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Theoretical study of water desalination by a falling film solar unit

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ABSTRACT

The productivity of a solar desalination unit with falling film is theoretically investigated. The theory is based on unsteady state energy balance of the three components forming the solar unit, namely the solar collecting surface (black plate), glass cover and the water film. The resulting sets of equations were integrated numerically by Runga–Kutta 4th order method using MATLAB. The effect of feed water flow rate, solar irradiation to mimic various seasons of the year, ambient temperature, plate temperature, glass cover temperature and feed water temperature on the productivity of the unit were investigated. The results showed that the unit productivity can be improved by decreasing the feed water flow rate and the glass cover temperature and by increasing the irradiation intensity, black plate temperature and the feed water temperature. The ambient temperature has an insignificant effect on the unit productivity. A linear relationship was found to exist between the amount of water produced and time. To investigate the effect of receiving the maximum irradiation during the day time, the equations were solved by taking the irradiation energy constant at its maximum value. Doing so, the amount of water produced increased by 27%. The theoretical results were compared to published experimental data, the agreement is excellent.

Keywords: Desalination; Solar irradiation; Falling film; Water; Solar collector

1. Introduction

In many regions worldwide, need for desalination of saline water is increasing due to an increase of population and limited supply of potable water. Among other techniques, solar desalination by distillation has been in practice for a long time. The conventional solar still is the mostly used approach in utilizing the solar energy for desalination. Many modifications have been made on the conventional solar still to improve its productivity. Among these modifications, a falling film approach in solar distillation systems has been considered by several studies [1–6], which has been in practice for about fifty years in conventional thermal desalination processes. The film is established on a flat plate or on tubes. In the case of a flat solar absorber plate, the feed water is spread as a falling film on an inclined plate which has a glass cover. This way the amount of water to be heated is reduced. Evaporation takes place from the falling film as it absorbs solar irradiation and condensation occurs on the glass cover. The heat and mass transfer coefficients of evaporation and condensation are very high, which results in higher system productivity. Such systems can be used to produce distillate water and hot water for domestic use depending on feed water salinity.

Aybar et al. [4] and Aybar [5] investigated experimentally and theoretically an inclined solar water distillation unit with a falling film. Three different surfaces of the

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absorber plate were used: bare plate and plate covered with black-cloth wick or with black-fleece wick. Covering the plate with black-fleece increased the system productivity. The theoretical investigations [5] revealed that their unit is capable of producing 3.5–5.4 kg/d.m^2 in a typical summer day.

Abu-Arabi et al. [6] investigated experimentally the effect of various parameters on the productivity of such a unit. The parameters investigated were feed water flow rate, ambient temperature, water salinity and cooling the outer glass surface. They reported about 0.6 L/h.m^2 of water was produced by the unit during the hot months. In this paper, theoretical investigation on the unit considered by Abu-Arabi et al. [6] is carried out. The theory is based on performing unsteady state energy balance on the three components forming the unit, namely the solar collecting surface (black plate), the glass cover and the water film. The resulting sets of equations are integrated numerically by Runga–Kutta forth order method using MATLAB. The effect of various parameters on the unit productivity are studied, namely; feed water flow rate, plate temperature, glass cover temperature, feed water temperature and solar irradiation to mimic various seasons of the year.

2. Theoretical development

Consider an inclined solar collector shown in Fig. 1 that receives a given amount of sun irradiation I. Feed water enters at a mass flow rate, $\dot{m}_f$, receives heat from the black plate where as a result some of it evaporates at a rate $\dot{m}_p$ and the rest exits the unit at a rate $\dot{m}_e$. A total mass balance yields

$$\dot{m}_f = \dot{m}_p + \dot{m}_e \tag{1}$$

Energy balance can be performed on the black plate, the glass cover and the falling film which gives:

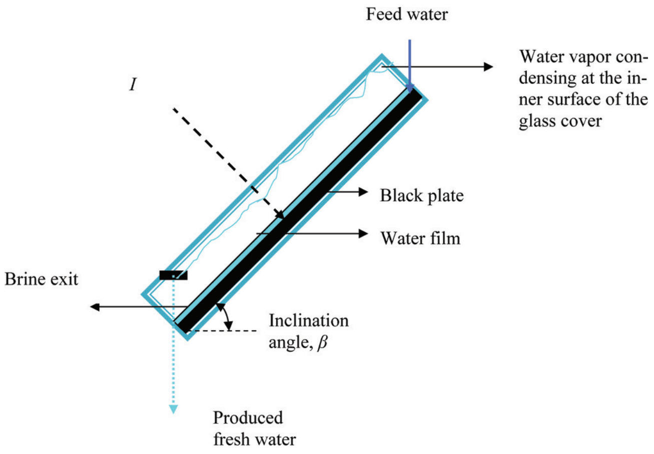

Fig. 1. Schematic diagram of the falling film unit.

Black plate:

$$m_b c_{pb} \frac{dT_b}{dt} = I(t) a_b - q_{c,b-wf} - q_{loss} \tag{2}$$

Water film:

$$m_{wf} c_{pw} \frac{dT_{wf}}{dt} = I(t) a_{wf} + q_{c,b-wf} - \dot{m}_{wf}\, c_{pw} \frac{\partial T_{wf}}{\partial x} dx - q_{c,wf-g} - q_{r,wf-g} - q_{evap,wf-g} \tag{3}$$

Glass cover:

$$m_g c_{pg} \frac{dT_g}{dt} = I(t) a_g + q_{c,wf-g} + q_{r,wf-g} + q_{evap,wf-g} - q_{r,g-sky} - q_{c,g-a} \tag{4}$$

Total water produced:

$$\frac{dm_p}{dt} = \frac{h_{evap,wf-g}\left(T_{wf} - T_g\right)}{h_{evap}} \tag{5}$$

where m is the mass, T is the temperature and c_p is the heat capacity. The subscripts b, wf, g and p represent the black plate, the water film, the glass cover and the produced water respectively. I is the irradiation solar energy, t is time, h_{evap} is latent heat of vaporization of water. q_{loss} is the heat lost from the black plate to the surrounding per unit area given by:

$$q_{loss} = U\left(T_b - T_a\right) \tag{6}$$

where U is the overall heat transfer coefficient and T_a is the ambient temperature. $q_{c,b-wf}$ is the convective heat transfer between the water film and the black plate given by

$$q_{c,b-wf} = h_{c,b-wf}\left(T_b - T_{wf}\right) \tag{7}$$

where $h_{c,b-wf}$ is the heat transfer coefficient. $q_{c,wf-g}$ is the convective heat transfer from the water film to the glass cover given by:

$$q_{c,wf-g} = h_r\left(T_{wf} - T_g\right) \tag{8}$$

$q_{r,wf-g}$ is the radiation heat transfer between the water film and the glass cover given by:

$$q_{r,wf-g} = h_r\left(T_{wf} - T_g\right) \tag{9}$$

where h_r is the radiation heat transfer coefficient given by [7] as:

$$h_r = \varepsilon_{eff}\,\sigma\left(T_{wf}^2 + T_g^2\right)\left(T_{wf} + T_g\right), \quad \varepsilon_{eff} = \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1\right)^{-1} \tag{10}$$

where ε_w and ε_g are the emissivities of water and glass.

σ is Stefan–Boltzmann constant. $q_{c,g-a}$ is the heat transfer by convection from the glass cover to the surrounding given by:

$$q_{c,g-a} = h_{c,g-a}\left(T_g - T_a\right) \tag{11}$$

and $h_{c,g-a}$ is the heat transfer coefficient. $q_{r,g-sky}$ is the rate of energy transferred by radiation between the glass cover and the surrounding given by:

$$q_{r,g-sky} = h_{r,g-sky}\left(T_g - T_{sky}\right) \tag{12}$$

where $h_{r,g-sky}$ is the heat transfer coefficient given by [7] as:

$$h_{r,g-sky} = \varepsilon_{eff}\sigma\left(T_g^2 + T_{sky}^2\right)\left(T_g + T_{sky}\right) \tag{13}$$

and T_{sky} is the sky temperature given by [7]:

$$T_{sky} = \left(T_a - 6\right) \tag{14}$$

$q_{evap,wf-g}$ is the heat transfer due to water evaporation from the water film, expressed as:

$$q_{evap,wf-g} = h_{evap,wf-g}\left(T_{wf} - T_g\right) \tag{15}$$

$h_{evap,wf-g}$ is the evaporation heat transfer coefficient between the water film and the glass cover given by [7]

$$h_{evap,wf\text{-}g} = 16.273\times10^{-3}\, h_{c,wf\text{-}g}\frac{\left(P_{wf} - P_g\right)}{\left(T_{wf} - T_g\right)} \tag{16}$$

$q_{c,wf-g}$ is the convective heat transfer rate between the water film and the glass

$$q_{c,wf-g} = h_{c,wf-g}\left(T_{wf} - T_g\right) \tag{17}$$

$h_{c,wf-g}$ is the convective heat transfer coefficient between the water film and the glass cover given by [7]

$$h_{c,wf-g} = 0.884\times\left(T_{wf} - Tg + \frac{\left(P_{wf} - P_g\right)T_{wf}}{268900 - P_{wf}}\right)^{1/3} \tag{18}$$

where P_{wf} and P_g are the vapor pressure of water at the water film and the glass cover temperatures, respectively. a_b, a_{wf} and a_g is the absorptance of the black plate, water and glass expressed by [7] as:

$$a_b = \left(1 - \rho_g - a_{wf} - a_g\right)\alpha_b \tag{19}$$

$$a_{wf} = \left(1 - \rho_g - a_g\right)\alpha_w \tag{20}$$

$$a_g = \left(1 - \rho_g\right)\alpha_g \tag{21}$$

where ρ_g is the reflectivity of the glass, α_g, α_w and α_b are the absorptivity of the glass cover, the water film and the black plate, respectively. The other parameters are kept constant. Table 1 summarizes the values of the parameters appearing in the above equations.

Table 1
The values of the various parameters used in the simulation

Parameter	Value
c_{pw}, J/kg-°C	4178
c_{pb}, J/kg-°C	473
c_{pg}, J/kg-°C	800
α_b	0.95
α_g	0.0475
α_w	0.05
m_{wf}, kg	0.1
ρ_g	0.0735
m_b, kg	11.75
m_g, kg	10.8
h_{evap}, J/kg	2.4×10^6
v_{wind}, m/s	3
T_a, K	303
h_{cbwf}, J/m²-K	135
U_b, J/m²-K	14
p_{wf}, Pa	1.2×10^4
p_g, Pa	4.210^4
ε_{wf}	0.96
ε_g	0.88
σ	5.6697×10^{-8}

3. Results and discussion

The equations developed in the previous section were integrated by Runga–Kutta 4th order method using MATLAB. The effects of the following parameters on water production were investigated: irradiation energy received by the solar collecting surface (I), feed water mass flow rate ($\dot{m}_f$), ambient temperature (T_a), cooling the glass cover expressed by its temperature (T_g), water feed temperature (T_{wf}), and black plate temperature (T_b). Regarding the radiation energy two theoretical cases were examined. In the first case, I is assumed to be constant having values of 1000, 800, 600, 400 and 200 W/m² representing hot and cold seasons or the maximum irradiation that can be received if a solar tracking unit is installed with the collector. In the second case, I was allowed to vary with day time as shown in Fig. 2. The other parameters appearing in the above equations were kept constant and their values are summarized in Table 1. In the investigation of the effect of the parameters other than the solar irradiation, I as represented in curve 2 Fig. 2 is used.

3.1. Effect of solar irradiation, I

Integrating the above equations simultaneously with initial conditions: at $t = 0$, $T_b = 333$ K, $T_{wf} = 298$ K, T_g

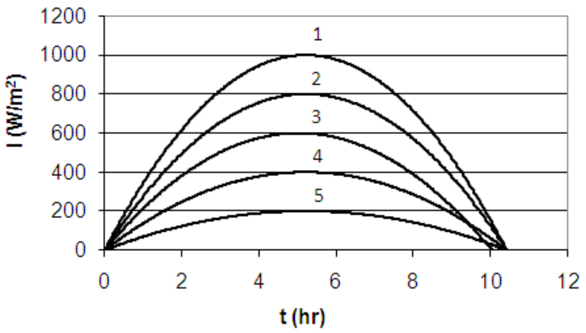

Fig. 2. Various solar irradiation as a function of day time.

= 303, m_p = 0 kg, yields the amount of water that can be produced with time. The result is depicted in Fig. 3. As expected the amount of water produced is proportional to the irradiation energy. No appreciable difference in water production was observed when the solar energy is weak (winter time), represented by curve 4 and 5 in Fig. 2.

The amount of water that can be produced is calculated assuming that the system receives the maximum solar irradiation at all times as shown in Fig. 2; namely 1000, 800 600, 400 and 200 W/m². The results of such calculations are shown in Fig. 4. A comparison between the two cases (I = constant = 800 W/m² and I is $f(t)$ as given by curve 2 in Fig. 2) is presented in Fig. 5. About 27% increase is achieved in the case where I is constant. The cumulative amount of water that can be produced by the above two methods of solar heating after 10 h/d operation is illustrated in Fig. 6.

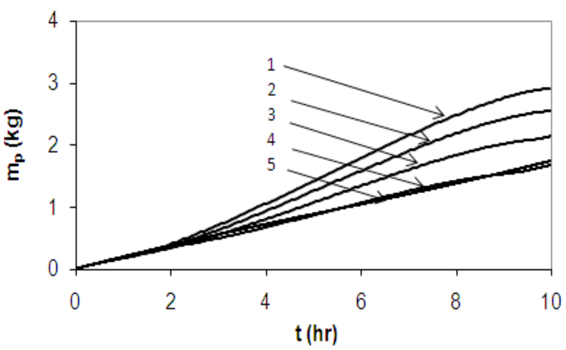

Fig. 3. The cumulative amount of produced water as a function of time. The numbers shown on the figure correspond to the amount of irradiation (I) shown in Fig. 2.

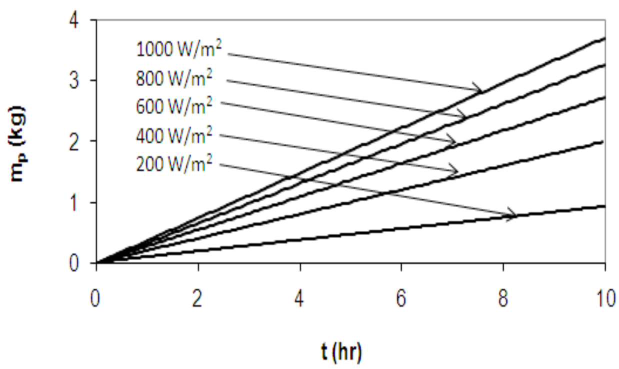

Fig. 4. The amount of water produced vs. time for maximum I.

3.2. *Effect of feed water flow rate*

The effect of feed water flow rate on the amount of water produced is shown in Fig. 7. As the flow rate decreases more water is produced since the residence time is larger and the amount of water on the collector's

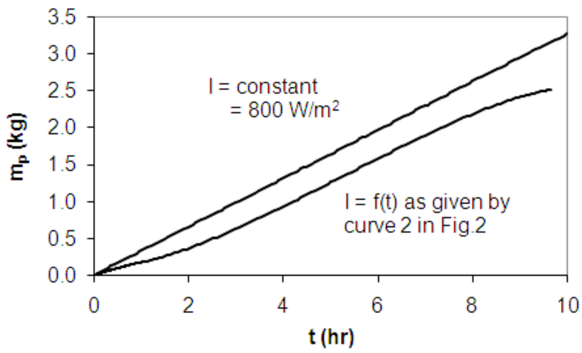

Fig. 5. The amount of water that can be produced for two cases of I.

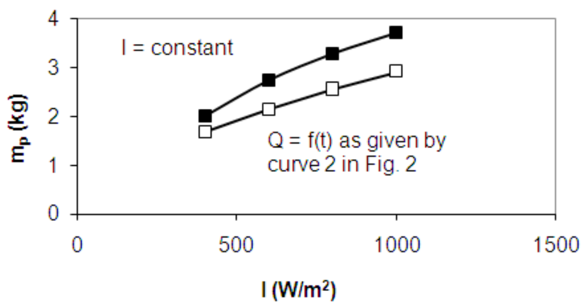

Fig. 6. The amount of water produced after 10 h of operation for the two cases of I.

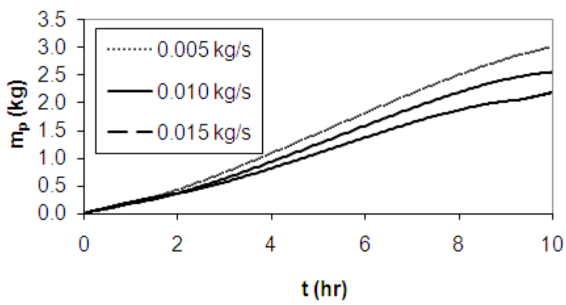

Fig. 7. The effect of feed flow rate on the amount of water produced.

surface is less leading to a higher film temperature. As a result of this the vapor pressure is higher and hence more evaporation takes place.

3.3. Effect of ambient temperature, T_a

The effect of ambient temperature was investigated when the temperature drops or increases due to weather conditions while I received by the collecting surface area is same. The result is portrayed in Fig. 8 where it can be seen that T_a has negligible effect on the amount of water produced. This can be explained as follows: When the ambient temperature is low, the glass cover is cooler and this enhances water production due to larger driving force ($T_{wf} - T_g$). At the same time the heat losses by conviction from the glass plate, $q_{c,g\text{-}a} = h_{c,g\text{-}a}\,(T_g - T_a)$, varies slightly. Moreover the heat losses from the still to the surrounding increase when T_a is lower. Thus, the two factors compete resulting in minor influence of T_a on water production.

3.4. Effect of the plate temperature, T_b

The effect of keeping the plate temperature constant on the water production is drawn in Fig. 9. The results show that the amount of water produced increases as the temperature of the black plate increases. In fact increasing the plate temperature by 30°C, doubled the amount of water that can be produced.

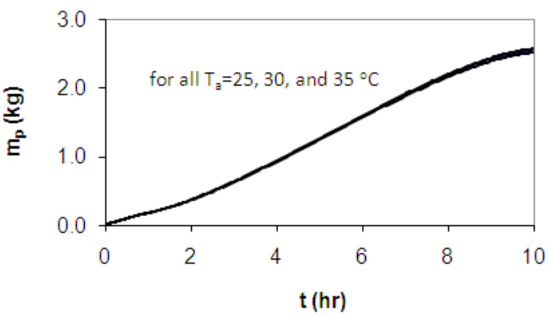

Fig. 8. The effect of ambient temperature on the amount of water produced.

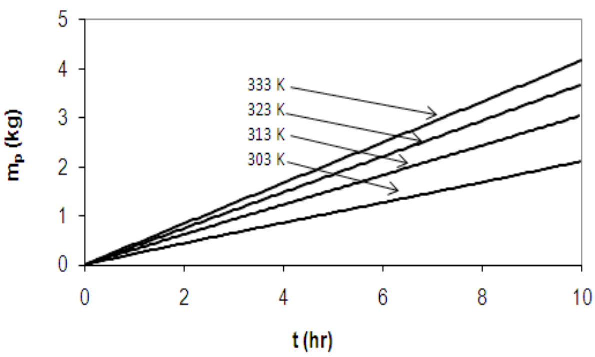

Fig. 9. The effect of plate temperature on the amount of water produced.

3.5. Effect of the inlet feed water temperature, T_{wf}

The effect of the inlet feed water temperature on the water production is drawn in Fig. 10. The feed water temperature has a strong effect on the productivity of the solar unit. In fact raising the feed water temperature from 298 K to 333 K can triple the amount of produced water. Increasing the feed water temperature to 333 K can be easily achieved in a house installed solar units. Therefore if the house installed solar unit is coupled with this system the amount of produced water can be tripled.

3.6. Effect of the glass temperature, T_g

The effect of keeping the glass cover temperature constant on water productivity is shown in Fig. 11. It can be seen that water production can be enhanced by cooling the glass cover. The results showed that the production can be enhanced by 26% if the glass cover is cooled from 303 K to 288 K.

It is interesting to know how much water can be produced if the best conditions tested above are utilized, i.e., the plate temperature is kept constant at 333 K, the glass cover is kept at low temperature 288 K and the water film temperature is kept hot at 333 K. These data are realistic and can be implemented experimentally and practically. The amount of water that can be produced is shown in

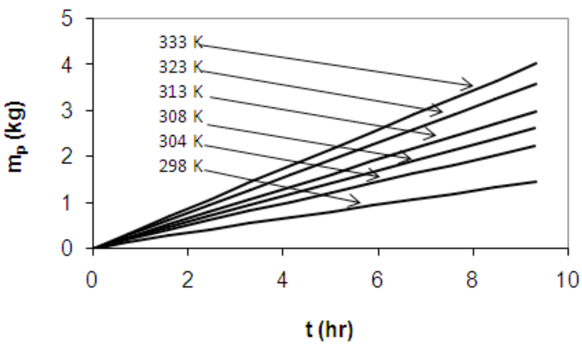

Fig. 10. The effect of feed water temperature on the amount of water produced.

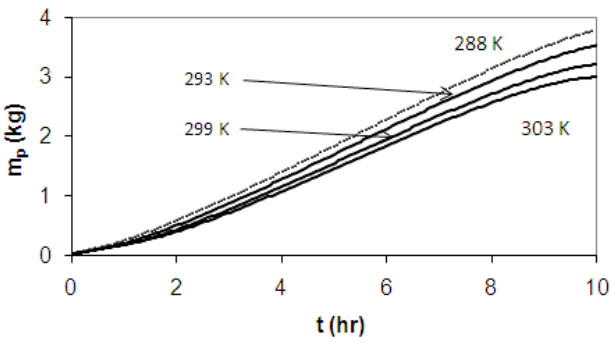

Fig. 11. The effect of cooling the glass cover on the amount of water produced.

Fig. 12. The results showed that 0.6 kg/h can be produced whereas 0.26 kg/h is produced under normal conditions of not controlling the temperatures i.e. 148% improvement in the production.

3.7. Comparison with experimental results

To check the theory a comparison with the experimental results obtained by Abu Arabi et al. [6] was performed. The values of T_{wf}, T_g, T_b and T_a are 25°C, 30°C, 60°C and 19°C respectively. Values of I are available from the work of Abu Arabi et al. [6]. A comparison between the experimental and the theoretical results is shown in Fig. 13 where it can be seen an excellent agreement is obtained.

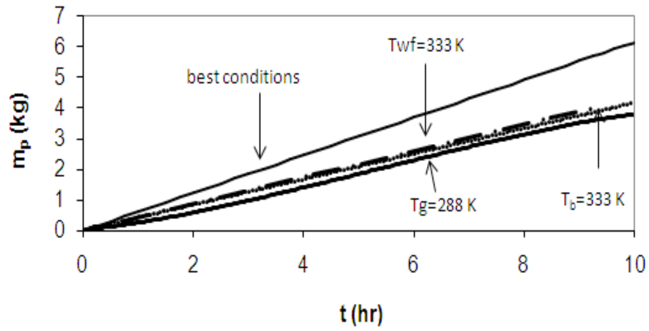

Fig. 12. The amount of water produced using the best conditions: T_b = 330 K, T_g = 288 K and T_{wf} = 333 K.

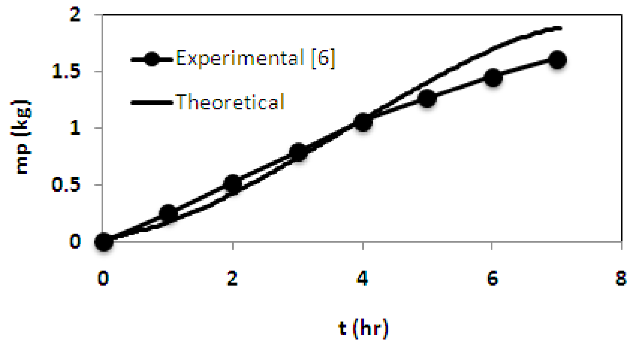

Fig. 13. Comparison between experimentally measured and the theoretically calculated m_p vs. time.

4. Conclusions

In this paper, the various parameters that affect the productivity of a falling film solar unit were theoretically investigated. The parameters considered are: feed water flow rate and temperature, solar irradiation, collector's temperature and glass cover temperature. The results showed that the unit productivity can be improved by lowering the feed water flow rate and the glass cover temperature and by increasing the collector's temperature and feed water's temperature. Ambient temperature has no significant effect on the unit productivity. The above parameters are easy to implement when designing such a unit.

Symbols

a	—	Absorptance, dimensionless
c_p	—	Heat capacity, kJ/kg °C
h	—	Heat transfer coefficient, kW/m² °C
m	—	Mass, kg
$\dot{m}$	—	Mass flow rate, kg/s
P	—	Pressure, Pa
q	—	Heat transfer rate/unit area, kJ/m²-s
I	—	Solar irradiation, kW/m²
Q	—	Heat, J
t	—	Time, s
T	—	Temperature, °C
U	—	Overall heat transfer coefficient, kW/m²°C
x	—	Direction along the plate length, m

Greek

α	—	Absorptivity
ε	—	Emmisivity
ε	—	Reflectivity
σ	—	Stefan-Boltzmann constant = 5.67×10^{8} W/m²-K⁴

Subscripts

a	—	Ambient
b	—	Black plate
c	—	Convection heat transfer
eff	—	Effective
$evap$	—	Evaporation
e	—	Exit
f	—	Feed
g	—	Glass cover
p	—	Product
r	—	Radiation
w	—	Water
wf	—	Water film

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