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Theoretical modeling of Solar Still with water cooled Integrated Built-in Condenser

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Abstract

Fresh water demand is growing every day in the world. Solar desalination using a still has been regarded as the sustainable solution in particular in rural and arid areas. Investigations and research has focused on exploring theoretical methods and finding ways to simplify the design process of solar stills. This research is essentially a theoretical approach focused on the effect of a water cooled passive built-in condenser incorporated into a conventional solar still daily productivity. The condenser plate is cooled by water falling film evaporation process to the surrounding air. Two approaches were studied; (1) a steady state water falling film and (2) a transient water falling models. It has been found that the condenser plate and the interface between the water film and the surrounding air temperatures deviate by a maximum of 4.7%. Also the deviation of accumulated daily production rate is 4.8%. Using water cooling, the daily production rate for the glass cover drops by 52% and increases for the condenser by 110% and the total production rate has increased by 9.3%..

Keywords: **Solar still; passive condensers; built-in condensers; solar distillations**

1. Introduction

The potable water demand worldwide is rapidly increasing. Access to potable water is narrowing down day after day all over the world. Clean drinking water is crucial for human being. Most of the human diseases are caused by polluted or non-purified water resources. Fresh and pure water is also required for agriculture and industrial applications. The ground water has been intensively exploited (Al-harahsheh et al., 2018; Sharshir et al., 2018). In recent periods, the freshwater scarcity is escalating and has become a profound worldwide crisis predominantly in secluded and arid areas due to increasing of energy crisis, drought, desertification climate change, and global warming. The present situation represents a serious and a big challenge due to the ever-increasing water demands, pollution and salinity. The situation is more critical in rural and arid areas such as North Africa and Middle East. Both these regions have coastal water where access to seawater is abundant but not to water. Therefore there is an urgent need for clean pure drinking water in many of these areas (Kalbasi et al. 2018 ; Ahmed et. Al. 2014, Yousef et al. 2017).

The positive outlook is that the majority of the areas that have deficiencies in fresh water supply have huge amounts of solar energy freely available. The Solar energy is an abundant and safe source of vitality and therefore is distinguished as one of the most promising alternative energy choices.

Solar desalination is great alternate solution to provide potable water in remote and isolated areas. Further, it represents an ecofriendly technology which can contributes efficiently in the social and economic development of countries. Solar still distillation systems offer sustainable tools for freshwater production (Ahmed, 2015; Kaviti et al. 2016). It is a simple technology in which solar energy is utilized to separate salts from brackish water to get pure drinking water. The device, called solar still, is used to execute the solar desalination process (Nayi et al., 2018).

The solar stills work by the simple concept of evaporation and condensation as a direct simulation of the green house effect. It utilizes the solar thermal energy for the evaporation of the basin water. The conventional still suffers from the major disadvantage of low efficiency and low productivity. Therefore, researches have focused on studying various parameters affecting the productivity by adopting different techniques and exploring new designs to improve the still's performance and increase productivity. One of these ways is to incorporate the conventional solar still with condensers (Ahmed et al., 2013).

Kabeel et al., (2016) conducted a detailed review of solar stills integrated with external or internal condenser with different design and configuration arrangements. They concluded that the incorporating condensers in conventional solar stills are deemed to be effective. Fath and ELsherbiny, (1993) conducted also a theoretical study to investigate the effect of adding a passive condenser on the performance of the single slope, basin type solar still using dry cooling. Hassan Fath, and Hosny, 2002 presented a theoretical study of the thermal performance of a single-sloped basin still with enhanced evaporation and a built-in additional condenser and found a yield increase of about 55% over the base case. Min and Tang (2015) conducted a theoretical analysis of water film evaporation characteristics on an adiabatic solid wall. Their model is using a partial differential transient heat conduction within the water film. Their results showed that s steady state is obtained within 10 to 30 seconds using convective heat transfer coefficient (ha) between 50 and 150 $\mathrm{W/m^2K}$. Also the time required to reach steady state at ha = 100 $\mathrm{W/m^2K}$ varies from 7.5 at o.1 mm film thickness to 40 seconds at1 mm film thickness.

Ibraim (1991) conducted a review on minimum wetting rates of falling films. He reported that water falling film over the condenser external wall in contact with the surrounding air will partially evaporate due to the difference in vapor pressure at the water air interface and the bulk air. The evaporation process to occur energy is removed from the remaining water. So the water temperature drops and in turn the condenser plate temperature decreases. The thinner the water film the faster the water is cooled. However, the minimum film thickness is limited to the minimum wetting rate (MWR) below which the water film thickness will breakdown. The MWR is depending on different surface and liquid properties such as surface tension, viscosity and angle of inclination.

The authors previously conducted an experimental test on conventional solar still with built in internal condenser (Ahmed et al., 2017). The present work is a theoretical study applied to the solar stills incorporating water cooled built in passive condenser. The aim of the study is to predict the solar still production rate under different cooling criteria.

2. Theoretical models

The present study applies two approaches; (1) an unsteady state water falling film and (2) an unsteady water falling models.

It is assumed that:

i) The total heat rate from the solar still is absorbed partially by the condenser plate and partially is rejected to the water film.

ii) The vapor pressure at interface between the water surface and the surrounding air is assumed saturated at the interface temperature

iii) The rate of evaporation is small compared to film flow rate i.e. the film thickness remains constant.

iv) Film thickness is 0.5 mm accepts mentioned otherwise.

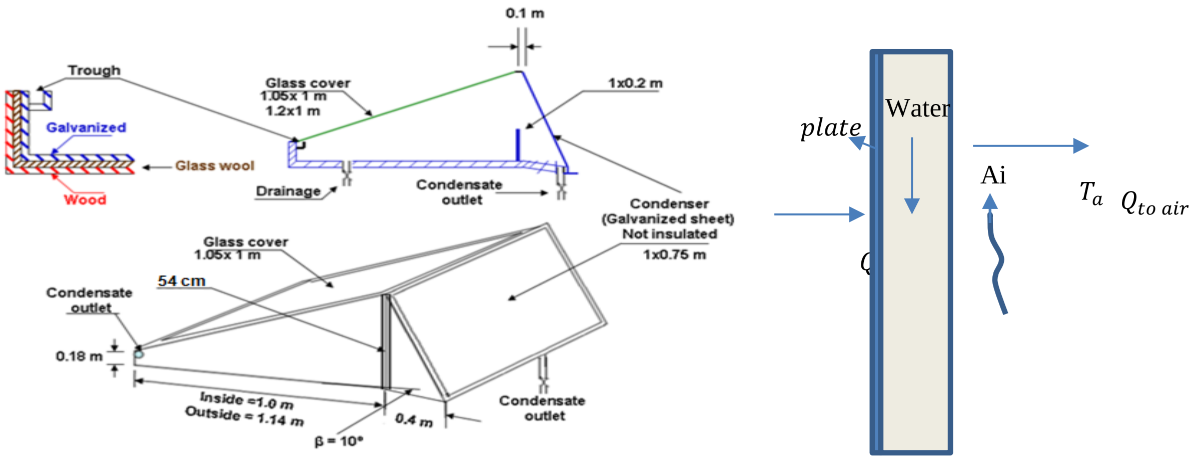

Fig.1. Schematic diagram of the solar still with built in condenser

3. Mathematical Model

3.1 Principles of Solar Still

Solar radiation is partially reflected to the outside and partially absorbed by the glass cover and mostly it is transmitted through the glass cover to the water in the basin. The water in turn absorbs small portion of the received solar radiation and transmit the rest to the basin in conventional solar stills. The solar radiation absorbed by water and the heat gain by the water from the basin will raise the water temperature above that of the glass cover. This allows the evaporated water to condense on the glass cover surface. Inside the solar still the air is trapped. The increase in saline water temperature causes the vapor pressure at the air water interface to increase above that in the bulk of the air. Thus the water evaporates as a result of the vapor pressure difference and the air humidity in the tank rise and so its dew point. Since

the glass cover temperature is lower than the dew point of the humid air, condensation occurs on the glass surface. The evaporated water must be compensated to keep the water level in the tank.
Adding a built in passive condenser that is completely in contact with trapped humid air trapped in the solar still. Similar to the glass cover, condensation will occur at the surface of the condenser with exception that the condenser is completely unexposed to any direct solar radiation. Therefore the same principles applied to the glass cover may be applied the condenser.

3.2 Thermal Analysis of the Solar Still

The operation of solar still is governed by the various heat and mass transfer modes occurring in the system. The major energy transport mechanism in the still is shown in figure 1.
Applying the conservation of energy to the conventional solar still components with built in condenser, namely the glass cover, saline water, basin and the galvanized steel condenser, the following equations are obtained.

3.2.1 Saline water:

Energy received by the saline water in the still (from sun and base) is equal to the summation of energy lost by (1) convective, radiative and evaporative heat transfer between water, and glass and condenser, plus (2) the energy by the replaced cooler water that replaces the evaporated portion, (3) side wall loss and (4) energy stored by the saline water. The water reflectance is negligibly small.

$$Q_{cw} = Q_{cwg} + Q_{cws};\ Q_{rw} = Q_{rwg} + Q_{rwc}\ ;\ Q_{ew} = Q_{ewg} + Q_{ewc}$$

$$I(t)A_w a_w + Q_{c,bw} = m_w Cp_w\left(\frac{dT_w}{dt}\right) + Q_{c,wg/c} + Q_{r,w} + Q_{e,w} + Q_{fw} + Q_{sw,loss} \quad (1)$$

3.2.2 Solar Still Basin;

Energy received by the solar still basin (from sun) is equal to the summation of energy (1) lost by convective heat transfer between basin and water, (2) heat lost from the bottom of the basin and (3) energy stored by the basin. It is assumed that all solar radiation reached the basin are absorbed by the basin with zero reflectance.

$$I(t)A_b a_b = m_b Cp_b\left(\frac{dT_b}{dt}\right) + Q_{c,bw} + Q_{b,loss} \quad (2)$$

3.2.3 Glass cover

Energy gained by the glass cover (from sun and convective, radiative and evaporative heat transfer from water to glass) is equal to the summation of energy lost by radiative and convective heat transfer between glass on one side and sky and ambient on the other side, and energy stored by glass.

$$I(t)A_g a_g + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} = m_g Cp_g\left(\frac{dT_g}{dt}\right) + Q_{r,g-sky} + Q_{c,g-a} \quad (3)$$

Where: $a_g = \alpha_g(1 - r_g)$; $a_w = \alpha_w \tau_g(1 - r_g)$; $a_b = \alpha_b \tau_g \tau_w(1 - r_g)$

3.2.4 Galvanized steel condenser;

Energy gained by the galvanized steel (from convective, radiative and evaporative heat transfer from water to galvanized steel condenser) is equal to the summation of energy lost by radiative and convective heat transfer between galvanized steel condenser on one side and sky and ambient on the other side, plus the energy stored by galvanized steel condenser.

$$Q_{c,w-c} + Q_{r,w-c} + Q_{e,w-c} = m_c Cp_c\left(\frac{dT_c}{dt}\right) + Q_{out} \quad (4)$$

Where Q_{out} is the rate of heat absorbed by the water falling film.

$$T_w = T_w + dT_w \quad (5)$$

$$T_g = T_g + dT_g \quad (6)$$

$$T_c = T_c + dT_b \quad (7)$$

$$T_b = T_b + dT_b \quad (8)$$

$$\frac{dm_c}{dt} = \frac{h_{e,wg}(T_w - T_g)}{h_{fg}} \quad (9)$$

$$Q_{c,bw} = h_{c,bw} A_b (T_b - T_w) \quad (10)$$

$$Q_{b,loss} = U_b A_b (T_b - T_a) \quad (11)$$

$$Q_{fw} = \dot{m}_e c_w (T_w - Ta) \quad (12)$$

$$Q_{sw,loss} = U_{sw} A_{sw} (T_w - T_a) \quad (13)$$

$$Q_{c,wg(c)} = h_{c,wg(c)} A_{g(c)} \left(T_w - T_{g(c)}\right) \quad (14)$$

Where the convective heat transfer coefficient between water and glass is

$$h_{c,wg(c)} = 0.884\left\{\left(T_w - T_{g(c)}\right) + \frac{(P_w - P_{g(c)})(T_w + 273.15)}{(286.9 \times 10^3 - P_w)}\right\}^{1/3} \quad (15)$$

The radiative heat transfers between water and the glass is

$$Q_{r,wg(c)} = h_{r,wg} A_{g(c)} \left(T_w - T_{g(c)}\right) \quad (16)$$

Where the radiative heat transfer coefficient between water and glass is

$$h_{r,wg(c)} = \varepsilon\sigma[(T_w + 273.15)^2 + \left(T_{g(c)} + 273.15\right)^2]\left(T_w + T_{g(c)} + 546\right) \quad (17)$$

Where $$\varepsilon_{eq} = \frac{1}{\left(\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_g}-1\right)} \quad (18)$$

The evaporative heat transfers between water and the glass is

$$Q_{e,wg(c)} = h_{e,wg(c)}A_{g(c)}\left(T_w - T_{g(C)}\right) \quad (19)$$

Where the evaporative heat transfer coefficient between water and glass is

$$h_{e,wg(c)} = (16.273 \times 10^{-3})h_{c,wg}\left(P_w - P_{g(c)}\right)/\left(T_w - T_{g(c)}\right) \quad (20)$$

The radiative heat transfers between sky and the glass is

$$Q_{r,g(c)-sky} = h_{r,g-sky}A_{g(c)}\left(T_{g(c)} - T_{sky}\right) \quad (21)$$

The radiative heat transfer coefficient between glass and sky is

$$h_{r,g(c)-sky} = \varepsilon\sigma[(T_w + 273.15)^4 + \left(T_{g(c)} + 273.15\right)^4]\left(T_{g(c)} + T_{sky}\right) \quad (22)$$

The effective sky temperature is

$$T_{sky} = T_a - 6 \quad (23)$$

The convective heat transfers between sky and the glass is

$$Q_{c,g(c)-a} = h_{c,g(c)-sky}A_{g(c)}\left(T_{g(c)} - T_a\right) \quad (24)$$

Where

$$h_{c,g(c)-a} = 2.8 + 3.0\,V \quad (25)$$

And V is the wind velocity

Bottom and side wall heat transfer coefficients;

Since the solar still contents (basin plate, water and moist air) are at a higher temperatures than the outside ambient temperatures. A heat loss is expected to occur. Therefore the bottom and side wall are insulated. If the insulation is properly applied, the insulation thermal resistance will be the dominant one to other thermal resistances such the inside convective and radiative. However all thermal resistance may be included. The overall heat transfer coefficient of bottom heat loss is obtained as

$$U_b = 1/\left(\frac{1}{h_a} + \frac{x_{pw}}{k_{pw}} + \frac{x_{in}}{k_{in}} + \frac{x_s}{k_s}\right) \quad (26)$$

Where in the thermal resistance of the insulation $\left(\frac{x_{in}}{k_{in}}\right)$is dominant
And the side wall overall heat transfer coefficient is approximated by researcher [Shadi et al., 2016; l., Madhlopa, 2009; Madhlopa and Johnstone 2009) as

$$U_{sw} = U_b \frac{A_{sw}}{A_b} \tag{27}$$

Some researchers embedded the side heat transfer coefficient in the U_b.In this case a value of $14\ \mathrm{W/m^2K}$ (Madhlopa,2009) and $20\ \mathrm{W/m^2K}$ (Panchal, 2016) were used. Madhlopa and Johnstone (2009) took the side wall heat transfer coefficient as $0.5\ \mathrm{W/m^2}$ K. In this current work the side wall heat loss is obtained as

$$U_{sw} = 1/\left(\frac{1}{h_a} + \frac{x_{pw}}{k_{pw}} + \frac{x_{in}}{k_{in}} + \frac{x_s}{k_s} + \frac{1}{h_{cw}+h_{rw}}\right) \tag{28}$$

Where $h_{cw} = h_{c,wg}$ and $h_{rw} = h_{r,wg}$. These coefficients are time dependent and must be calculated at each time step.

4. Water falling film models

4.1 Unsteady Flow Model

$$\rho c_p \frac{\partial T}{\partial t} = k_w \frac{\partial^2 T}{\partial y^2} \tag{29}$$

Boundary conditions
Condenser plate

$$Q = k_w A_s \frac{\partial T}{\partial y} \text{ this is the } Q_{out} \text{ in equation 4.} \tag{30}$$

Water film and air Interface

$$Q = ha\ (Ti - Ta) + KA_s(w_i - w_a)h_g + h_{rsky\ A_s}(T_i - T_{sky}) \tag{31}$$

$$Q = k_w A_s \frac{\partial T}{\partial y} + h_f \tag{32}$$

4.2 Steady state model

The rate of heat between the water film surface and air

$$Q = ha\ (Ti - Ta) + KA_s(w_i - w_a)h_g + h_{rsky}\ A_s(T_i - T_{sky}) \tag{33}$$

The heat transfer across the water film thickness is due to conduction and energy of liquid water which is about to evaporate. This equal to the rate of heat transferred from the condenser plate to the water film.

$$Q = k_w A_s \frac{(T_s - T_i)}{\Delta} + h_f \text{ this equal to the } Q_{out} \text{ in equation 4} \tag{34}$$

Equating both equations give

$$\frac{(T_s - T_i)}{\Delta} = ha\,(Ti - Ta) + KA_s(w_i - w_a)h_{fg} + h_{rsky}\,A_s\left(T_i - T_{sky}\right) \qquad (35)$$

The relation between heat and mass transfer coefficients [26]

$$Le^{2/3} = \frac{ha}{K\,Cpm} \qquad (36)$$

5. Results and Discussions

In this research, the effect of incorporating water cooled built-in passive condenser with conventional, basin type solar still on the solar still productivity has been theoretically investigated.

The mathematical solar still model (equations 1-28) was solved using Euler modified method. The water cooled condenser unsteady and steady models were solved and compared at convective heat transfer coefficient, ha range of 5.7 to 150 $\mathrm{W/m^2\,K}$ and relative humidity range of 50 to 100%.

Fig 2 shows that the plate and water air interface temperatures obtained by the steady and unsteady flow models have insignificantly small deviation. The maximum deviation is of 4.8% based on average. The deviation at the applicable heat transfer coefficient ha < 10 $\mathrm{W/m^2}$ K is 0.37%. This indicate that using the steady state models is satisfactory.

The effect of relative humidity is shown in Fig. 3. The increase in relative humidity reduces the difference of humidity ratio at the water air interface and the bulk air. This in turn reduces the energy removed from the water film and the plate temperature rises.

As can be seen from Fig. 3, the production rate for glass cover increases by 42% and for the condenser decreases by 26% with increasing with relative humidity from 50% to 100%. The total production as expected decreases by 7% with increasing relative humidity from 50% to 100%.

The total accumulated rate of production of the solar still using condenser will increase compared with conventional solar still. The total production rate of solar still with condenser is accumulated by the glass cover and the condenser plate. However, the production rate over glass cover decreases relative to the conventional solar still and compensated by the condenser. It can be seen from Fig. 4 that the total accumulated production rate of a solar still with water cooling increases over that of dry cooling by 9.3%. Compared to dry cooling the saline water, basin, glass and condenser plate temperatures of solar still with water cooling condenser drop by 13.5%, 13.3 %, 8.5% and 26.8% respectively Fig. 5 and Fig. 6. The reason why the saline, basin and glass cover temperatures drop is because of the decrease in the plate temperature which in turns increases the heat loss from the saline water thorough the condenser, and feed water increase. The decrease in saline water temperature will increase the rate of absorbed from the basin and decrease the rate of heat given off to the glass temperature.

Table 1 applied parameters

Parameter	Symbol	Saline water	Basin	Glass cover	Galvanized steel condenser
Absorptivity	α	0.05	0.90	0.05	-
Transmissivity	τ	0.95	-	0.9	-
Emissivity	ϵ	0.96	-	0.98	0.28
Reflectance	ϕ	0.05	-	0.13	-
Specific heat	$c_p(J/kg\ K)$	4187	490	670	510

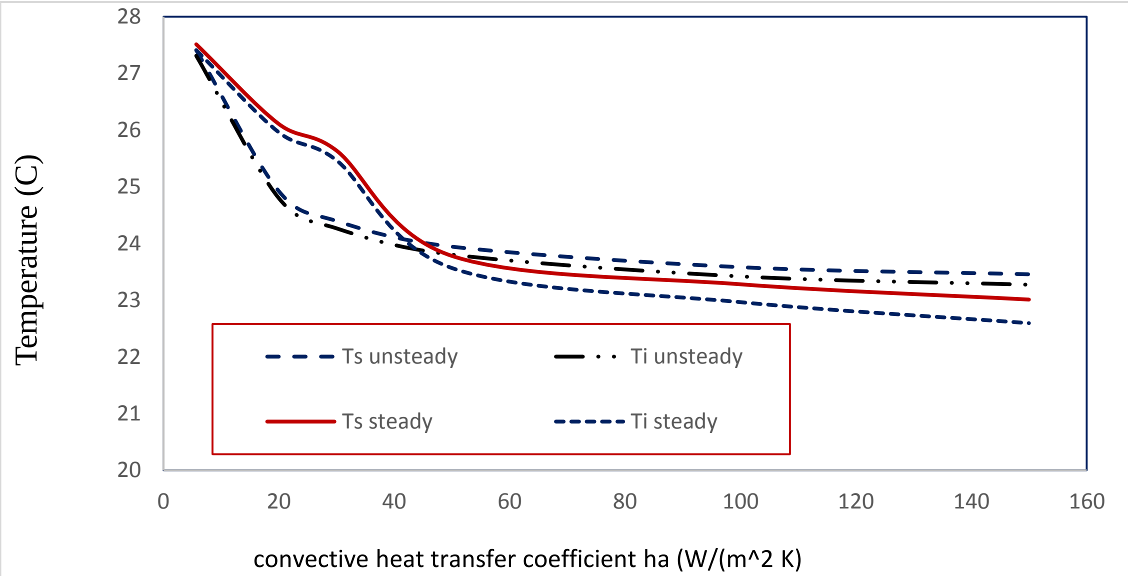

Fig. 2 The condenser plate and water air interface temperatures versus the convective heat transfer coefficients using both steady and unsteady model.

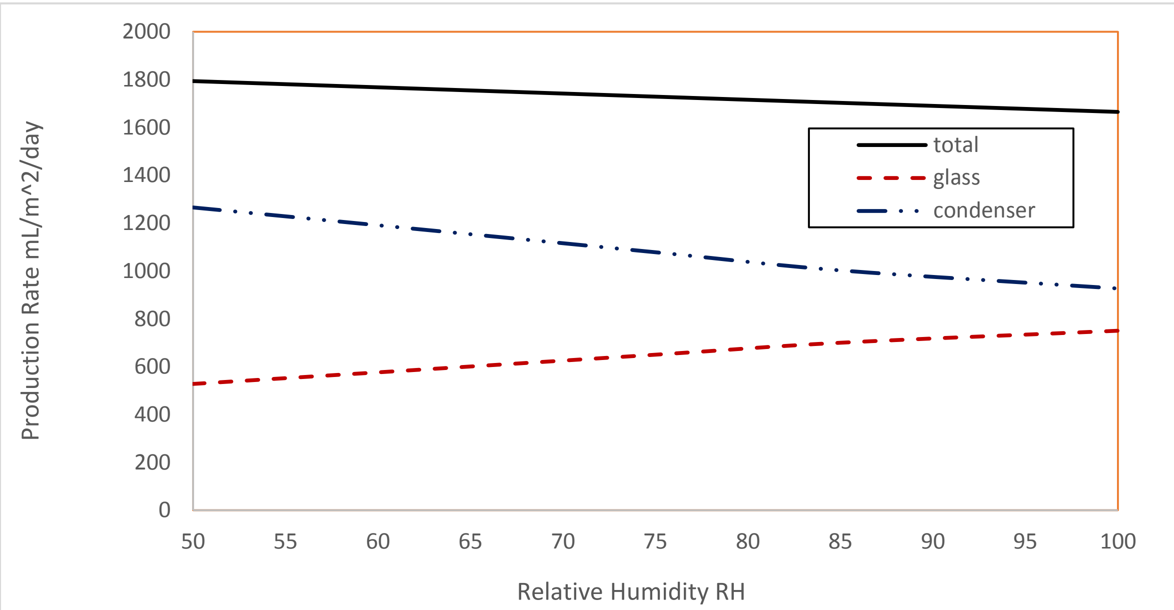

Fig.3 Effect of relative humidity on the production rate using ha = 2.8 + 3V

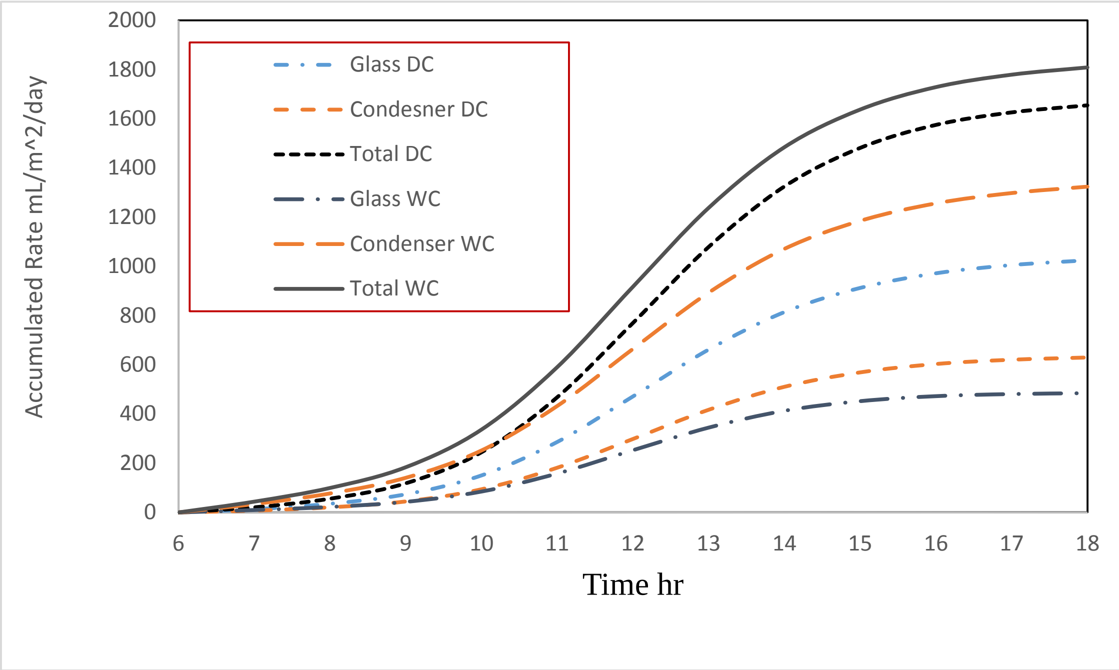

Fig. 4 Accumulated production rate for the glass cover, condenser and total for dry cooling (DC) and water cooling (WC) using ha = 2.8 + 3V.

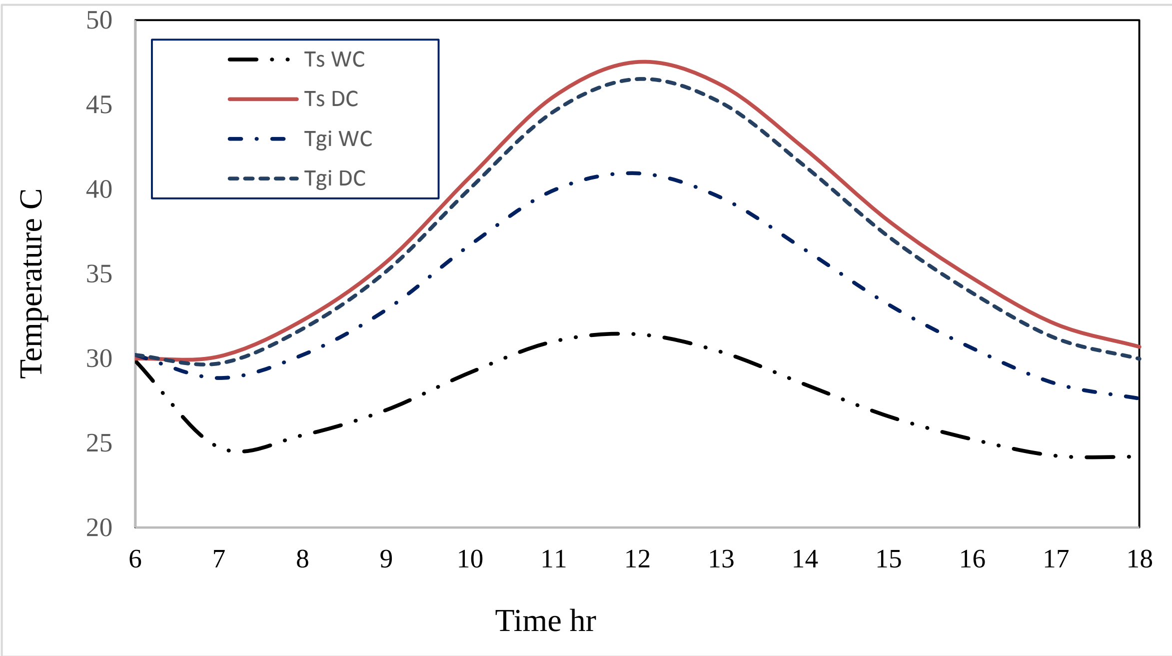

Fig. 5 Saline water and basin temperatures; a comparison between water cooling and dry cooling of a conventional solar still with condenser

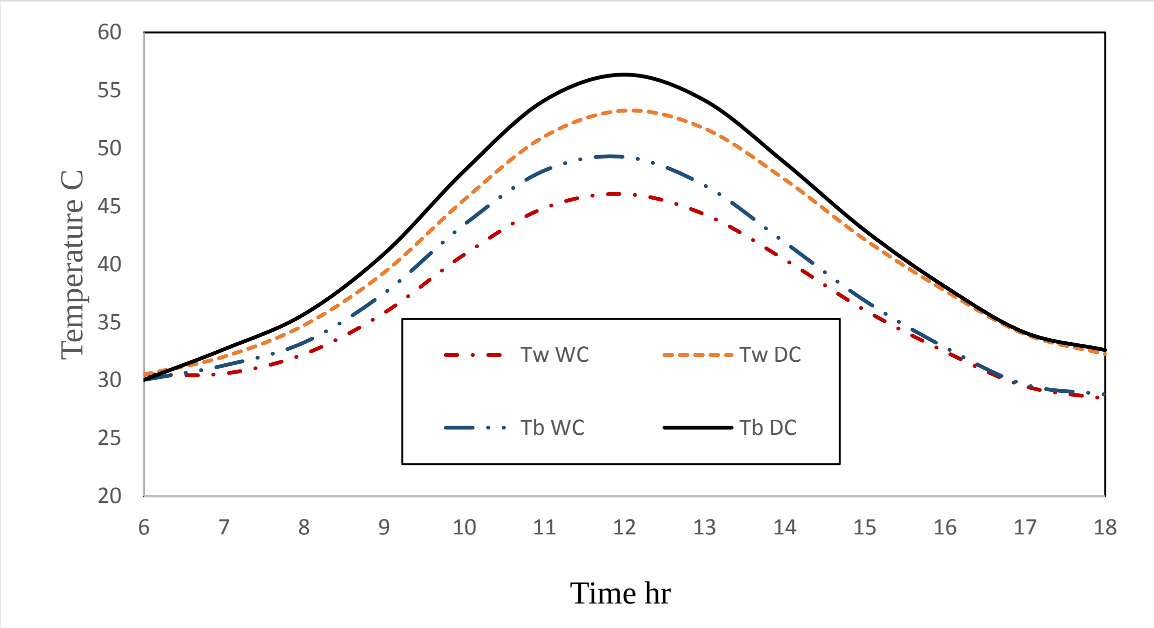

Fig. 6 Rate of heat transferred to the outside through the glass cove and the galvanized steel condenser.

6. Conclusions

This study is an attempt to predict production rate of the conventional solar still with water cooled incorporated built in condenser. The comparison between the unsteady and steady water falling film evaporation models showed that using steady state falling film model is satisfactory with 0.3% deviation at low convective heat transfer coefficient.

The total production rate of the solar still with water cooling is 9.3% higher than that produced with the dry cooling condenser. The saline water, basin, glass and condenser temperatures are lower with water cooling than with dry cooling.

Nomenclatures

A	area,(m^2)
a	solar radiation factor
C	specific heat, (J/kg K)
h	heat transfer coefficient, (W/m^2K)
h_{fg}	enthalpy of evaporation at Tw, (J/kg)
I(t)	intensity of solar radiation, (W/m^2)
K	mass transfer coefficient (kg/m^2 s)
Le	Lewis number
m	mass, (kg)
P	partial pressure, (Pa)
r	reflectance

T	temperature, ^{o}C
U	heat transfer coefficient, (W/m^2K)
V	wind velocity, (m/s)
t	time
x	thickness (m)
y	coordinate in the direction across the film (m)
w	humidity ratio (kg_v/kg_a)

Greeks

α	absorptivity
Δ	water film thickness
ε	emissivity
ρ	density, (kg/m^3)
τ	transmissvity

Subscripts

a	ambient
b	basin
bw	basin-water
c	convective, condenser
e	evaporation
eq	equivalent
fw	feed water
g	glass
g(c)	either glass or condenser used to distinguish the equation above
g-sky	glass-sky
i	water air interface
in	insulation
pw	plywood
pm	humid air
r	radiation
s	steel (galvanized)
sw	side wall
w	water
$w-g$	water-glass

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