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Research Paper

Performance enhancement of wick solar still using rejected water from humidification-dehumidification unit and film cooling

S.W. Sharshir [a,b,c], M.O.A. El-Samadony [c], Guilong Peng [a,b], Nuo Yang [a,b,*], F.A. Essa [c], Mofreh H. Hamed [c], A.E. Kabeel [d]

[a] State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Nano Interface Center for Energy (NICE), School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[c] Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, Egypt
[d] Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

HIGHLIGHTS

- The performance of a modified wick still is investigated theoretically.
- The effect of feed water flowing over the wick is considered in the present work.
- The productivity of the wick still with film cooling is higher than the conventional basin by 210.22%.

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ABSTRACT

The performance of a modified wick still is investigated theoretically. The still is fed by the rejected warm water from Humidification-Dehumidification (HDH) unit. The performance is investigated also for using the glass film cooling. In addition, the effect of feed water flowing over the wick is considered. The still output yield would be predicted through this study for both day and night times. Results show that during the daytime, the wick still productivity decreases with increasing the flow rate and increases with film cooling. While, during the night time, the productivity increases for both with and without cooling film. The yield of wick still when using the glass film cooling is more than that without film cooling by about 5.3%, 30% for day and night times respectively. Therefore, the productivity of the wick still with and without film cooling is higher than that of conventional basin by 278.4% and 210.2% respectively.

1. Introduction

It is known that potable water means life for humans. But, only about 1% the earth's water is drinkable while the largest percent of 97% is saline and brackish and finally the frozen in polar glaciers has the remaining amount 2% [1]. Solar still is a useful device to get freshwater from saline or brackish water. Improving the evaporation rate of solar still and hence its productivity by different techniques took too much effort by scientists [2]. They used dyes [3], charcoal pieces [4], heat material storing, and wick in the basin [5–7].

Still productivity is affected by water depth, the area of surface basin water, the higher evaporation rate. Using proper storing materials leads to increase the water surface in solar still. Sponge cubes, gravel, wicks and phase change materials are considered as proper storing materials [8–13]. Using wick increases the surface area of basin water. The wick helps to avoid the dry spots inside the solar still. The distillate yield of a tilted wick still was 20–50% more than conventional still [14]. The experimental setup of double-condensing and multi-wick still was carried out by Tiwari et al. [15]. The evaporation rate can be improved by reducing the glass heat load and glass cover temperature because of condensing the excess vapor on the additional surface. Twenty percent increase in still productivity was achieved [15].

Omara et al. [16] have conducted an experimental modification to investigate the performance of corrugated and wick absorbers of solar stills integrated with external condenser. The performance of corrugated wick still (CrWSS) with internal reflectors, integrated

* Corresponding author at: Nano Interface Center for Energy (NICE), School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China.

E-mail address: nuo@hust.edu.cn (N. Yang).

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Nomenclature

A	area of solar still, m^2
b	breath of wick solar still, m
Cp	heat capacity, J/kg K
h	heat transfer coefficient, W/m^2 K
h_{bw}	convection heat transfer coefficient between the basin and saline water, W/m^2 K
h_{ca}	convection heat transfer coefficient with the ambient, W/m^2 K
h_{cf}	convection heat transfer coefficient between the glass in basin and film, W/m^2 K
h_{cw}	convection heat transfer coefficient between the water in basin and glass, W/m^2 K
h_{fg}	latent heat of vaporization for solar still, J/kg
$I(t)$	solar insolation normal to glass cover, W/m^2
K_i	thermal conductivity of insulation, W/m K
K_f	cooling water thermal conductivity, W/m °C
L	glass cover length, m
L_i	thickness of insulation, m
m	mass, kg
m_{ew}	rate of productivity, kg/h
m_{rf}	cooling water flow rate, kg/s
Pr	Prandtl number
P_g	water vapor pressure at glass temperature, Pa
P_w	water vapor pressure at water temperature, Pa
Q_{bw}	heat transfer from basin to water in basin, W
Q_{ca}	heat transfer from film to ambient, W
Q_{cf}	heat transfer from glass to film, W
Q_{cg}	heat transfer from glass to ambient, W
Q_{cw}	heat transfer from water in basin to glass, W
Q_e	heat transfer due to evaporation, W
Q_{loss}	heat transfer from basin to ambient, W
Q_{mw}	energy needed to heat makeup water to water basin temperature, W
Q_{rf}	radiation heat transfer from film cooling to ambient, W
Q_{rg}	radiation heat transfer from glass to ambient, W
Q_{rw}	radiation heat transfer from water in basin to glass, W
Re_L	Reynolds number based on L
T	temperature, °C
t	time, s
V_a	air velocity, m/s
V_f	film velocity, m/s
Vol_f	water film cooling volumetric flow rate, m^3/s
d	width of the glass cover, m
χ_f	cooling film thickness, m
U	heat loss coefficient from basin and sides to ambient, W/m^2 K
U_L	overall heat transfer coefficient, W/m^2 K

Greek letters

μ_f	fluid viscosity (N s/m^2)
α	absorption coefficient
ε	emissivity coefficient
ρ	density (kg/m^3)
η_d	daily efficiency
σ	Stefan-Boltzmann constant, W/m^2 K^4

Subscripts

a	ambient
b	basin
c	convective
e	evaporative
f	film
g	glass
r	radiative
sky	sky
w	water

with external condenser and using different types of nanoparticles was also investigated and compared with conventional still under the same metallurgical conditions. Experimentations obtained that the yield of CrWSS with reflectors when providing vacuum was about 180% higher than that of conventional still.

Samuel et al. [17] used different types of low-price energy storage material to improve the freshwater productivity in a CSS. They carried out both theoretical and experimental investigations to evaluate the performance of a CSS. The results illustrated that the output of freshwater using ball-shape as a heat storage and sponge reaches the extreme yield of 68.18% and 22.72%, respectively compared with CSS.

EL-Agouz et al. [18] studied the performance of a steeped SS with and without a water closed loop. They showed that steeped SS with a make-up water reinforce the freshwater output by 57.2% compared to traditional still.

Kabeel [19] made experimentations on a wick concave still. A surface of wick was used for more evaporation rate due to capillary effect. Results revealed that the distillate output in daytime was around 4.1 kg/m^2 on average and it reached the greatest value of about 0.5 kg/h per m^2 in the afternoon. The largest instantaneous efficiency of the system was found to be 45% but the average daily efficiency was 30% per day.

Janarthanan et al. [20] designed a floating tilted-wick still. Brine flowed slowly over a sloping surface paved with a thin layer of wicks. The brine evaporated rapidly owing to its little heat capacity. In comparison with a basin solar still, the wick solar still needs a minimal time to produce freshwater at the beginning. Also, the output yield can be improved by approximately 16–50%.

On the other hand, the glass-water temperature difference is a main factor affecting the output yield of the solar still [21]. To keep up this temperature difference as a maxima value, several researchers had investigated the mechanisms of flowing water over the glass cover. The condensation rate can be enhanced and hence the productivity also can be enhanced by increasing the cooling water flow rate and decreasing the inlet cooling water temperature as obtained from the results of Nafey et al. [22]. The main function of glass cover cooling is to increase the difference between glass and water temperatures and hence to increase the water productivity [23]. Results showed an increase of water productivity by about 17–23% when cooling the glass cover. The distillate output was improved by Velmurugan and Srithar [21] who used the technique of sprinkler (cooling film for the outer side of glass cover). Their results revealed an enhancement of 22% in productivity. In addition, the conventional still efficiency can be improved by about 20% as Abu-Hijlew and Mousa [24] investigated numerically by using the film cooling for the glass cover.

It's well-known that preheating the makeup water is one of the modifications to increase the water-glass temperature difference and then enhance the productivity of solar still. It is easy to preheat feed water by integrating the solar still with solar collectors [25–27] and coupling the solar still with storage tank and solar collector [28]. However, using a solar collector increases the cost of the desalination system and reduces the capital efficiency for solar still.

Besides solar stills, humidification–dehumidification (HDH) is another popular method of desalination. The productivity of HDH is affected by several factors such as preheating feed water, preheating feed air, using fined coil to increase the condenser heat transfer area, increasing wet area by packing material and forced air circulation [29].

Sharshir et al. [30]. studied the performance of a continuous SS joined with HDH. Results showed that the output of the SS with rejected water from HDH is enhanced by 242% compared with CSS and the gain output ratio was enhanced by about 39%.

Hamed et al. [31] studied mathematical and experimental investigation of a solar HDH desalination unit. A comparison study had been presented to show the effect of the different operating times during the day on the productivity of the system. First period operates from 9 am to 17 pm, while the second period operates from 13 pm to 17 pm. The highest fresh water productivity is found to be in the period from 13 to 17 pm, where high direct solar radiation and long solar time are expected. Thus, the water in the solar collector is heated to maximum value about 86 °C at 13 pm and showed high productivity due to preheating.

Nowadays, many researches use the mathematical modeling or numerical techniques in their research studies. This is because mathematical modeling is an attractive alternative to investigate and develop better designs for solar still under various working parameters. Thermal or mathematical models can be simply established based on the energy balances for all the components of solar still.

Based on the results of Ref. [30], the first period operates from 9 am to 17 pm the fresh water obtained from this period about 8 kg/m^2 day, and the rejected water from HDH has very low temperature due to the low temperature of the feed water to humidifier, while the second period operates from 13 pm to 17 pm. The highest fresh water productivity is found to be in the period from 13 to 17 pm about 11 kg/m^2 day, as a result of stored energy in the solar collectors during sunrise. Thus, the water in the solar collector is heated to maximum value about 86 °C at 13 pm and showed high productivity due to preheating. And the rejected water from the humidifier bottom with high temperature of about 60–75 °C is rejected to surrounding without any benefits. Then, the cold water enters to the dehumidifier and becomes heated by the latent heat of condensation. The warming water exits from the condenser (dehumidifier) to the evacuated tube solar collector to become more heated, then enters to the humidifier. The hot water is sprayed on the packing materials and the hot rejected water exits from the humidifier. If we reuse this rejected water with high temperature again in HDH (dehumidifier), the productivity will decrease as the condensation will decrease. This is because the temperature difference between the humidified air and the rejected water will be very small as mentioned in Ref. [31]. Also, this rejected water is not needed to feed the humidifier because we use the exit hot water from the dehumidifier to feed it. Moreover, the HDH needs large amount of water about 2 kg/min (120 kg/h), and gives low productivity if we used the rejected water to feed HDH at 70 °C and the productivity is much low more than wick solar still so it is better.

The warm rejected water from the bottom of humidifier is pumped to an isolated storage tank to be desalinated in a wick solar still unit to distillate water further. The wick still unit can work during daytime as well as nighttime. The main objective of this study is to enhance the productivity with feeding the wick still by hot rejected water from HDH and also using glass film cooling. The effect of varying the feed water flow rate inside the wick still is also investigated. A MATLAB 2014b code is developed to understand the process of using the rejected water with high temperature from HDH as a feed water to the wick still with and without film cooling (Assume feed water temperature to wick still; T_w = 70 °C). The rejected water from HDH has high temperature water enough to feed water to wick solar still during 24 h. In addition, a comparison of performance between the conventional and modified wick stills is explained.

2. System process model

The investigated desalination system compasses three parts; the first one is the tank storing the warm water rejected from humi dification–dehumidification (HDH) unit, and the second part is the modified wick solar still, while the third part is the conventional still. The system is illustrated in Fig. 1. The three solar stills have an effective area of 1 m^2 for each. The conventional still has the dimensions of 70.98 cm as a height of high-side wall and 15 cm as a height of the low-side wall. All walls of the basin stills are considered to be well insulated. A glass cover with 3 mm thickness is used to cover the top of basin. The tilt angle of the glass cover is chosen to be 30° horizontally, which is the latitude of Wuhan, China. The glass cover of wick solar still is tilted also at the same angle (30°).

The conventional still is fed by saline water drawn from the brackish water feeding tank. The wick solar still with and without film cooling is fed by the rejected warm water from the HDH unit through another tank (warm water storing tank). It should be noted that each main feeding water tank (saline water for conventional still and exit HDH hot water tank) was filled separately. The exit HDH hot water tank (insulated tank) was used to feed the wick still with hot water during day and night times. The porous black jute wicks of fabric are used as a productivity enhancing factor inside the solar still to be called "wick solar still". The base and all vertical walls are covered with the developed wicks. The good capillarity of a jute wick and a reasonable tilt angle of the absorber plate (30°) are used to create a sufficient water rate flowing from the top point inside the still.

Fig. 2 shows more details for a zoomed section (B-B) inside the basin still. This section has the dimensions of (100 × 15 × 30 cm). The authors called the "Zero Datum" for water inside the wick still at the level of 30 cm to compare with the other cases of investigations as shown in Fig. 2.

3. Mathematical modeling

The energy balance for the solar still may be presented for three regions: water, absorber plate and glass cover. The mathematical model is developed to be able to estimate the water, basin plate and glass cover temperatures at any time. With the help of A MATLAB 2014b software, the differential equations can be solved.

The next assumptions are taken into consideration for the solar still energy equations:

- Steady state conditions through the solar stills.
- The glass cover is suggested to be thin enough to hinder absorption of any incident radiation as well as the glass conduction resistance could be neglected.
- The leakage of vapor is prevented through the solar stills.
- The water film cooling is considered to be thin, therefore no incident radiation will be absorbed by the film.
- Evaporation from the water film cooling is negligible.

3.1. Conventional type solar still

Energy balance equation for the absorber liner [32]

$$m_b c_{pb}(dT_b/dt) = I(t)A_b\alpha_b - Q_{bw} - Q_{loss} \quad (1)$$

Energy balance for the water inside the still [33,34].

$$m_w c_{pw}(dT_w/dt) = I(t)A_w\alpha_w + Q_{bw} - Q_{cw} - Q_{rw} - Q_e - Q_{mw} \quad (2)$$

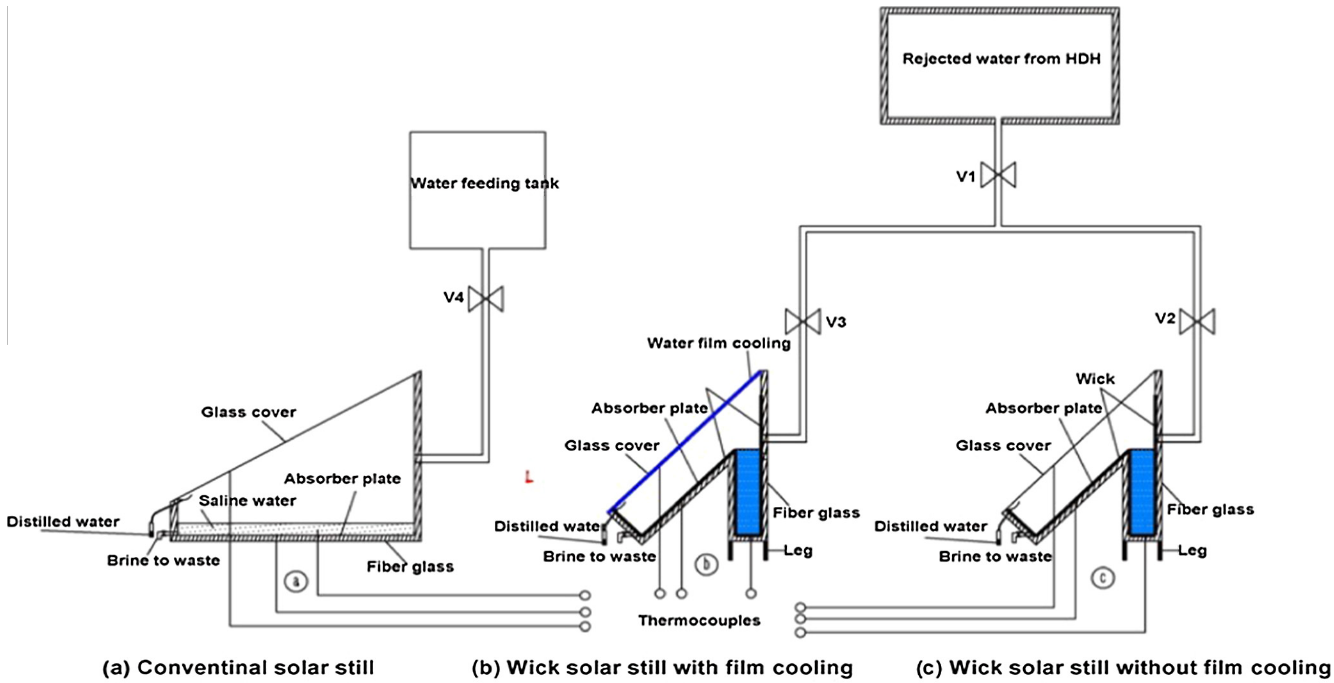

Fig. 1. Schematic diagram of the desalination system.

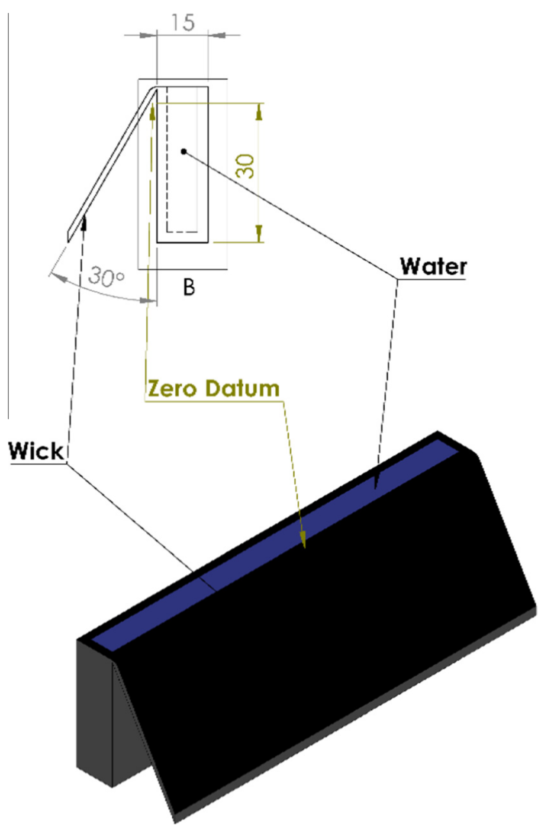

Fig. 2. More details about the wick solar still.

Energy balance for the glass cover [32]

$$m_g c_{pg}(dT_g/dt) = I(t)A_g\alpha_g + Q_{cw} + Q_{rw} + Q_e - Q_{rg} - Q_{cg} \tag{3}$$

The convective heat transfer rate between basin plate and water [34,35]

$$Q_{bw} = h_{bw}A_b(T_b - T_w) \tag{4}$$

The convective heat transfer coefficient between basin plate and water, h_{bw} is given as 135 W/m^2 K [34,35].

The convective heat loss rate from the still to the surrounding is expressed as [36],

$$Q_{loss} = U_b A_b \times (T_b - T_a) \tag{5}$$

where $U_b = K_i/L_i$, and K_i, L_i are thermal conductivity and thickness insulation, respectively.

The convective heat transfer rate between water and glass cover is expressed by [34,35]

$$Q_{cw} = h_{cw}A_w(T_w - T_g) \tag{6}$$

Whereas the water-glass convective heat transfer coefficient is expressed by [37],

$$h_{cw} = 0.884\left\{(T_w - T_g) + \frac{[p_w - p_g][T_w + 273.15]}{[268,900 - p_w]}\right\}^{1/3} \tag{7}$$

Whereas

$$P_w = e^{\left(25.317 - \frac{5144}{Tw+273}\right)} \tag{8}$$

$$P_g = e^{\left(25.317 - \frac{5144}{Tg+273}\right)} \tag{9}$$

The heat rate transferred by radiation from the basin plate to glass is expected from [33],

$$Q_{rw} = \sigma\varepsilon_{eq}A_w[(T_w + 273)^4 - (T_g + 273)^4] \tag{10}$$

Whereas

$$\varepsilon_{eq} = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1\right]^{-1} \tag{11}$$

The evaporative heat transfer rate between water and glass is expressed by [34,35],

$$Q_e = (16.237 \times 10^{-3})h_{cw}A_w(P_w - P_g) \tag{12}$$

Besides, the authors suggested that the temperature of feed water (for conventional still) during daytime is approximately the same as that of surrounding air temperature. In addition, this feed water is going to be heated from basin liner and still walls. The heat taken by the makeup water is deduced from [33],

$$Q_{mw} = m_{dss} C_w (T_a - T_w) \tag{13}$$

The rate of heat transfer radiated from glass cover to the sky Q_{rg} is expressed using [38,32],

$$Q_{rg} = \varepsilon_g A_g \sigma [(T_g + 273)^4 - (T_{sky} + 273)^4] \tag{14}$$

The sky temperature is given by [36],

$$T_{sky} = T_a - 6.0 \tag{15}$$

The convective heat transfer rate between glass cover and atmosphere is expressed by [39]

$$Q_{cg} = h_{ca} A_g (T_g - T_{sky}) \tag{16}$$

where h_{ac} is taken from [39],

$$h_{ca} = 5.7 + 3.8 \times V_a \tag{17}$$

Solar still productivity

$$m_{dss} = \frac{Q_e}{h_{fg}} \tag{18}$$

The daily efficiency, η_d, is obtained by the summation of the hourly productivity multiplied by the latent heat of vaporization h_{fg} divided by the daily average solar radiation $I(\mathrm{t})$ over the whole area A of the device [39]:

$$\eta_d = \frac{\sum m_{dss} \times h_{fg}}{\sum I(\mathrm{t}) \times \mathrm{A}} \tag{19}$$

3.2. Wick type solar basin still

The theoretical analysis of wick solar still is taken to be the same as that for the aforementioned previous section, except the energy balance for water mass flow rate through the wick. Energy balance for water mass flow rate can be written as [40]

$$[\tau_w I(t) - h_{1w}(T_w - T_g) - U_b(T_w - T_a)] b dx = m_w C_w \left(\frac{dTw}{dx}\right) dx \tag{20}$$

where

$$h_{1w} = h_{cw} + h_{rw} + h_{ew} \tag{21}$$

The basin water temperature T_w is given as [40];

$$T_w = \left\{\frac{\tau_w}{U_L} I_{(t)} + T_a\right\} \left(1 - \exp\left(-\frac{U_L bx}{m_w C_w}\right)\right) + T_{wi} \exp\left(-\frac{U_L bx}{m_w C_w}\right) \tag{22}$$

At $x = L, T_w = T_{wo}$ the water temperature at outlet is given as [40]

$$T_{wo} = \left\{\frac{\tau_w}{U_L} I_{(t)} + T_a\right\} \left(1 - \exp\left(-\frac{U_L A}{m_w C_w}\right)\right) + T_{wi} \exp\left(-\frac{U_L A}{m_w C_w}\right) \tag{23}$$

Further average of water temperature could be calculated as [40] by:

$$\bar{T}_w = \frac{1}{L}\int_0^L T_w dx = \left\{\frac{\tau_w}{U_L} I_{(t)} + T_a\right\} \left(1 + \frac{\exp(-U_L A/m_w C_w)}{(-U_L A/m_w C_w)}\right) + \frac{T_w}{(U_L A)/(m_w C_w)} \left(1 - \exp\left(\frac{-U_L A}{m_w C_w}\right)\right) \tag{24}$$

where

$$U_L = \left(\frac{h_{1w} \times h_{2g}}{h_{1w} + h_{2g}}\right) + h_b \tag{25}$$

And;

$$h_{2g} = h_{rg} + h_{cg} \tag{26}$$

The heat loss rate due to exit water flow would be calculated as [40] by;

$$\dot{q}_u = m_w C_w (T_{wo} - T_{wi}) \tag{27}$$

The hourly productivity can be calculated using the equation as [40];

$$\dot{m}_{ew} = h_{ew}(\bar{T}_w - T_g) \times 3600 / h_{fg} \tag{28}$$

The overall thermal system efficiency of the output yield and excess hot water is expressed as [40];

$$\eta_o = \frac{\sum m_{ew} \times h_{fg} + \sum q_u}{\sum A \times I(t)} \tag{29}$$

3.3. Film cooling

Energy balance for water in the film cooling is expressed as [41,42]

$$m_f C_{pf} (dT_f/dt) = m_{rf}(C_{p1} T_{f1} - C_{p2} T_{f2}) + Q_{cf} - Q_{ca} - Q_{rf} \tag{30}$$

where

$$T_f = \frac{T_{f1} + T_{f2}}{2} \tag{31}$$

It should be noted that the inlet and exit temperatures of cooling water are required for the energy equation of the water film cooling.

The heat rate transferred from the glass to the water film cooling [41,42]

$$Q_{cf} = h_{cf} A_g (T_g - T_f) \tag{32}$$

where

$$h_{cf} = \frac{K_f}{L} \times Re_L^{1/2} \times Pr_f^{1/3} \quad \text{If } Re_L \leqslant 5 \times 10^5 \tag{33}$$

$$h_{cf} = \frac{K_f}{L} \times \left(0.037 Re_L^{4/5} - 871\right) \times Pr_f^{1/3} \quad \text{If } Re_L \succ 5 \times 10^5 \tag{34}$$

where

$$Re_L = \frac{\rho_f L V_f}{\mu_f} \tag{35}$$

$$V_f = \frac{Vol_f}{\chi_f \times d} \tag{36}$$

The rate of heat transfer radiated from water film cooling to the sky is expressed as [40,41];

$$Q_{rf} = \varepsilon_f A_f \sigma [(T_f + 273)^4 - (T_{sky} + 273)^4] \tag{37}$$

The sky temperature is given by Ref. [37] in Eq. (15)

The convective heat transfer between film cooling and sky is expressed as [41,42],

$$Q_{ca} = h_{ca} A_g (T_f - T_{sky}) \tag{38}$$

and h_{ca} is given by [39] in Eq. (17).

The basin liner and glass cover temperatures are assumed to be equal to the environmental temperature during the first iteration of the developed mathematical model for conventional and wick stills. In addition, the saline water temperature is taken as 70 °C for the wick still while it is taken as the ambient temperature for the conventional still. The increase of basin plate temperature (dT_b), basin water temperature (dT_w) and glass cover temperature (dT_g) are calculated by solving Eq. (1)–(3), (20) and (30) of conventional solar still. The authors used the first order backward difference formula to solve the equations numerically. The time interval of each step is 1 s. For the next solution iteration, the parameters would be calculated as follows

$$T_b = T_b + dT_b$$

$$T_w = T_w + dT_w$$

$$T_g = T_g + dT_g$$

$$T_{f2} = T_{f2} + dT_f$$

To be transferred to the applicable conditions, solar radiation I (t) and environmental temperature (T_a) are recorded at various days from 8 am to 18 pm in the period from July to August 2015 at the School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, China. Depending upon the weather conditions, the environmental temperature is varied from 26 to 35 °C and the wind speed is varied from 0.1 to 5 m/s during different days and solar radiation is varied from 20 to 880 W/m^2. The average values of insulation and environmental temperature are utilized. The physical parameters that employed in the mathematical model calculations are illustrated in Table 1. The physical parameters involved are taken as that of Ref. [42].

4. Partial validation and verification of present work

The numerical code was checked and was found to be valid for wide range of time steps and different metrological parameters with measurement uncertainties. To verify our proposed method (first order backward difference formula) which used to solve the equations numerically, we compared its results with the results obtained by Omara et al. [28] at the same operating conditions. It was found that both results were agreed. This present work is partially validated with Ref. [28] for the working part of wick only because there is no work compromising the wick with film cooling. Omara et al. [28] studied mathematically and experimentally the performance evaluation of a new hybrid desalination system using wicks/solar still and evacuated solar water heater. Fig. 3 presents a comparison between the present theoretical work of wick solar still and that of Ref. [28]. The output results for hourly productivity of wick solar still show a good agreement between the two works. On the other hand, Fig. 4 shows agreement to a great extent between the present theoretical work for CSS and experimental work by Omara et al. [28]. The obtained theoretical gain by introducing a wick solar still desalination system fed by rejected warm water from HDH unit is obtained to be lower in reality due to losses.

Table 1
Physical parameters used in the mathematical calculations [42].

Item	Specific heat (J/kg K)	Absorptivity	Emissivity	Initial temperature (°C)
Saline water	4190	0.05	0.96	70
Glass cover	840	0.05	0.85	26
Basin plate	460	0.95	–	26

Latent heat at h_{fg} = 2,335,000 J/kg.

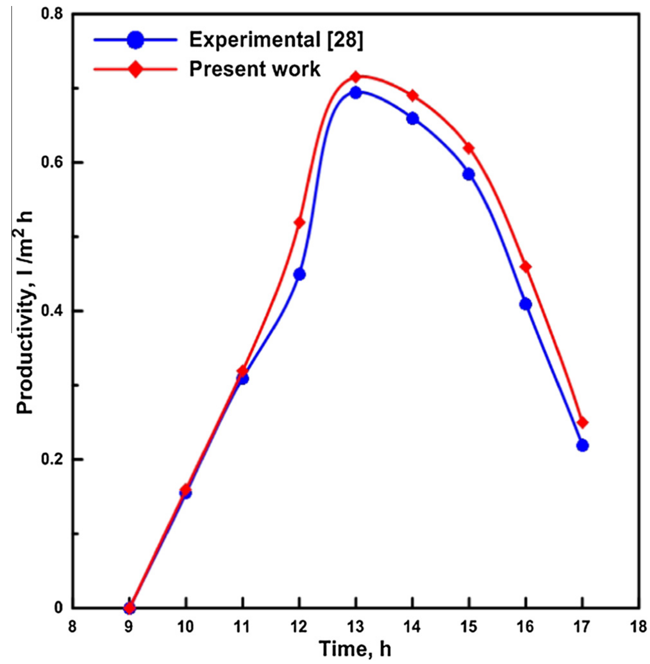

Fig. 3. Comparison between the present work wick solar still and Omara et al. [28] of hourly productivity.

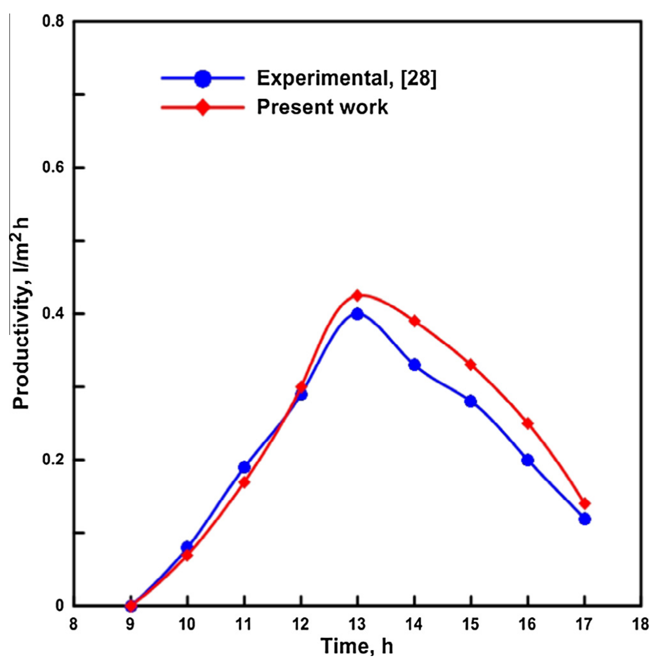

Fig. 4. Comparison between the present work and Omara et al. [28] of hourly productivity for conventional solar still.

5. Results and discussion

5.1. Effect of solar intensity on the solar still performance

Fig. 5 shows the variation of solar intensity, basin plate temperature, water temperature and outside glass temperature for conventional still and wick solar still fed by rejected warm water from HDH with and without film cooling. The figure shows temperature changes for the solar stills, which means that the maximum temperature was maintained for several hours between

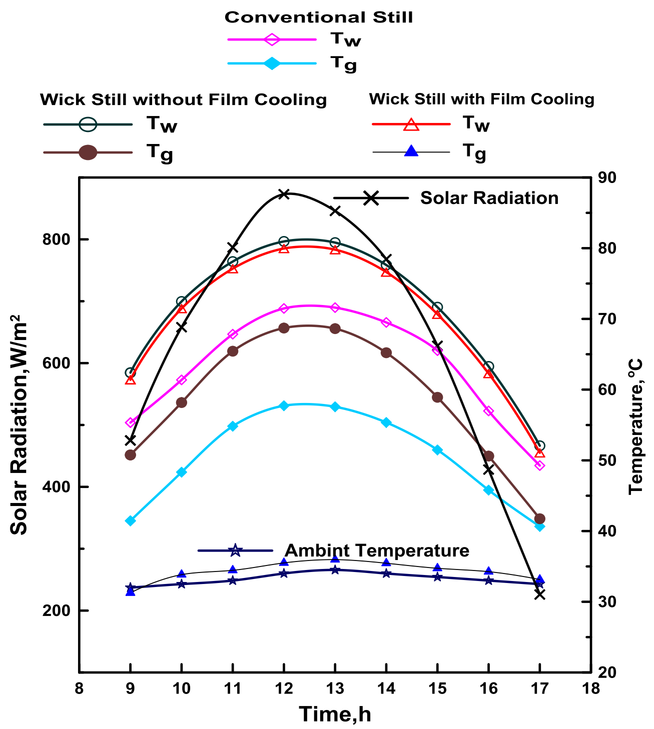

Fig. 5. Hourly temperature variation and solar radiation for solar stills.

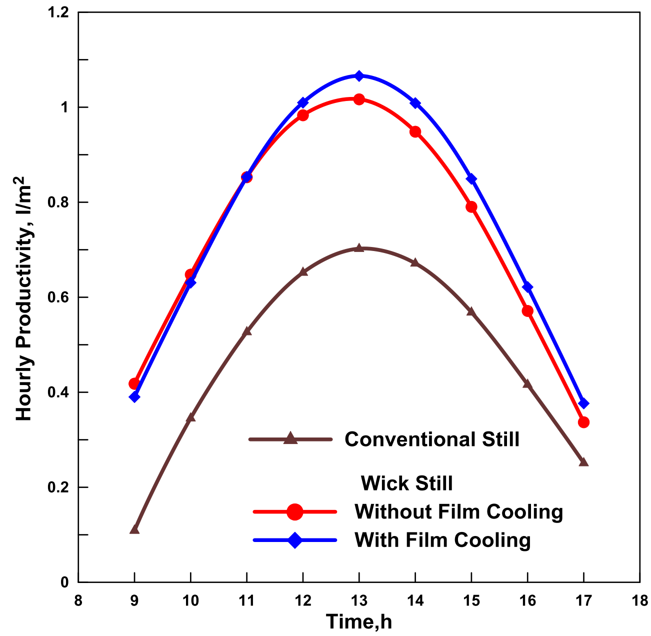

Fig. 6. The variation of fresh water productivity for the wick solar still with rejected water from HDH and the conventional solar still during the daytime.

11 am up to 3 pm. In addition, during the period from 8 am to 1 pm, the solar intensity increases the temperatures of all system components. After that, the solar intensity is noticed to be decreased with time, and as a result of that, the temperatures begin to decrease. The productivity of the solar still is maxima at mid-noon because the solar intensity is maxima at this time. Therefore, the ambient, still glass, and water temperatures are also maximum, and hence the solar still performance has its highest values at this time. Using hot water gave better performance because this hot water enhances energy input to the wick solar still with and without film cooling fed by rejected water from HDH. The results indicated that, the glass and water temperatures of wick still with and without film cooling are higher than that of conventional type. Consequently, the evaporation and condensation rates in wick solar stills with and without film cooling were increased.

As a result of that, the glass cover temperature is increased and this has a bad effect on the productivity because the condensation rate is decreased. To get the glass temperature down again to increase the water-glass temperature difference, cold water flowing on the glass should be used. Therefore, using the cooling film over the glass cover has a positive effect for the productivity. In addition, the system efficiency is increased as a result of glass cover continuous cleaning from dirt and other types of filth because of cooling water film.

Also from Fig. 5, it can be seen that the glass covers temperature of wick still with film cooling decreases lower than that of conventional still by about 6–20 °C due to cooling of wick still glass cover. Results indicate that the difference between the basin water and glass cover temperatures for wick still increases with cooling by about 45 °C, and about 17 °C for wick still without film cooling.

5.2. Hourly water productivity for solar stills during the daytime

A theoretical comparison between the average hourly variation of freshwater productivity for wick solar stills with and without film cooling and conventional still is illustrated in Fig. 6. From the figure, it is found that the average maximum freshwater productivity has its maximum values at noon for the current solar distillation systems. In addition, it can be obtained from the figure that the water output productivities are changed from minimum to maximum values with time from the morning to noon respectively. Besides, the higher water distillate output is observed in wick still with film cooling compared with conventional still and wick still without film cooling. This is due to high temperature deference between the water and glass temperatures due to wick still with and without film cooling at all times and does not need time to warm up therefore, the film cooling decreases the temperature of the glass which increases the rate of water vapor condensation on the inner side of the glass and consequently increases the distillate yield but low temperature of water in the conventional still in the early morning and water needs more time to warm up. In addition, it can be seen that the maximum productivity occurs at maximum temperature of saline water.

Fig. 6 shows that the variation of the hourly solar still distillate yield to daytime for wick still with and without film cooling. Water productivity reaches 0.109, 0.39 and 0.42 L/m^2 h in the early mornings, reaching up to 0.7, 1.066 and 1.016 L/m^2 h as a maximum productivity at noon for conventional still and for wick still with and without film cooling, respectively. Consequently, at mid-noon period, the solar still has minimal thermal losses, and hence the performance is improved proportionally.

5.3. Water productivity during the daytime from solar stills

Fig. 7 shows a theoretical comparison between the average hourly accumulative variations of fresh water productivity from 9 am to 17 pm. It is found that the amount of accumulated distillate for wick solar still with and without film cooling is higher than that of conventional solar still at all times, where the average hourly freshwater productivity is higher for wick still with and without film cooling. In addition, the distillate reaches 6.85, 6.5 and 4.2 L/daytime, for wick still with and without film cooling and conventional still, respectively. In this case, the increase in distillate production for wick solar still with and without film cooling is 63.1% and 54.76% higher than that for conventional type. The

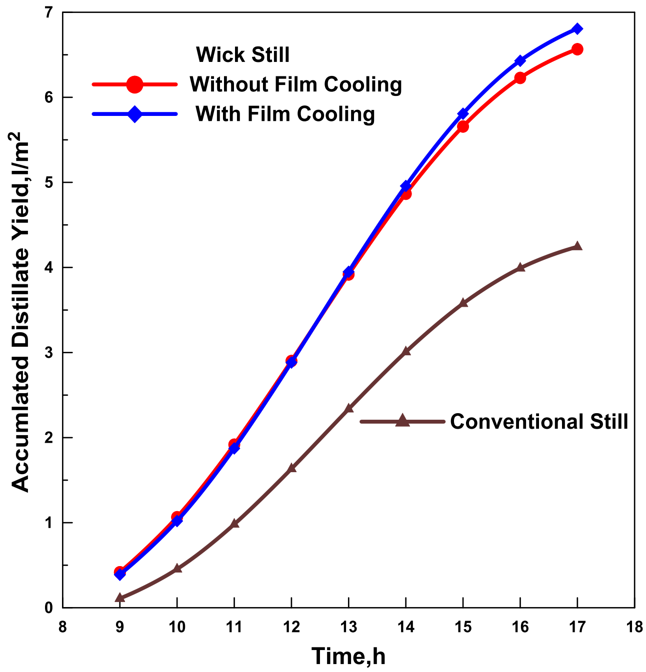

Fig. 7. The accumulative variation of fresh water for the wick solar still feed by rejected water from HDH and the conventional solar still during the daytime.

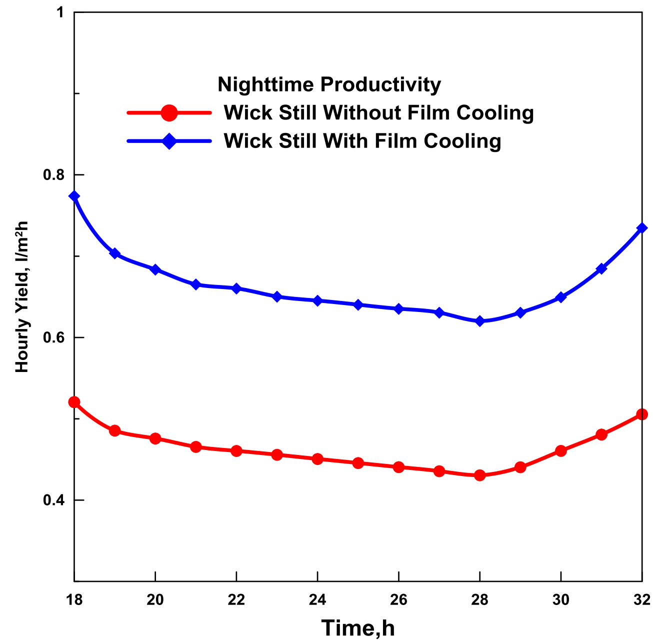

Fig. 8. The hourly productivity during the nighttime from wick solar still fed by rejected water from HDH with and without film cooling.

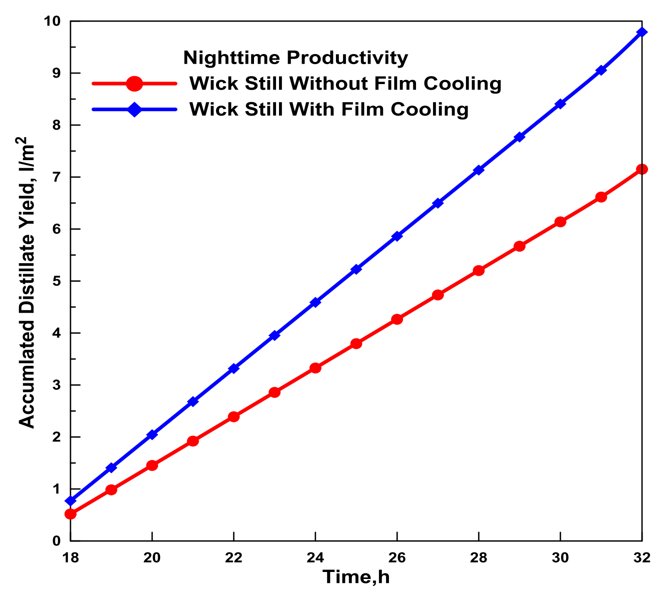

Fig. 9. The accumulated productivity during the nighttime from wick solar still fed by rejected water from HDH with and without film cooling.

effect of film cooling during the daytime for wick solar still is only about 5.38%.

5.4. Effect of feeding rejected water from HDH during nighttime on the solar stills productivity

The use of nighttime production in the solar still as in [36,37] causes a great enhancement in the configuration of standard solar still. Isolated storage tank has been used to feed water to the wick solar still with and without film cooling during nighttime. Fig. 8 illustrates the average prediction of the alteration of fresh water productivity per hour from wick solar still with and without film cooling during nighttime at inlet water temperatures of about 70 °C. The ambient air temperature is in the range of 26–35 °C, whereas wind velocity is in the range of 0.1–5 m/s during the average measurement day. During the early hours of the night, productivity decreases gradually because of the decrease of surrounding air temperature and increase of temperature difference between the wick still and the surrounds and more heat losses. On the other hand, the first hours of the second day cause an increase in the productivity due to sunrise and decrease the temperature difference between the still and surrounds and decrease heat losses.

Fig. 9 shows the accumulative productivity of fresh water per hour from 18 pm to 32 am. The distillate reaches 0.2, 9.8 and 7.153 L/nighttime for conventional still and for wick solar still with and without film cooling. It is found that the productivity during the nighttime of the wick solar still with film cooling is increased by approximately 30% as compared to the wick solar still without film cooling.

5.5. Effect of feed water flow rate on wick solar still productivity

Variation of water distillate productivity of wick solar still with and without film cooling with feed water flow rate during day and night times is obtained in Figs. 10 and 11. The effect of feed water flow rate on the wick still productivity was investigated over the range from (0–0.01 L/s as tabulated in Table 2) through the daytime as shown in Fig. 10. As mentioned before, there is a datum for the zero flow rate, and this datum means the highest point in the feed water tank inside the solar still. This zero point can be explained by the water rate flowing because of the capillary effect. It can be seen from the figure that the productivity of wick solar still is decreased when the flow of water is increased. The water yield is decreased because the water is flowing over the wick with higher velocity than that when operating under the capillary effect conditions. Thus, less evaporation rate is resulted, and hence, lower productivity is achieved.

It is obtained from Fig. 10 that when using the cooling film, the water productivity is increased. This is because the water flowing over the glass cover decreases its temperature and hence, the temperature difference between water and glass is increased and

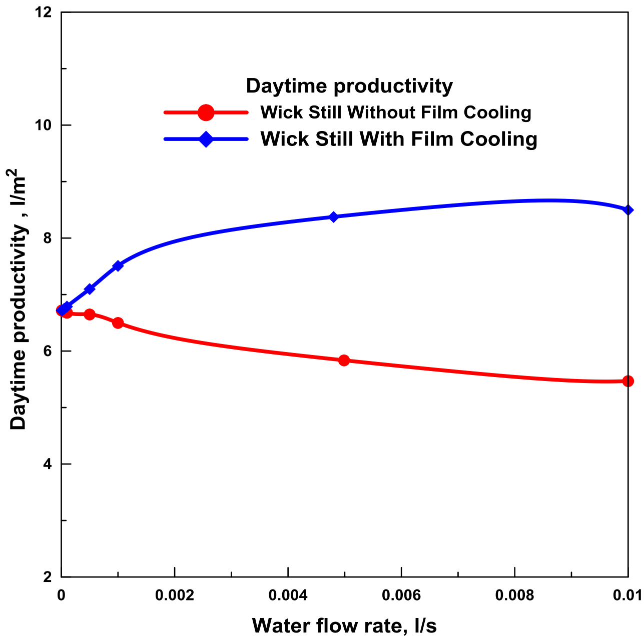

Fig. 10. Variation of water productivity of wick solar still with and without cooling film with feed water flow rate during day time.

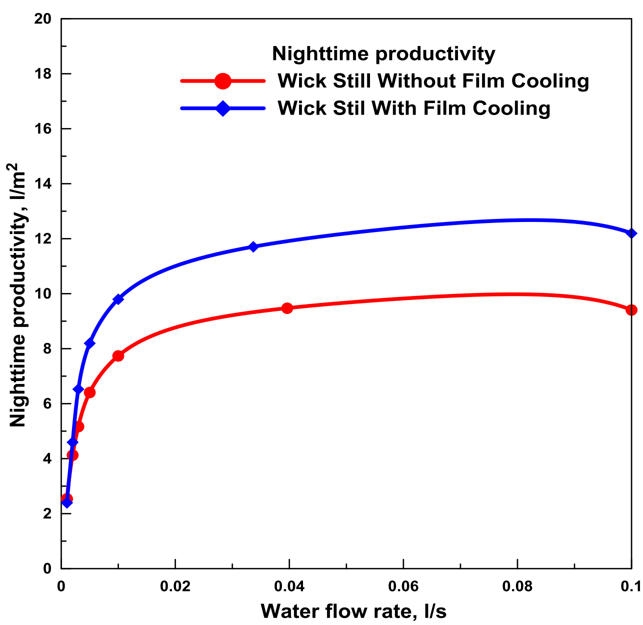

Fig. 11. Variation of water productivity of wick solar still with and without cooling film with feed water flow rate during nighttime.

Table 2
Range of parameters values used in the mathematical calculations.

Item		Range value
Water flow rate (L/s)	Daytime	0–0.01
	Nighttime	0–0.1
Ambient air velocity (m/s)		0.1–5
Glass cooling flow rate (L/s)		0–1e–4

therefore, the productivity is increased. In addition, it is illustrated from the figure that the water productivity is going to be constant when the water flow rate is more than 5×10^{-3} L/s.

The effect of feed water flow rate on the wick solar still productivity was investigated over the range from ($0–1 \times 10^{-1}$ L/s as tabulated in Table 2) through the nighttime as shown in Fig. 11. It is obtained from the figure that the water productivity is increased for both with and without cooling film. But, when using the cooling film, the water distillate yield is higher than that without water cooling film. This difference is occurred because the feed water temperature is constant (about 70 °C), hence, the evaporation rates inside the investigated solar stills are approximately equal. So, when using the cooling film, the water-glass temperature difference is bigger than that for the wick solar still without cooling film. Therefore, the productivity of distillate water is higher for the wick solar still with film cooling than that for without film cooling through the nighttime. In addition, it is illustrated from the figure that the water productivity is going to be constant when the water flow rate is more than 4×10^{-2} L/s.

5.6. Effect of cooling film flow rate on the wick solar still productivity

Distribution of day and night productivities as a function of film cooling flow rate for wick and conventional stills is illustrated in Figs. 12 and 13. It can be seen from the figure that when increasing the film cooling flow rate, the daily productivity increases. When the film cooling flow rate increases with keeping constant thickness, its speed growths gradually. Therefore, the convective heat transfer coefficient between the glass and the film cooling is improved and thus, the glass temperature is decreased well and consequently, the productivity is increased. In addition, the thermal heat capacity of cooling water would reduce the glass temperature and hence help to increase the distillate yield. Moreover, it is shown from Figs. 12 and 13 that the water productivity is going to be constant when the film cooling flow rate is more than 1×10^{-4} m^3/s for both day and night times. The distilled yield of the wick solar still when using the glass film cooling is more than that without film cooling by about 5.38%, 30% for day and night times respectively. The big difference in productivity between that of day and night times when using the glass cooling film is occurred because, at the night time, the glass temperature is more decreased with film cooling that for the day time, hence, the

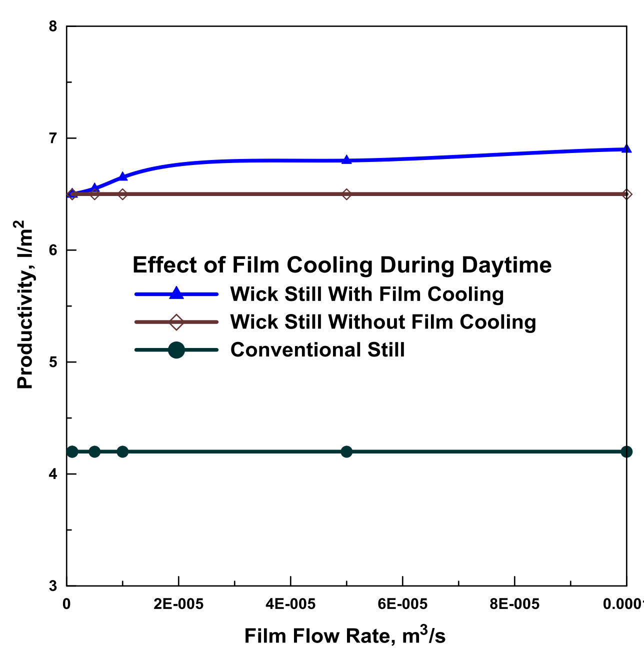

Fig. 12. Variation of the solar still distillate daily productivity with water film cooling flow rate during the daytime.

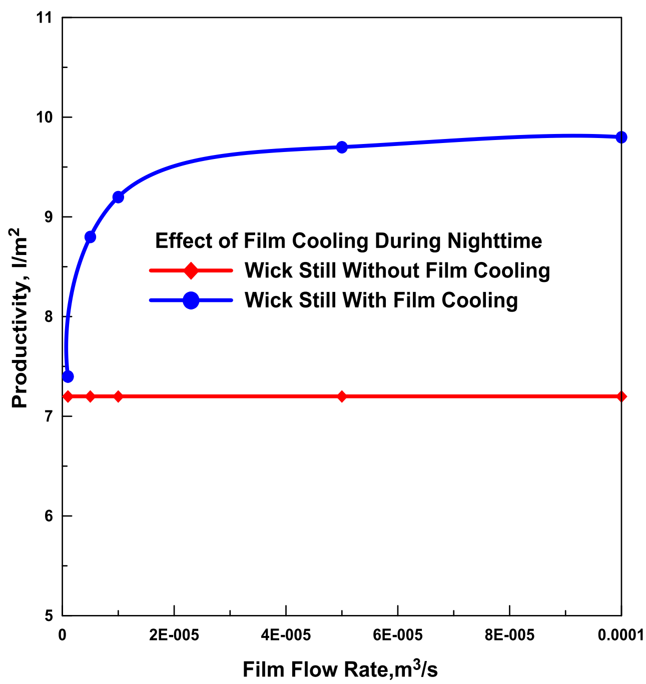

Fig. 13. Variation of the solar still distillate daily productivity with water film cooling volumetric flow rate during the nighttime.

water-glass temperature difference for the night time is higher than that for the day time, and therefore, the productivity of the wick solar still with film cooling through the night time 30% is higher than that for the day time 5.38%.

6. Conclusions

Performances of a wick solar still desalination system fed by rejected warm water from HDH unit with and without film cooling have been studied theoretically. To efficiently increase the fresh-water productivity, wick solar still should operate with rejected water from HDH unit. Daytime and nighttime productivities of the desalination system are also investigated.

The results analyses from the theoretical simulation obtained the following conclusions:

- The productivity when using film cooling is more than that without film cooling by about 5.38%, 30% for day and night times respectively.
- The average output productivities during the day-time are 4.2, 6.85, and 6.5 L/m^2 for conventional and wick still with and without film cooling respectively. While, during the nighttime, the productivities are 0.2, 9.8, and 7.15 L/m^2 for conventional and wick still with and without film cooling respectively.
- The productivity of the wick still with and without film cooling is higher than that of conventional basin by 278.4% and 210.22% respectively.

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