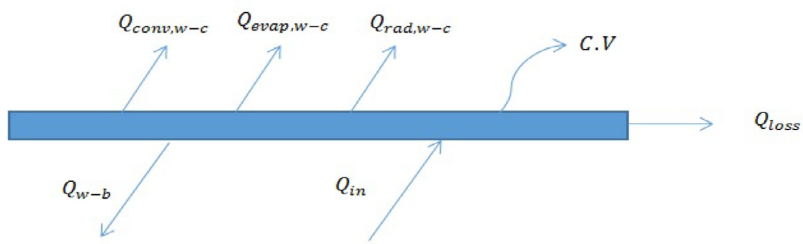

Fig. 2. Schematic of control volume for water in the basin.

the water and the first stage cover, and Q_{w-b} is the amount of heat transferred to basin from the water.

By implementing the energy balance for the water in all stages, basin and covers, a system of differential equations, Eqs. (5)–(9), are developed. By solving these equations simultaneously, one can obtain the temperature of basin, covers and water in all stages.

$$M_b c_b \frac{d(T_b)}{dt} = h_{w-b} A_w \left(T_{w,1} - T_b\right) - U_{b-a} A_b (T_b - T_a) \tag{5}$$

$$c_w \frac{d(M_{w,1} T_{w,1})}{dt} = Q_{in} - h_{tot,1} A_w \left(T_{w,1} - T_{c,1}\right) - h_{w-b} A_w (T_{w,1} - T_b) \tag{6}$$

$$M_c c_c \frac{d(T_{c,i})}{dt} = h_{tot,i} A_w \left(T_{w,i} - T_{c,i}\right) - h_{c,i-w,i+1} A_c (T_{c,i} - T_{w,i+1}) \tag{7}$$

$$c_w \frac{d(M_{w,i} T_{w,i})}{dt} = h_{c,i-1w,i} A_c \left(T_{c,i-1} - T_{w,i}\right) - h_{tot,i} A_w (T_{w,i} - T_{c,i+1}) \tag{8}$$

$$M_c c_c \frac{d(T_{c,n})}{dt} = h_{tot,n} A_w \left(T_{w,n} - T_{c,n}\right) - h_{c,c-a} A_c \left(T_{c,n} - T_a\right) - h_{r,c-s} A_c (T_{c,n} - T_{sky}) \tag{9}$$

where each term on the left-hand side of Eqs. (5)–(7) are the storage terms for the basin, water and cover, respectively. There are various heat transfer coefficients between the water, covers, in addition to, the last cover to ambient as well as basin to ambient, which can be evaluated by Eqs. (10)–(25) as follows:

$$h_{r,w-c} = \varepsilon_{eff} \sigma \left[(T_w + T_c)({T_w}^2 + T_c^2)\right] \tag{10}$$

In Eq. (10), $h_{r,w-c}$ is the radiation heat transfer coefficient with an effective emissivity given by Eq. (11):

$$\varepsilon_{eff} = \frac{1}{\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_w} - 1} \tag{11}$$

In Eq. (11), ε_c and ε_w are the cover and water emissivities, respectively.

Various models are available for the convection heat transfer between the water and the cover; in this research, the Zheng model (Hongfei et al., 2002) is used:

$$h_{c,w-c} = \frac{k_\vartheta}{X_\vartheta} \times c\,(\mathrm{GrPr})^n \tag{12}$$

$$\mathrm{Gr} = \frac{\beta g {X_\vartheta}^3 {\rho_\vartheta}^2 \Delta T'}{{\mu_\vartheta}^2} \tag{13}$$

$$\mathrm{Pr} = \frac{\mu_\vartheta c_p}{k_\vartheta} \tag{14}$$

$$\Delta T' = (T_w - T_c) + \frac{(p_w - p_c) T_w}{(268.9 \times 10^{-3} - p_w)} \tag{15}$$

$$p_w = exp\left[25.317 - \left(\frac{5144}{T_w}\right)\right] \tag{16}$$

$$p_c = exp\left[25.317 - \left(\frac{5144}{T_c}\right)\right] \tag{17}$$

In Eq. (12), the reported values (Hongfei et al., 2002) for c and n are 0.2 and 0.26, respectively. k_ϑ is thermal conductivity of water and X_ϑ is the characteristic length (average distance between water and cover) of the system. Kumar et al. (2015) proposed a model for the evaporation heat transfer based on the variation of the temperature for each cover stage as given by Eq. (18).

$$\mathrm{h_{e,w-c}} = 16.273 \times 10^{-3} \times h_{c,w-c} \times \left[\frac{(\mathrm{p_w} - \mathrm{p_c})}{\mathrm{T_w} - \mathrm{T_c}}\right] \tag{18}$$

In Eqs. (6)–(9), $h_{tot,i}$ is the sum of radiation, convection and evaporation heat transfer coefficients, which can be estimated using Eq. (19) as follows:

$$h_{tot,w-c} = h_{e,w-c} + h_{\mathrm{c,w-c}} + h_{r,w-c} \tag{19}$$

Moreover, heat is lost into ambient from the last cover through convection plus radiation heat transfer which can be evaluated by using Eqs. (20)–(24):

$$h_{r,c-s} = \varepsilon_c \sigma \left[\frac{{T_c}^4 - {T_{sky}}^4}{T_c - T_{sky}}\right] \tag{20}$$

$$\mathrm{T_{sky}} = \mathrm{T_a}\left[\left(0.74 + \left(0.00006 t_p\right)\right)^{0/25}\right] \tag{21}$$

$$t_p = 237.3 \frac{\ln RH + \frac{17.2\mathrm{T_a}}{\mathrm{T_a}+273}}{17.2 - \ln RH + \frac{17.2\mathrm{T_a}}{\mathrm{T_a}+273}} \tag{22}$$

$$h_{c,c-a} = 2.8 + 3 \times \mathrm{V}\ ;\ \mathrm{V} \le 5\ \frac{\mathrm{m}}{\mathrm{s}} \tag{23}$$

$$h_{c,c-a} = 6.15\mathrm{V}^{0.8}\quad ;\ \mathrm{V} \ge 5\ \frac{\mathrm{m}}{\mathrm{s}} \tag{24}$$

In Eqs. (20)–(24), *RH* and $\mathrm{T_a}$ are relative humidity and the ambient temperature of the air outside of the solar still. It is worth to note that the convection heat transfer coefficient between the last stage cover and ambient depends on wind velocity, which is governed by Eqs. (23) and (24) (Tiwari et al., 2003). Finally, the overall heat transfer coefficient between the basin wall and ambient is calculated using Eq. (25).

$$U_{b-a} = \left[\frac{L_b}{K_b} + \frac{1}{h_{b-a}}\right]^{-1} \tag{25}$$

In Eq. (25), L_b is the characteristic length of the basin and K_b is the thermal conductivity of the structure of the basin.

3. Numerical approach

In order to solve the system of differential equations, Eqs. (5)–(9), they are turned into a system of algebraic equation by using the finite difference method, which is then solved through an iteration procedure. Unlike other previous works, which assumed the mass of water in the basin, a constant property, in this research the actual situation is modeled by varying the amount of water in each stage. After finding the temperature of different parts for each stage, the hourly total productivity of each stage as well as the total amount of water produced by the multistage basin solar still are evaluated using Eqs. (26)–(28).

$$m_{out,i}(t) = \frac{h_{evap,i}(T_{w,i} - T_{c,i})}{h_{fg}} \times 3600 \tag{26}$$

$$m_{out,tot,i} = \sum_{t=1}^{24} m_{out,i}(t) \tag{27}$$

$$m_{out,tot}(t) = \sum_{i=1}^{n} m_{out,i}(t) \tag{28}$$

$$m_{out,tot} = \sum_{t=1}^{24} m_{out,tot}(t) \tag{29}$$

Eq. (26) calculates the hourly yield of each stage; the amount of water produced in each stage is simply the heat of vaporization $h_{evap,i}(T_{w,i} - T_{c,i})$ divided by the latent heat of evaporation h_{fg}. The daily productivity of each stage, hourly productivity in addition to the amount of water produced by the device in one day are obtained using Eqs. (27), (28) and (29), respectively.

3.1. Hypothesis of analysis

Considering all parameters in order to determine the temperature of the basin, the water as well as the covers would lead to sets of nonlinear partial differential equations, which is costly and needs a lot of time to be solved. However, by some simplifications in addition proper assumptions, the basin solar still can be modeled with negligible error between the present model and the Karimi's experimental data (Estahbanati, 2013). In addition, there are various convection and evaporation heat transfer models proposed in the literature that implementing them into the current model, improves the results. Here are the hypothesis that are used in the present study:

1- Vapor leakage from the device is neglected because of the sealing of the basin.

2- Since the water in the basin and trays are shallow, then its temperature is assumed constant through the depth.

3- Due to the insulation of the solar still, the heat loss from the perimeter of the basin and all stages has been neglected.

The validity of the proposed methodology is carried out by modeling a single basin still and compared the obtained results with the available experimental data. The physical and thermal properties for the single and multistage basins are the same as those given by Karimi's experimental data (Estahbanati, 2013) which are given in Table 1. It is worth to mention that the numerical values of the ambient temperature, relative humidity, wind velocity and the irradiance used in the model are given in the Figs. 3–4.

Table 1
The geometrical properties of the basin still.

Parameter	The numerical value
Area of basin (m^2)	0.47
Slop of covers (deg)	10
Area of collector (m^2)	1.62
Efficiency of collector	0.41
Thickness of basin and covers (mm)	2
Mass of water in basin (kg)	20
Mass of water in trays (kg)	14
Density of water (kg/m^3)	1000
Density of basin and cover (kg/m^3)	2700
Thermal conductivity of basin and cover (W/m K)	205
Specific heat of water (J/kg K)	4186
Specific heat of basin and covers (J/kg K)	900

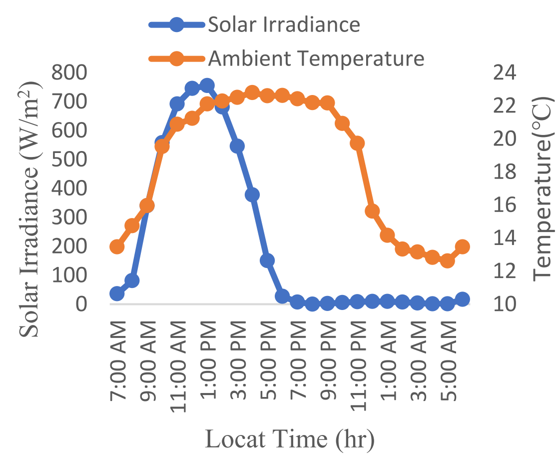

Fig. 3. The variations of solar and ambient temperature during the experiment.

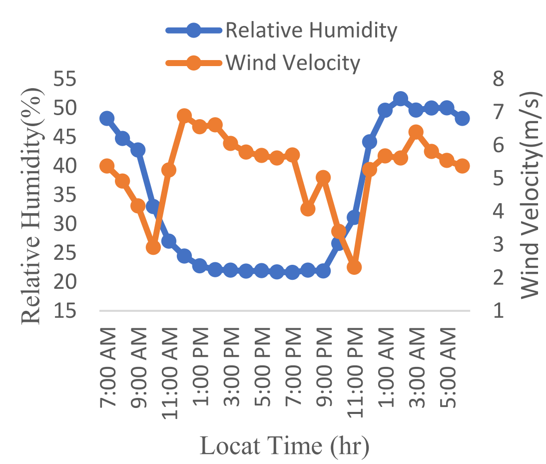

Fig. 4. The variation of wind velocity and relative humidity during the experiment.

As pointed above, in order to validate the proposed model, the current results are compared with the experimental data of Karimi (Estahbanati, 2013). As can be seen from Fig. 5, the maximum difference between the present results and the experimental data of Karimi (Estahbanati, 2013) is about 7%.

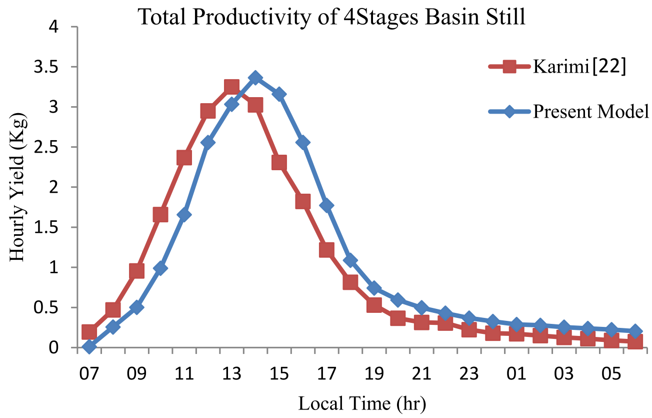

Fig. 5. Comparison of the present results with the experimental data of Karimi (Estahbanati, 2013).

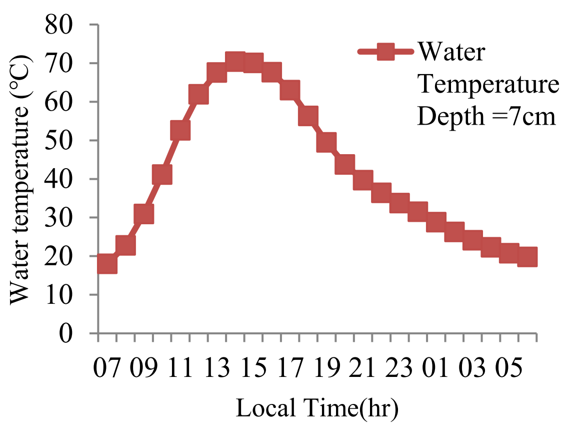

Fig. 6. Temperature variation of single basin still with time.

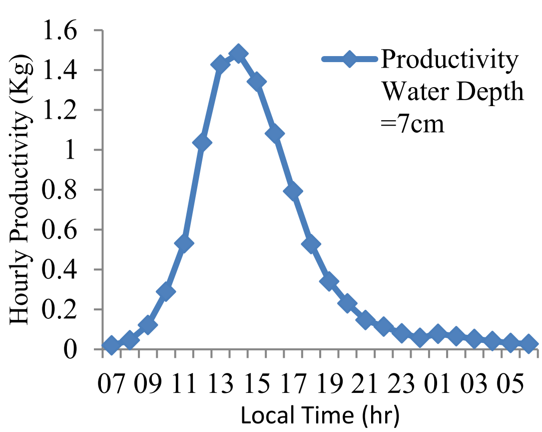

Fig. 7. Hourly productivity of single basin still.

As clear from Fig. 5, the suggested model can predict the trend and the amount of total productivity of four stages basin still with a good approximation.

4. Results and discussion

In this article, the goal is to model the performance of a multistage basin solar still analytically using the energy balance for different parts of the still. To achieve the objective, a thermodynamic approach is applied to different parts of the solar still, which leads to a set of nonlinear ordinary differential equations.

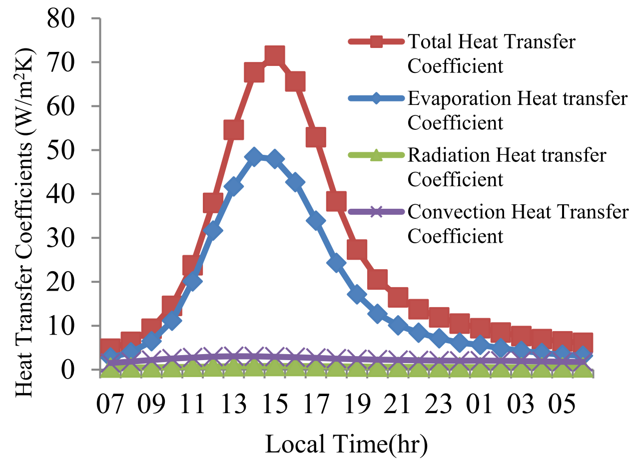

Fig. 8. Heat transfer coefficients between water and cover.

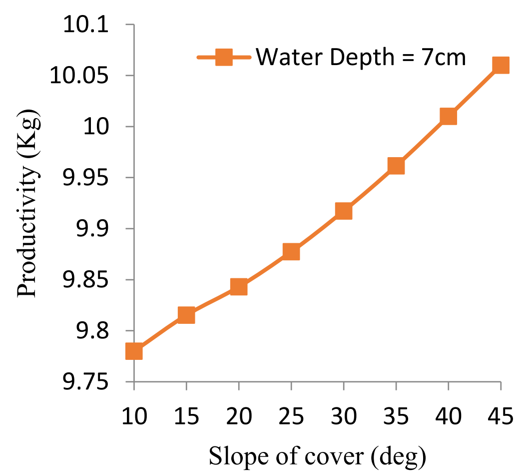

Fig. 9. Variation of productivity with slope of cover.

Then, by solving the equations, the temperature of different parts of the solar still are obtained. The effect of number of stages, cover angle and the different depth of water on the performance of the still have been examined and will be presented next.

The trend of the temperature and the productivity of the water for a single stage basin still as demonstrated in Figs. 6–7 is similar to the variation of solar irradiance. However, the peaks of the hourly productivity and the temperature of the water in the still took place at some time later with respect to the peak of the solar irradiance in that day. The reason of this behavior is due to the thermal capacity of water, which stores some heat causing a delay in rising the water temperature and consequently the productivity. Different heat transfer coefficients between the water in the basin and the cover above it, are provided in Fig. 8. Moreover, it is obvious that the dominant mechanism in these devices is evaporation. In addition, different slopes of the still cover have been modeled in order to determine the correlation between the productivity and the angle of the cover. As a result, which can be seen from Fig. 9, there is no significant change for the amount of fresh water with the slope since in active basin stills input energy is obtained through a collector not directly from the cover.

One of the most important issues that multistage passive stills have, is the fouling problem which causes reduction in the amount of yield. In order to enhance the productivity of a multistage basin still, active ones are the most useful ones. In

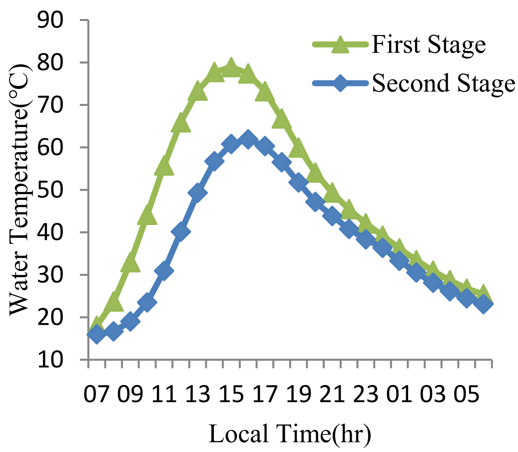

Fig. 10. The variation of water temperature in 2-stages still.

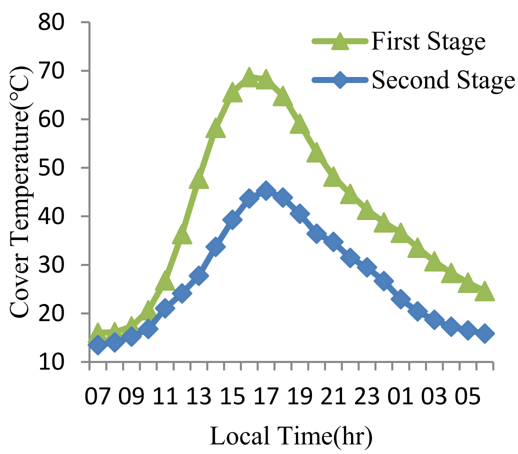

Fig. 11. The variation of cover temperature in 2-stages still.

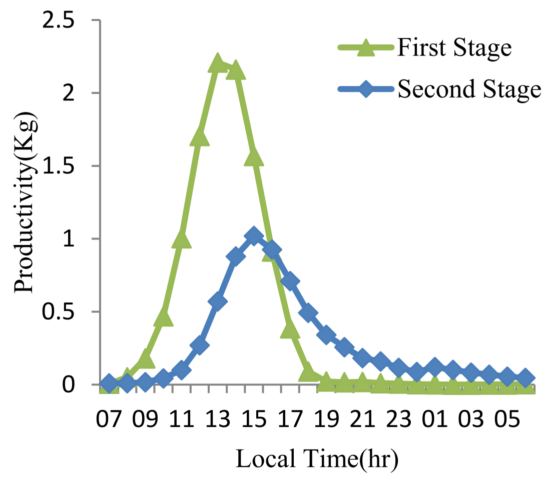

Fig. 12. The amount of yield water in each stage of 2-stages still.

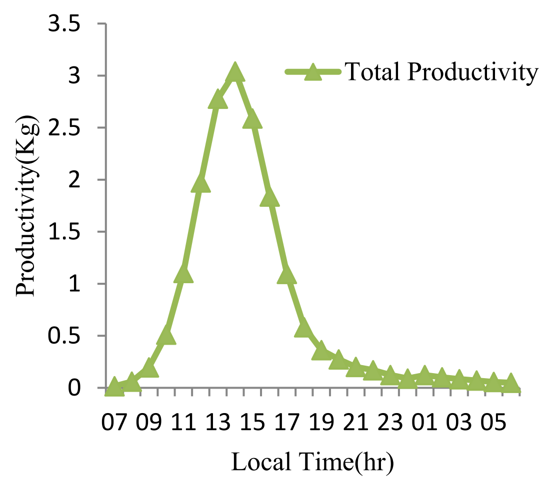

Fig. 13. Total productivity of 2-stages still.

previous works, the amount of water in the basin and other trays were taken constant through the whole day, which is not realistic. However, in this article, basin and other stages are filled with an initial amount of water and in each time step the remaining water is calculated based on the productivity. Then, the depth of the water in each tray and the basin is calculated in order to get the maximum productivity at the end of the day. If the amount of water in the basin and trays are less than the maximum, it means that at some time within a day all water is vanished. However, there is still a potential to get distilled water out of the still. On the other hand, pouring more water in the stages than the maximum amount would lead to the higher resistance of water in the basin and stages due to thermal storage. Therefore, the peak of the water temperature and consequently productivity occurs later in that day, which lead to the lower total productivity (see Fig. 12).

4.1. Effects of number of stages on the productivity

In Fig. 10, the temperature of the water in the basin is higher than in the tray above the basin. This is because of the heat storage in the water of the basin. This temperature trend is also seen in Fig. 11 for the cover, where the top cover is cooler than the lower one due to the exposure of the last cover to the ambient. The amount of the yield in the basin is approximately twice the tray above it in the same still and its peak at sooner time as a result of the storage term of the water in the basin. Fig. 13 demonstrates the total productivity of the two stages basin. For the three as well as four stages basin solar stills, the temperature of the water in the basin and trays are depicted in Figs. 14 and 18, respectively. It can be seen from these two figures that by increasing the number of stages, the maximum temperature of water in the first stage of four-stages basin still is higher than the one in the three-stages still. This happens because there are more stages between the water in the first stage and the air on the last cover, so the thermal resistance above the water in the four stages basin is higher than the three stages. For the same reason the temperature of the covers in the four-stages basin still are higher than those in three-stages active solar basin still as it is demonstrated in Figs. 15 and 19. By increasing the number of the stages, the higher stages produce less amount of fresh water, so there should be a balance between the number of stages and the cost of the basin still. In Figs. 16 and 20, the hourly productivity of three and four stages basin still are presented respectively. By comparison between them, it can be concluded that there is a noticeable drop in the productivity from the first stage to the next one. This is due to the heat source location, which is located in the water in the first stage, so the water in the basin is directly in contact with the hot tubes from the output of the flat plate collector, however the next stages gain their energy from the water in the lower stages. The overall productivity of the three and four stages active basin still during a day are shown in Figs. 17

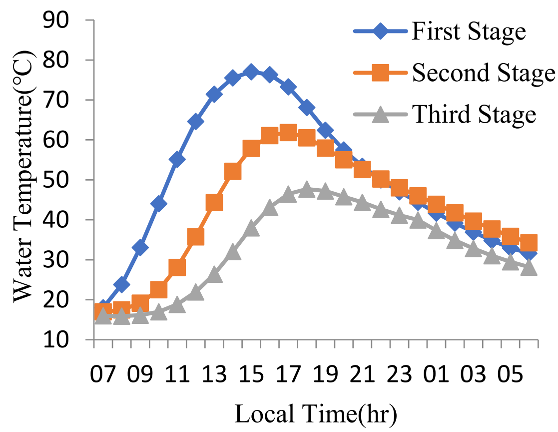

Fig. 14. The variation of water temperature in 3-stages still.

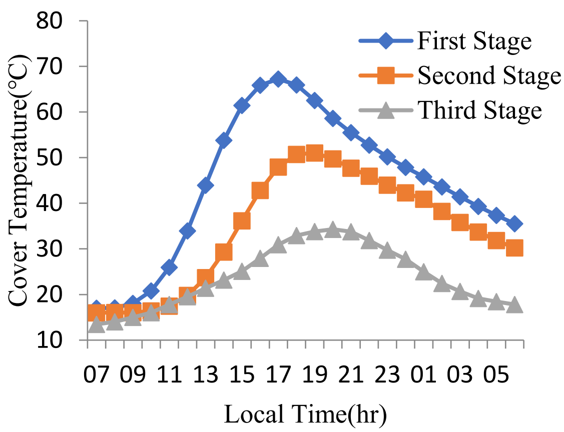

Fig. 15. The variation of cover temperature in 3-stages still.

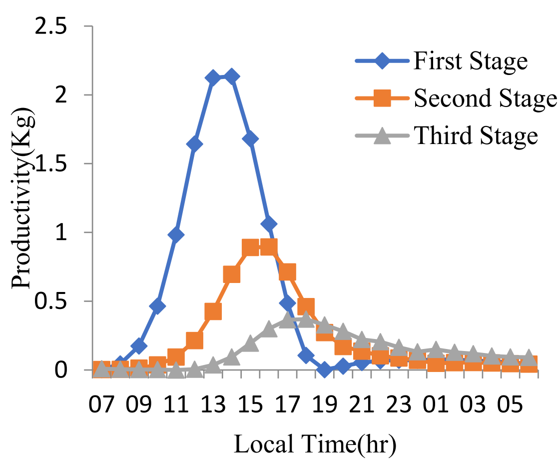

Fig. 16. The amount of yield water in each stage of 3-stages still.

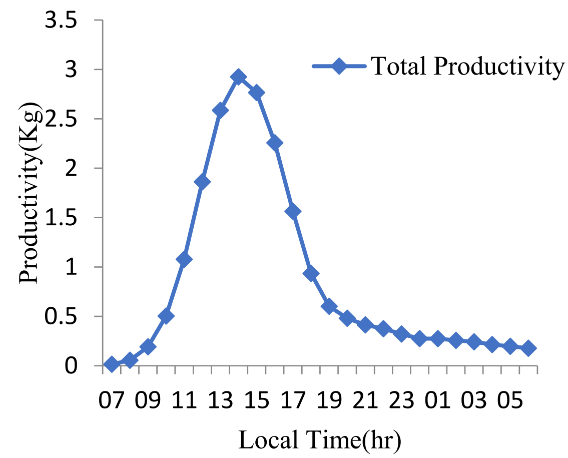

Fig. 17. Total productivity of 3-stages still.

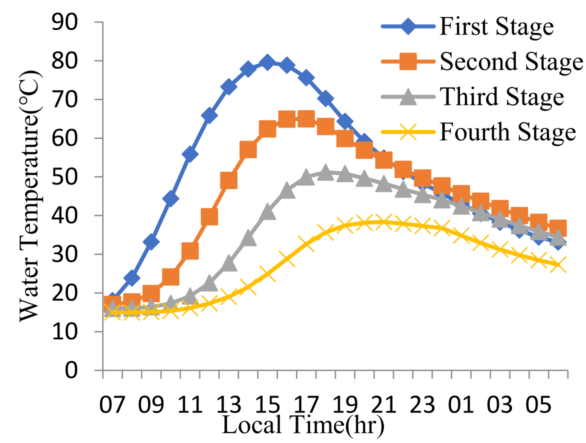

Fig. 18. The variation of water temperature in 4-stages still.

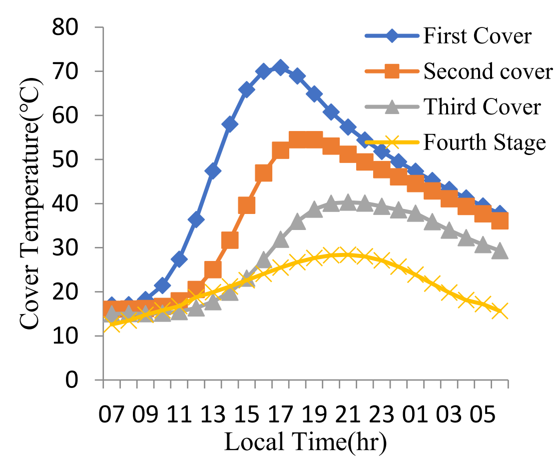

Fig. 19. The variation of cover temperature in 4-stages still.

and 21, respectively. Not only the amount of yield is higher in the four-stages basin, but also the productivity of four stages basin still in the afternoon is more than the three, two and one stages basin still.

The trend of temperature variation of the water in the basin as well as in the trays, in addition to cover temperature are commensurate with the changes in solar irradiance and ambient temperature. For lower stages, the dominant effect on the temperature of the water and covers trends is the solar radiation input; however, for the last stage, the variation of temperature of the water and the cover follows the ambient temperature changes. The total productivity for a special case (with specific geometry and thermo-physical properties as in Table 1) for one, two, three and four stages are 11.92, 17.12, 20.56 and 23.23 kg, respectively. As Fig. 22 shows the total amount of water in one, two, three as well as four stages basin solar stills, it is clear that by adding more stages, i.e., two, three, in addition to four, the

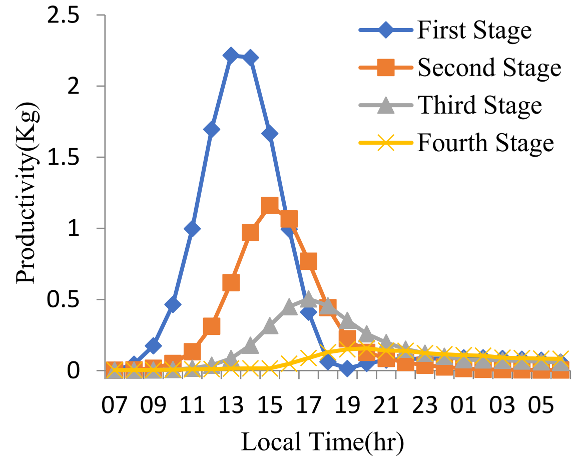

Fig. 20. The amount of yield water in each stage of 4-stages still.

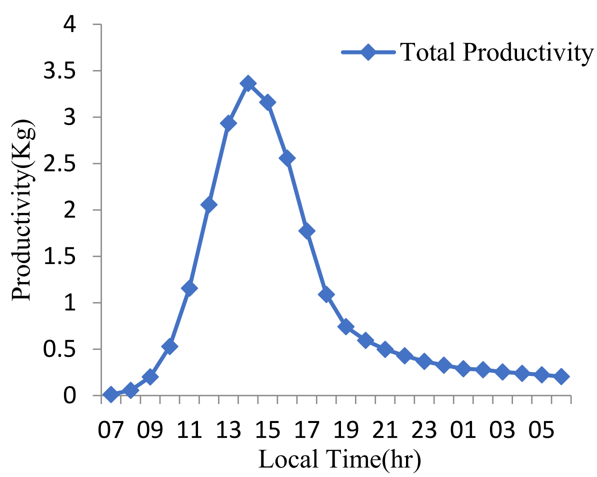

Fig. 21. Total productivity of 4-stages still.

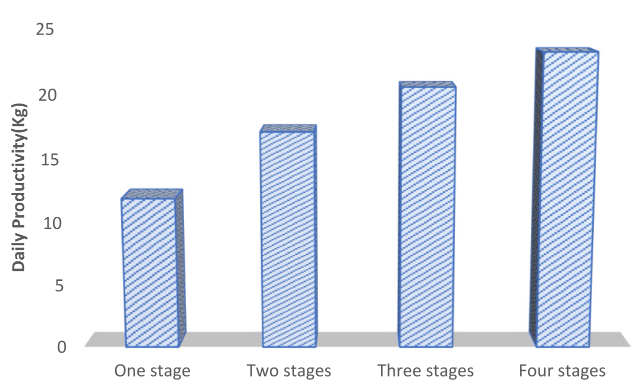

Fig. 22. The total amount of yield for a basin solar still with different stages.

productivity increased 43%, 72% and 94% more than the one with one stage, respectively.

4.2. Comparison between number of stages and the effect of seasons

Fig. 23, depicts the comparison of the total productivity for different stages of one to four multi-stage active solar basins. It is obvious that by increasing the number of stages the total productivity of the whole basin increases, too. However, the productivity

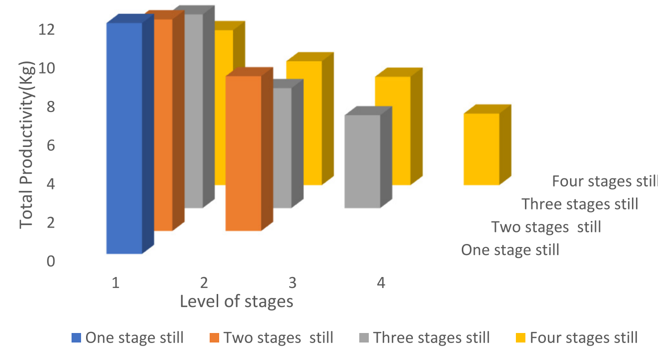

Fig. 23. The comparison of each stage productivity for different multistage stills.

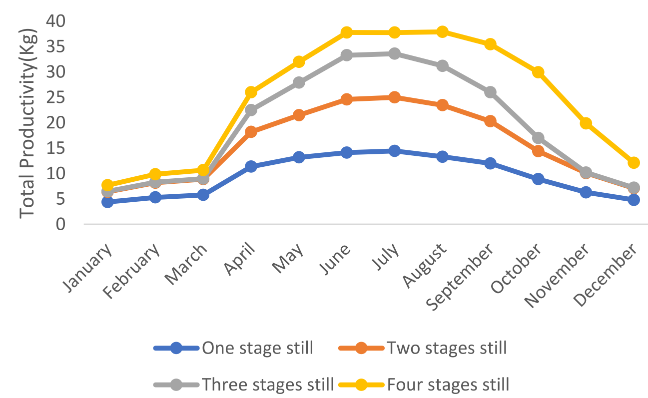

Fig. 24. The variation of daily productivity of various multistage stills in different months of a year.

of the first stage in solar stills with less number of stages is higher than active solar stills with more stages. This is due to the higher amount of the total heat transfer coefficient from the water in the first stage to the cover above that stage for single stage basin still.

From Fig. 24, it is clear than in winter due to the low irradiance, the total productivity is much less than in summer (when the irradiance is higher). Therefore, the current model can also predict the monthly variation of the productivity with a good approximation with respect to different time of the year.

4.3. Correlation

In order to find an optimum depth of water for a single stage basin solar still, at which the productivity is maximum, the present model analyzed different masses of water in the basin. It is obvious that there is a peak in total productivity of one stage basin still for a specific depth, while in previous works, depth of the water in the basin was considered constant. Because of this, it was concluded that with the reduction of mass (depth) of the water in the basin, the productivity would increase without any limit. However, this statement is not true for a fixed mass basin still as it is demonstrated in Fig. 25. By using the polynomial fitting method, the following correlation between the productivity P as well as the depth x of the water in the basin for a single basin solar still has been developed as given by Eqs. (30) and (31). The mean square root error of the following equation with respect to the analytical results is 90%:

$$P(x) = A_6x^6 + A_5x^5 + A_4x^4 + A_3x^3 + A_2x^2 + A_1x + A_0 \quad (30)$$

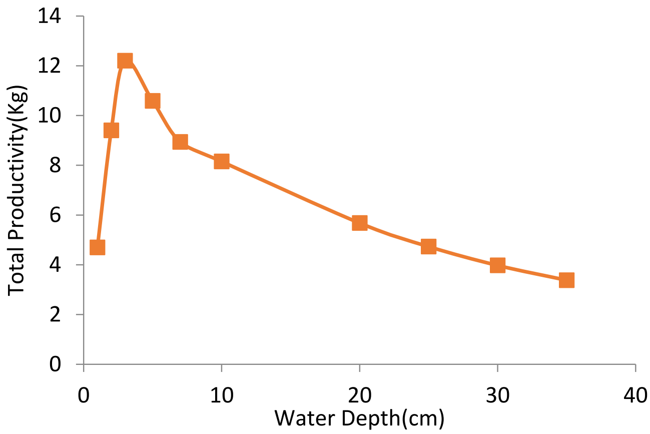

Fig. 25. The variation of productivity of single stage with water depth.

The coefficients in Eq. (30) have been obtained through fitting a polynomial on the amount of the fresh water output for different depth of the water in the basin:

$$A_6 = -1.565e - 06 \quad A_5 = 0.0002 \quad A_4 = -0.008 \quad A_3 = 0.172$$
$$A_2 = -1.83$$
$$A_1 = 8.319 \quad A_0 = -1.44 \tag{31}$$

5. Conclusion

In the present study the effect of water depth and number of stages on the productivity of an active basin solar still are investigated. Unlike previous researches, in this research the amount of water in the basin and in the trays has not been considered constant. Due to this assumption, the mass of water will alleviate during a day and there is an optimum value of the water that would cause the solar still to produce the maximum fresh water. Moreover, a set of differential equations was solved in order to calculate the temperature of the basin, the water and covers. Also, the effect of the cover slop on the still's yield was examined as well. In addition, implementing a polynomial fitting provided a model to predict the amount of fresh water for the single stage basin solar still. The results of the suggested model are summarized as follows:

- By examining the effect of cover slope on a single stage active basin still, it was clear that the slope has a negligible effect on the performance of the active basin still.
- The production of basin stills increases as the number of stages increases; however, the cost of the basins should also be taken into account.
- With an increase in the number of stages from one to four, the production of fresh water increases by 42%, 72% and 94%, with respect to one stage, respectively. In addition, the increase in the amount of water in three stages basin still compared to two stages and also the four stages to three stages are 20% and 13%, respectively.
- In cases with more stages, the time at which the peak of the water temperature and the amount of yield water reaches, occur at some hours later relative to the less number of stages, which is due to the thermal resistance of the stored water in trays of lower stages.
- By observing the different heat transfer coefficients, it is concluded that the effect of convection and radiation heat transfer are negligible compared to the evaporation heat transfer; besides, the dominant effect on the rate of fresh water production is the heat transfer mechanism through the phase change.
- By comparing the amount of production during different months of the year in Shiraz (29.6° North), it was observed that the highest amount of production occurs in the sixth month because of the highest amount of solar irradiance in that period.
- The maximum output for a single stage basin still occurs at a specific depth of water.
- A nonlinear correlation based upon the results of the presented model with a 90% mean square root error with respect to the output of the current model was derived to predict the amount of fresh water for a single basin still.

Nomenclature

A_b	Area of basin still (m^2)
A_c	Area of tilted cover of still (m^2)
A_w	Area of water in basin and trays in stages (m^2)
C_b	Specific heat of basin material (J/kg °C)
C_c	Specific heat of cover material (J/kg °C)
C_w	Specific heat of water (J/kg °C)
Gr	Grashof number
h_{b-a}	Convective heat transfer between basin and ambient air (W/m^2 °C)
$h_{c,i-1,w,i}$	Convective heat transfer between cover and water on it (W/m^2 °C)
$h_{c,c-a}$	Convective heat transfer between last cover and ambient air (W/m^2 °C)
$h_{e,w-c}$	Evaporation heat transfer between water and cover (W/m^2 °C)
h_{fg}	Latent heat of vaporization of water (kJ/kg)
$h_{r,c-s}$	Radiation heat transfer between cover and sky (W/m^2 °C)
$h_{r,w-c}$	Radiation heat transfer between water and cover (W/m^2 °C)
h_{tot}	Total heat transfer between water and cover (W/m^2 °C)
K_b	Thermal conductivity of basin and cover plate (W/m°C)
L_b	Characteristic length of basin (m)
M_b	Basin mass (kg)
M_c	Cover mass (kg)
M_w	Water mass (kg)
$m_{out,i}$	Hourly yield of each stage (kg/h)
$m_{out,tot}$	Total yield of each stage (kg)
p_c	Partial vapor pressure at cover temperature (N/m^2)
p_w	Partial vapor pressure at water temperature (N/m^2)
Pr	Prandtl number
Q_{col}	Thermal energy gained by flat collector (W)
RH	Relative humidity of air (%)
t_p	Correction factor for sky temperature
T_a	Ambient temperature (°C)
T_b	Basin temperature (°C)
T_c	Cover temperature (°C)
T_w	Water temperature (°C)
T_{sky}	Sky temperature (°C)
U_{b-a}	Overall heat transfer coefficient from basin to ambient (W/m^2 °C)
V	Wind velocity (m/s)

Greek Letters

β	Coefficient of volume expansion of water (1/K)
g	Gravitational constant (m/s^2)
μ	Dynamic viscosity of water (kg/m s)
ρ	Density of water (kg/m^3)
σ	Stefan Boltzmann constant (5.67032×10^{-8} W/m^2 K^4)
ε	Emissivity
η	Efficiency

CRediT authorship contribution statement

E. Davani: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **K. Jafarpur:** Conceptualization, Resources, Writing – review & editing, Project administration. **M.R. Karimi Estahbanati:** Conceptualization, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data

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