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Theoretical and experimental investigations on single slope solar still

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ABSTRACT

This study presents performance investigations of modified solar still placed under Jordan Mediterranean climate conditions. The effect of the condenser surface area on solar still productivity at different basin water depth has been analyzed. The effect of wind speed on solar still performance has been studied. An accurate theoretical model of the thermal behavior of solar still is developed. The highly complex behavior of the solar still is accurately described by the developed mathematical model. A numerical technique (Runge–Kutta method) is used to solve the non-linear system of differential equations. The water temperature, glass temperature, heat transfer coefficients, and productivity of the still have been analyzed. The present theoretical study is compared against experimental work and found in good agreement. The results show that solar still performance is inversely proportional to the saline water depth. Moreover, it is found that the effect of the condenser surface area depends on the water depth. Furthermore, the results show that there is a critical depth of water (2.5 cm) beyond which the productivity of solar still increases as wind speed increases until a specific value of wind speed (8 m/s) beyond which the effect of wind speed becomes insignificant. On the other hand, as basin water depth decrease than the critical depth, it is found that the productivity still decreases as wind speed increase until a specific value of wind speed (8 m/s) beyond which the effect of wind speed becomes insignificant. Also, the results show that decreasing basin water depth from 8 to 0.5 cm, the daily distillate output increases from 2,620 to 4,211 g/m^2/d respectively at 0 wind speed.

Keywords: Solar still; Water distillation; Wind speed; Condensation surface area; Theoretical modeling

1. Introduction

Production of freshwater is still a major challenge in several parts of the world, especially in the Middle East and North Africa [1]. Population growth and accelerated urbanization are the two main factors that placing pressure on the demand for freshwater. Desalination technologies are considered an attractive solution to meet this large demand growth of freshwater. Conventional desalination technologies that depend on fossil fuels have high performance, but the fossil fuel resources in the world are finite and are harmful to the environment. This has led to a search for alternative desalination processes that depend on renewable energy sources. Desalination technologies driven by solar energy systems are a good choice in regions that have high levels of solar radiation [2].

The daily production of solar still depends on several factors such as climatic conditions (solar radiation intensity, ambient temperature, and wind speed), condensation surface inclination, insulation type and thickness, solar still geometry, the orientation of still and depth of salty water. The daily production of distillate in single slope solar still is still not acceptable, ranging between 1,500–3,000 g/m^2/d. Significant research has been conducted aiming to increase the productivity of such systems [3–15]. It is found that the two main approaches for enhancing productivity are;

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increasing basin water temperature and lowering the condensation glass cover temperature. Reducing thermal losses by careful selection of insulation thickness and insulation material found to be an effective strategy for enhancing productivity [8,9]. Moreover, increasing the basin temperature by incorporating auxiliary low-quality external heating source has a remarkable effect on system efficiency. This heat source could be from the waste heat recovery system. Furthermore, wind speed has a positive effect on the productivity of the solar still. This due to the fact that increasing wind speed leads to increase convective heat losses at the condensation surface and which results in decrease temperature of the glass cover plate. It is worth mentioning that the experimental study conducted by El-Sebaii et al. [10] concluded that the productivity still increases with increasing wind speed up to a particular value (10 and 8 m/s in summer and winter respectively) past that, the wind speed becomes insignificant. Kabeel et al. [11] used a mathematical model to investigate the effect of utilizing a different type of phase change materials (PCM) to enhance solar still performance [11]. The theoretical results showed that the A48 type of PCM has the highest increase in efficiency reach up to 92%. Al-Harahsheh et al. [12] conducted an experimental study on single slope solar still integrated with PCM connected with a solar water collector to enhance basin water temperature of solar still. The results of the experiment showed that the daily distillate output increased with the increasing flow rate of hot water, where the daily distillate output reached up to 4.3 $kg/m^2/d$ at 30 ml/s hot water flow. Fathy et al. [13] investigated the effect of basin water temperature of double slope solar still when coupling with fixed and tracked parabolic trough collector (PTC) [13]. The experimental results showed that the daily distillate outputs are 4.51 and 2.31 kg/m^2 for conventional solar still (CSS), 8.53 and 4.03 kg/m^2 for solar still with fixed PTC, and 10.93 and 5.11 kg/m^2 for solar still with tracked PTC in the summer and winter season respectively at 0.02 m saline water depth. Pounraj et al. [14] designed a sustainable hybrid PV/T active solar still system to improve the performance of solar still. Their results showed that the efficiency of the proposed system is increased by 30%. Samuel Hansen et al. [15] enhanced solar still productivity by using a fin-shaped absorber configuration. Their results showed that solar still efficiency increased by 25.75%. Omara et al. [16] integrated fan inside solar still operated by the wind turbine to increase convection heat transfer with different water depth. The experimental results concluded that the daily productivity of still is enhanced by 17% at 3 cm and 30 rpm. Bhardwaj et al. [17] examined the effect of decreasing condensation temperature using the external fan on the solar distillation device. They found out that the productivity of solar still is increased from 0.020 to 0.110 kg due to decrease condenser temperature from 42°C to 13°C. El-Bahi and Inan [18] studied the performance of solar still when separate condenser about the evaporator. Their results showed that the efficiency is increased from 48% to more than 70% when the condenser cover is cooled down. Furthermore, El-Sebaii et al. [10] conducted a set of experiments to study the effect of wind speed on water yield. They found out that the productivity of solar still increased with increasing wind speed up to a particular value (10 and 8 m/s in summer and winter respectively, past that the increase in wind speed becomes inefficient. Applying the flow of cooling water film over the condensation surface of solar still has increased performance by 20% [19]. Using internal and external sunlight radiation reflectors has improved the performance and efficiency of solar still with little effect during the summer period [5]. It has been reported that the productivity of solar still increases with decreasing water depth [20]. Tiwari et al. [21] found out that the optimal inclination angle depends on the season and latitude angle of the solar still location. For example, they found out that the productivity of solar still in India region increases with increasing inclination angle in winter and vice-versa in summer. Feilizadeh et al. [22] studied the effect of solar still shape. It was concluded that the optimal width to length ratio is 0.4. Saadi et al. [23] examined the effect of integrating a multi-tray evaporator on the rear wall of solar still to increase the water area. It was found that the productivity of the proposed solar still is increased by about 47.18%–104.73%. Madhlopa and Johnstone [24] found out that utilizing multi evaporators and multi condensers have improved the solar still performance by 62%.

The main objective of this study is to theoretically investigate the effect of increase condenser surface area, wind speed, at effect basin water depth on solar still yield under Jordan climatic conditions (32° 28′ 26.39 N latitude and 35° 59′ 3.59 E longitude). An accurate mathematical model allows a deeper understanding of the main involved physical processes. The developed mathematical model will be used to determine the basin water temperature, glass cover temperature, heat transfer coefficients, and daily water distilled of the proposed solar still and compared with a conventional one.

2. Theoretical modeling

Mathematical model development for the modified solar still is presented in this section. This model is used to describe the basin liner temperature, basin water temperature, and glass cover temperature to fully understand the complex behavior of solar still. Solar still mainly consists of a condensation glass cover, basin liner water, and collecting channels as shown in Fig. 1. Collecting the evaporated water (distilled) by condensing it on a cool sloping surface

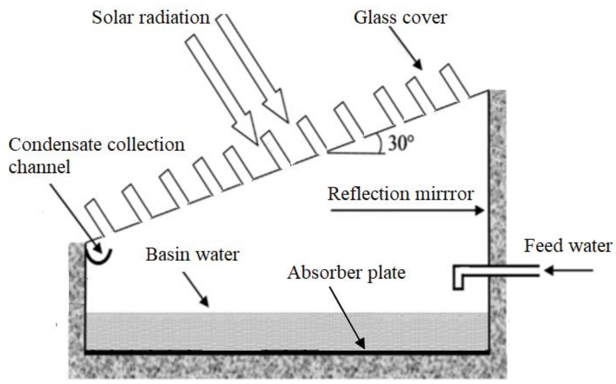

Fig. 1. Schematic diagram of modified solar still (changing the condenser area).

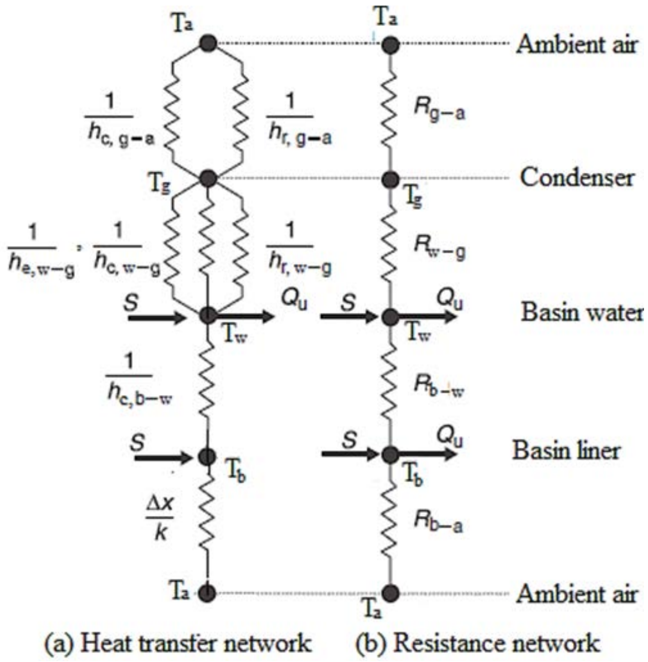

Fig. 2. The thermal network of single slope solar still.

is the basic working principle of solar still. The saline water in the black painted basin liner is heated by the transmitted solar radiation that has been absorbed by the basin liner. In this technique, the basin and the salty water are acting as an evaporator, while the glass surface acting as a condenser. The bottom and all side-walls of the basin liner are well insulated. The wind speed can be easily varied by using a variable speed fan placed next to the solar still. The condenser area can be varied as shown in Fig. 1. All solar radiation fell on the basin liner of solar still is release by convection to the basin water and by conduction to the ambient. Moreover, heat is transferred from basin water of the still to the condenser by convection, radiation, and evaporation. Furthermore, all heat reached to the condenser is lost by convection, and radiation to the ambient and sky respectively as shown in Fig. 2.

The detailed description of the main energy balance equations for basin liner, basin water, and glass cover can be summarized in Table 1 [25–29]. The correlations for the main heat transfer coefficients are obtained from [25–29].

3. Experimental setup

In order to validate our mathematical model, the available pyramid solar still is used [30]. The experiments have been carried out at the Jordan University of Science and Technology Campus located in Irbid, Jordan (latitude 31.9° North, longitude 35.9° East). A photograph of the experimental setup is displayed in Fig. 3. The solar still consists of a glass cover, internal galvanized iron sheet, insulation, and an external galvanized iron sheet. The glass cover has a thickness of 4 mm, each glass plate of the glass cover has a width of 60 cm, a height of 25 cm, and a sloping angle of 20°. The 1.25 mm-thick internal galvanized iron sheets

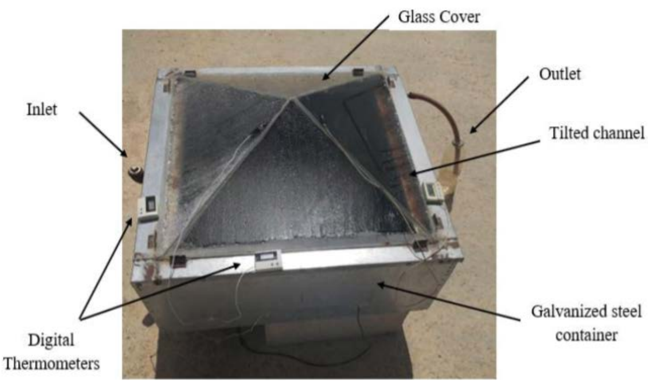

Fig. 3. Solar still that used in the validation.

were compound together forming a closed box with a base area (absorber area) of 0.36 m^2 (0.6 m × 0.6 m), and a height of 25 cm. Furthermore, the 0.9 mm-thick external galvanized iron sheets were compound together forming the outer surface with a base area of 0.49 m^2 (0.7 m × 0.7 m), and a height of 25 cm. and between them, there is 5 cm polystyrene insulation.

4. Numerical solution

The previously presented mathematical model was numerically solved to investigate the effect of key factors affecting the solar still performance. The system of non-linear differential equations for the thermal model described previously contains 3 variables and 3 derivatives. The best method for solving this system of equations is the Runge–Kutta fourth-order method known as rk4. These equations can be formulated as an initial value problem. The initial values of the variables are known and the integration is performed time step equal to 1 s. The unknown variables T_b, T_g, T_w, h_{e-g}, h_{r-g}, h_{c-g} and the quantity of distilled water productivity were evaluated per hour. Initial conditions corresponding to the main temperatures of the solar still were assumed to be equal to that of the ambient temperature at 8 A.M. Meteorological conditions (solar radiation, ambient temperature, and wind velocity) and their variation throughout the test day are introduced in the model as boundary conditions. The amount of water inside the solar still is assumed to remain constant. Using these values of temperatures; different heat transfer coefficients from base water to condensation surface and from condensation surface to ambient were calculated for a time interval (t = 1 s) as stated in the program.

5. Results and discussions

A detailed description of Jordan weather conditions can be found in Bataineh et al. [29]. Weather conditions data for the year 2018 is used in this study.

5.1. Model validation

The present mathematical work is compared against previously published experimental work of [16]. Omara

Table 1
Summary of the main equation describing a mathematical model for single sloped solar still [25–29]

$$\sum Q_{\text{in}} = \sum Q_{\text{out}}$$

$$I_t A_b \alpha_b \tau_g \tau_{\text{nf}} = m_b \text{cp}_b \frac{dT_b}{dt} + Q_{\text{cb-nf}} + Q_{\text{loss-ba}}$$

$$I_t A_{\text{nf}} \alpha_{\text{nf}} \tau_g + Q_{\text{cb-nf}} = m_{\text{nf}} \text{cp}_{\text{nf}} \frac{dT_{\text{nf}}}{dt} + Q_{\text{cnf-}g} + Q_{\text{enf-}g} + Q_{\text{rnf-}g} + Q_{\text{mw}}$$

$$I_t \; A_g \alpha_g + Q_{\text{cnf-}g} + Q_{\text{enf-}g} + Q_{\text{rnf-}g} = m_g \text{cp}_g \frac{dT_g}{dt} + Q_{\text{rg-sk}} + Q_{\text{cg-}a}$$

$$Q_{\text{cb-nf}} = h_{\text{cb-nf}} A_b \left(T_b - T_{\text{nf}}\right)$$

$$h_{\text{cb-nf}} = \text{Nu} \frac{K_{\text{nf}}}{\delta}$$

$$\text{Nu} = 0.54 \left(\text{Gr} \cdot \text{Pr}\right)^{0.25}$$

$$\text{Gr} = \left(\frac{gB\left(T_b - T_{\text{nf}}\right) \rho_{\text{nf}}^2 \delta^3}{\mu_{\text{nf}}^2} \right)$$

$$\text{Pr} = \left(\frac{\mu_{\text{nf}} \text{cp}_{\text{nf}}}{K_{\text{nf}}} \right)$$

$$Q_{\text{loss-ba}} = \frac{K_i}{L_i} A_b \left(T_b - T_a\right)$$

$$Q_{\text{cnf-}g} = h_{\text{cnf-}g} A_{\text{nf}} \left(T_{\text{nf}} - T_g\right)$$

$$h_{\text{cw-}g} = 0.884 A_w \left(\left(T_w - T_g\right) + \frac{\left(P_w - P_g\right)\left(T_w + 273.15\right)}{268,900 - P_w} \right)^{\frac{1}{3}}$$

$$P_w = \text{EXP}\left(25.317 - \frac{5,144}{\left(T_w + 273.15\right)} \right)$$

$$Q_{\text{rw-}g} = \sigma.\varepsilon_{\text{eff}} A_w \left(\left(T_w + 273.15\right)^4 - \left(T_g + 273.15\right)^4 \right)$$

$$\varepsilon_{\text{eff}} = \frac{1}{\left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1 \right)}$$

$$Q_{\text{ew-}g} = h_{\text{ew-}g} A_w \left(T_w - T_g\right)$$

$$h_{\text{ew-}g} = \frac{0.0162 h_{\text{cw-}g} \left(P_w - P_g\right)}{\left(T_w - T_g\right)}$$

$$Q_{\text{mw}} = m' \left(\text{cp}_w \cdot T_w - \text{cp}_a \cdot T_a \right)$$

$$Q_{\text{rg-sk}} = h_{\text{rg-sk}} A_g \left(T_g - T_{\text{sk}}\right)$$

$$h_{\text{rg-sk}} = \sigma \varepsilon_g A_g \left(\frac{\left(\left(T_g + 273.15\right)^4 - \left(T_{\text{sk}} + 273.15\right)^4 \right)}{\left(T_g - T_a\right)} \right)$$

$$T_{\text{sk}} = T_a - 6.0$$

$$\eta = \frac{\sum m' \cdot hfg}{\sum A_g I_t}$$

$$\text{cp}_{\text{bf}} = 4.217 - 0.0056 T_{\text{bf}} + 0.00129 T_{\text{bf}}^{1.5} - 0.000115 T_{\text{bf}}^2 + 4.149 \times 10^{-6} T_{\text{bf}}^{1.5}$$

$$K_{\text{bf}} = 0.565 + 0.00263 T_{\text{bf}} - 0.00015 T_{\text{bf}}^{1.5} - 1.515 \times 10^{-6} T_{\text{bf}}^2 - 0.00094 T_{\text{bf}}^{1.5}$$

$$\mu_{\text{bf}} = 2.414 \times 10^{-5} \times 10^{\frac{247.8}{\left(T_{\text{bf}} + 273\right) - 140}}$$

Table 2
Specifications of the experimental solar still

Solar still part	Specification
Basin	$\alpha_b = 0.90$
	A_b (m^2) = 0.36
	cp_b (J/kg K) = 460
Glass	Glass thickness (m) = 0.004
	$\alpha_g = 0.05$
	$\tau_g = 0.85$
	$\varepsilon_g = 0.88$
	A_g (m^2) = 0.4
	cp_g (J/kg K) = 840
	ρ_g (kg/m^3) = 2,500
	m (kg) = 10
Base fluid	$\alpha_w = 0.05$
	$\tau_w = 0.9$
	$\varepsilon_w = 0.96$
	A_w (m^2) = 0.36
	$hfgw$ (J/kg) = 2,350,000

et al. [16] built two single-sloped solar stills, namely, fan solar still (FSS) and CSS. They compared the performance of internal and external FSS against CSS. They presented a detailed description of their experimental works which allows simulating their CSS accurately. In order to validate our developed model, simulated cases are built according to the specification of the CSS of Omara et al. [16]. Comparison curves presented in Fig. 4 show that there are close matches between current theoretical predictions and previously published experimental work. Moreover, the numerical solution was also able to accurately predicts the hourly variations of both basin water temperature and glass temperature of tested stills.

The shadow effect of the side walls has a significant and negative impact and should be accurately determined. The CSS has lower output compared to the pyramid solar still due to the shadow of the side walls. The current mathematical model accurately calculates the solar radiation absorbed by the basin water and basin liner considering the solar path diagram and hourly variation of beam radiation falling on the tilted surfaces. To further check that our model accurately captures the solar radiation absorption and reflection, the available pyramid solar still described previously is simulated under typical Jordan weather conditions. Fig. 5 shows that our numerical model is capable of accurately include the effect of the shade of the side-walls and matches very well the experimental results for two consecutive days.

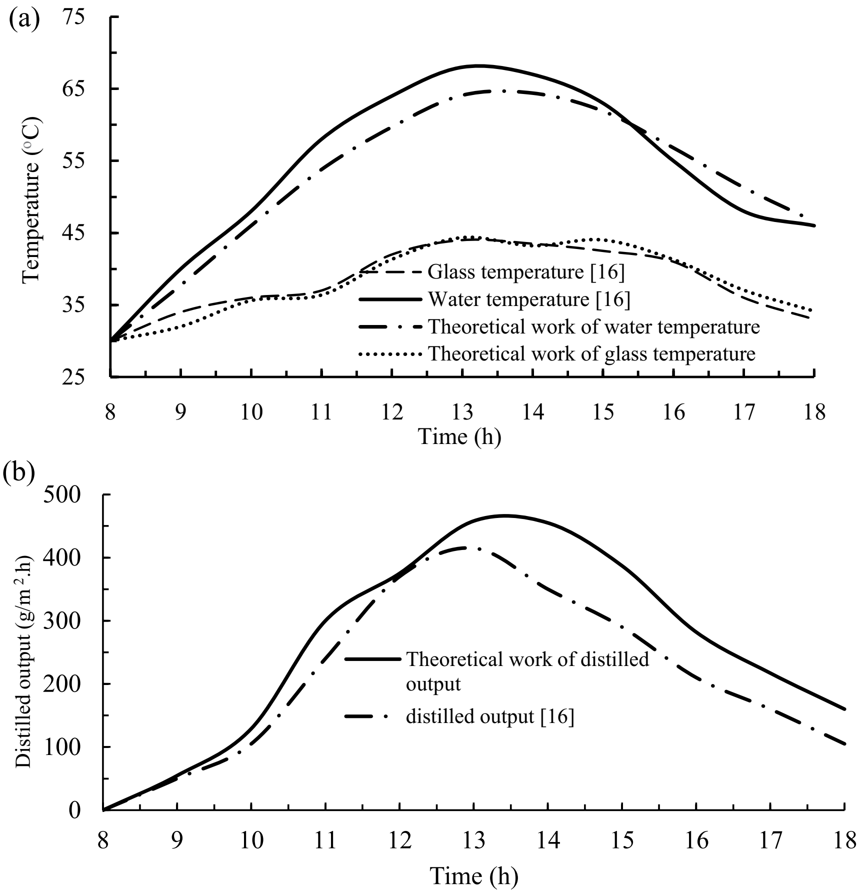

Fig. 4. Comparison between theoretical model predictions and experimental work [16], (a) temperature and (b) distillate output, single slope solar still.

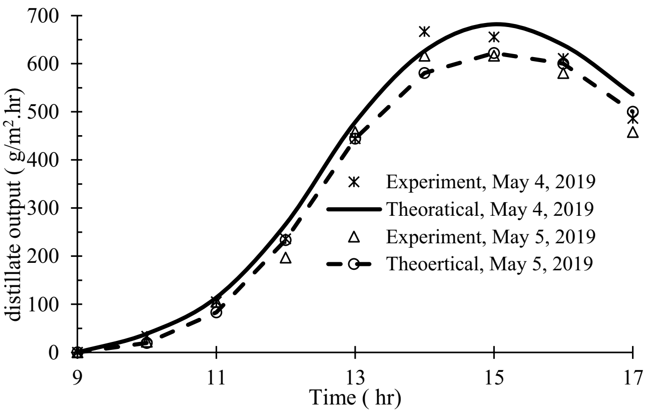

Fig. 5. Comparison between theoretical model predictions and experimental work under Jordan conditions, pyramid solar still.

5.2. *Effect of condenser surface area*

Decreasing glass cover temperature has a significant effect on enhancing solar still productivity. The glass cover area is increased by allowing a woven surface. Simulations results presented in Fig. 6 show that the glass cover area has a small effect on improving solar still efficiency at a certain water depth (2.5 cm). More specifically, the daily distillate output increases from 3,686 to 3,746.4 g/m^2 d when the glass cover area increased from 0.4 to 1.2 m^2. The reason behind this negligible increase can be explained by exploring curves presented in Fig. 7. Figs. 7a and b show that increasing the condensation area leads to a reduction in both glass cover temperature and water temperature respectively. This reduction can be clearly seen in Figs. 7c and d where thermal losses from both condensation and water temperature

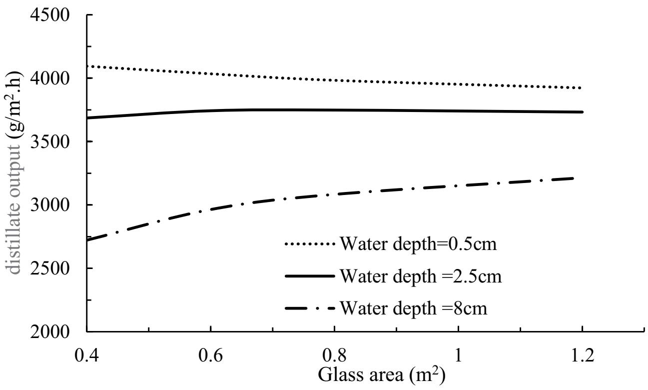

Fig. 6. Daily distillate output at different glass cover area.

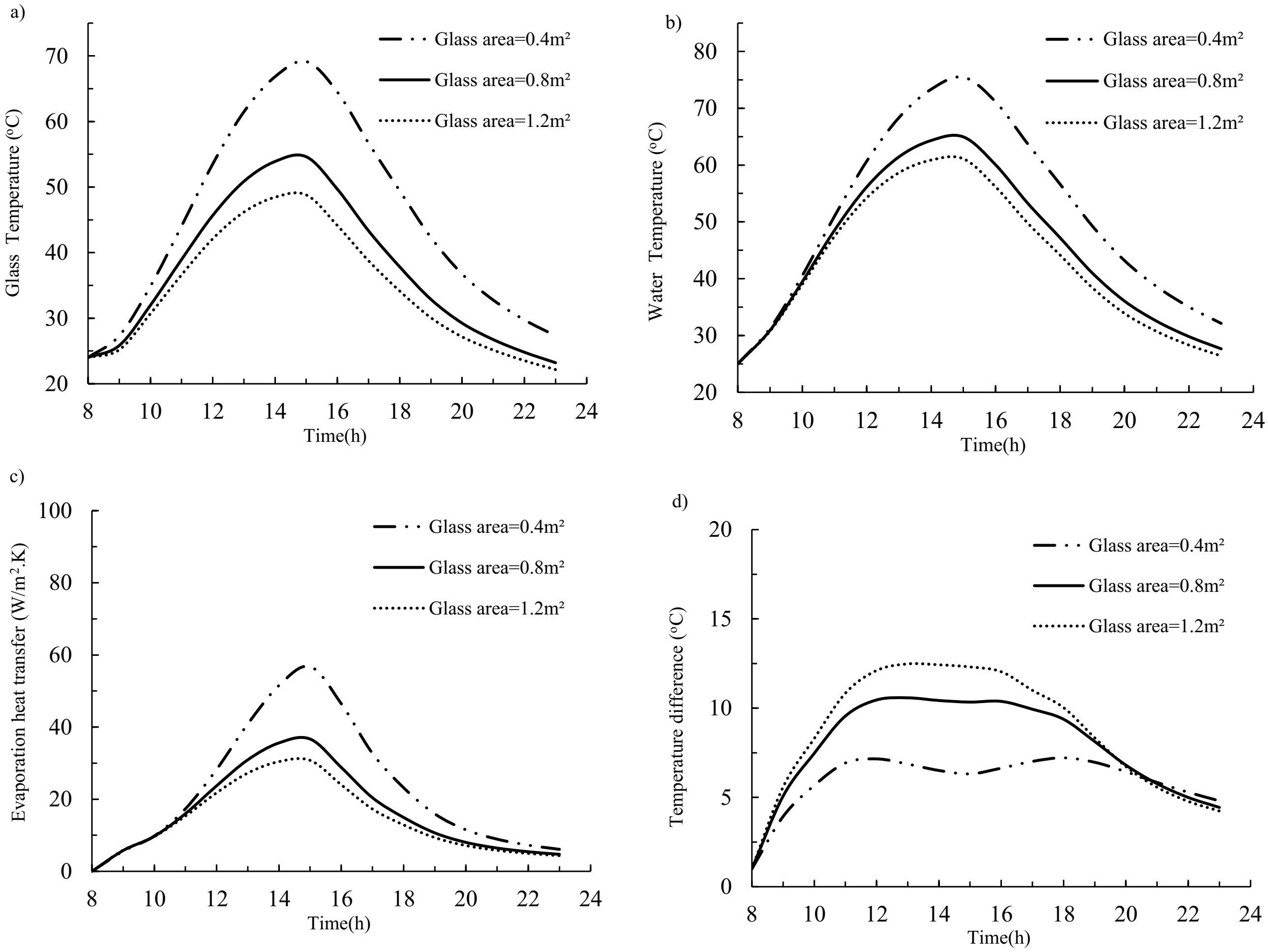

Fig. 7. Effect of condensation surface, (a) glass temperature, (b) basin water temperature, (c) evaporation heat transfer, and (d) temperature different temperature ($T_w - T_g$).

increase with increasing condensation area. The two main quantities that affect the solar still productivity are temperature difference between water and glass, and evaporative heat transfer. The temperature difference increases with increasing condensation surface area. However, this is accompanied by decreasing evaporative heat transfer which negatively affects the solar still performance. The two opposite behavior is responsible for the negligible effect of the condensation surface area of the daily distillate output at specific water depth. On the other hand, as basin water depth decrease than the critical depth, it is found that the productivity still decreases as condenser area increase until a specific value of area (0.8 m^2) beyond which the effect of increasing area becomes insignificant. Moreover, as basin water depth increase than the critical depth, it is found that the productivity still increase as condenser area increase until a specific value of area (0.8 m^2) beyond which the effect of increasing area becomes insignificant.

5.3. Effect of wind speed

Several simulation cases are performed to study the effect of wind speed on the daily output of solar still. It is worth mentioning that the literature regarding the effect of wind speed on solar still productivity has conflicting results. References [31–38] have reported that wind speed has a positive effect, while references [39–42] have reported that wind speed has a negative effect. While others have reported that wind speed has no significant effect [43]. Fig. 8 shows the effect of wind speed on the daily distillate output for several water depths. For water depth equals to 0.5 cm, the daily productivity decreases with wind speed up to a certain value of wind speed, beyond that, the effect becomes insignificant. On the other hand, for water depth equal to 8 cm, the wind speed has a positive effect on productivity up to a certain value, beyond that, the wind sped effect becomes negligible. For water depth equal to 2.5 cm, the wind speed has no significant effect on solar still productivity. These results can be explained through the investigation of water basin temperature and glass temperature, and evaporative heat transfer shown in Fig. 9 for water depth = 2.5 cm. The solar still productivity is directly proportional to both the temperature difference between glass and water and the rate of evaporation heat transfer. Although increasing wind speed leads to a decrease in glass cover temperature and but is accompanied by a reverse

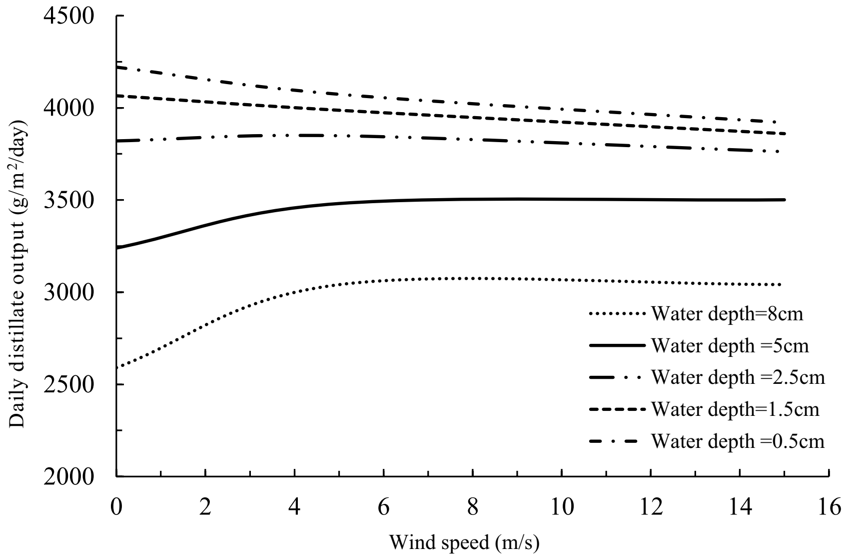

Fig. 8. Daily distillate output for solar still at different wind speeds and different water depths.

effect in saline water temperature (Fig. 9a). In other words, the thermal losses from both saline water and glass increase

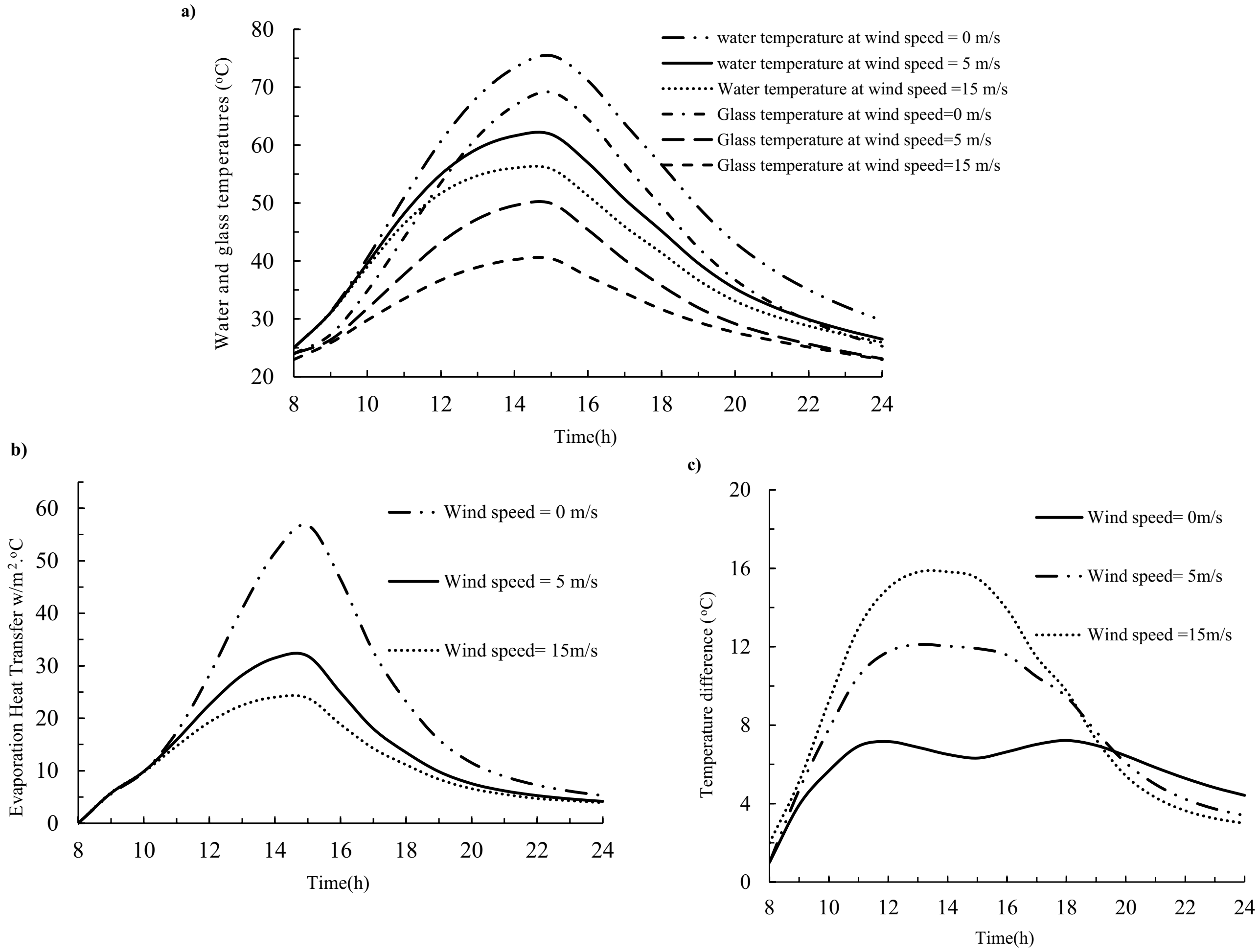

Fig. 9. Hourly variation of (a) glass temperature and water temperature, (b) evaporation heat transfer, and (c) different temperature ($T_w - T_g$).

with increasing wind speed. Increasing wind speed leads to more heat energy loss by convection from glass to ambient. As shown in Fig. 9b, the rate of evaporation heat transfer decreases with decreasing water temperature. Furthermore, the temperature difference between basin water and glass cover for different values of wind speed is shown in Fig. 9c. It is seen that as wind speed increases, the temperature difference increases during the period from mid-day until sunset after that, ($T_w - T_g$) dramatically decreases due to the increased heat losses due to the wind. Due to all the above, the product of temperature difference and evaporation heat transfer almost remains constant with wind speed variations at critical water depth.

6. Conclusions

An accurate mathematical model for the thermal behavior of solar still is developed. The model was validated against experimental work and found in very good agreement. The non-linear system of differential equations is numerically solved for a deeper understanding of the thermal behavior of solar still. The effect of condenser area and wind speed on solar still productivity has been experimentally and numerically analyzed. Moreover, the effect of basin water depth of a solar still ranging from 0.5 to 8 cm was theoretically investigated. The results are summarized as follows:

- Increasing condenser area has an insignificant effect on overall solar still productivity at certain basin water depth (2.5 cm).
- There is a critical depth of water (2.5 cm) in which the productivity of solar still remains constant with varying wind speed.
- Beyond the critical depth, the productivity of solar still increases with wind speed up to a certain value (8 m/s) beyond that leads to a negligible increase in productivity.
- Below the critical depth, it is found that the productivity still decreases with increasing wind speed until the specific value (8 m/s) beyond that, the effect of wind speed becomes insignificant.
- The productivity of solar still is the inversely proportional to depth of basin water. More specifically, the productivity of solar still reaches (4,211 g/m^2/d) at 0.5 cm while its productivity is (2,620 g/m^2/d) at 8 cm.

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Conflicts of interest

The authors declare no conflict of interest.

Symbols

A — Area, m^2
C_{pw} — Water specific heat, J/kg K
C_{pa} — Air specific heat, J/kg K
h — Heat transfer coefficient, W/m^2 K
h_{fg} — Enthalpy of evaporation, J/kg
I — Solar radiation, W
K_i — Thermal conductivity, W/m K
L_i — Thickness, m
m — Mass, kg
m' — Mass output, kg/s
P — Partial Pressure, Pa
Pr — Prandtl number
Q — Heat transfer, W
Ra — Rayleigh number
t — Time, s
T — Temperature, °C
V — Wind speed, m/s

Greek symbols

ε — Emissivity
α — Absorptivity
τ — Transmissivity
ε_{eff} — Water-glass effective emissivity
B — Thermal expansion coefficient
ρ — Density, kg/m^2
σ — Stefan–Boltzmann constant, W/m^2 K^4
δ — Characteristic length, m
μ — Dynamic viscosity, N/m^2 s
g — Gravity acceleration, m/s^2
η — Daily efficiency of the still

Subscripts

a — Ambient
b — Basin liner
bf — Base fluid
c — Convection
e — Evaporative
g — Condensation glass
m_w — Make up water
r — Radiative
sk — Sky
I — Solar radiation, W/m^2

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