Modeling of a new triangular shape solar distillation system integrated with solar PV panel and DC water heater

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ARTICLE INFO

ABSTRACT

A new triangular shape solar distillation system is fabricated using locally available materials by integrating with solar PV panel connected to DC water heater. It is designed for the first time to distill saline water or seawater using solar heat energy directly (to heat sample water) and indirectly (through water heater to heat sample water). The trough is made of Plexiglass and painted in black color which is placed inside the triangular frame made of UPVC pipe. The performance of the still is experimented in field. The diurnal variations of solar heat energy, distillate output, various temperatures and relative humidity are observed. A few linear proportional relationships are obtained between the sunlight heat energy and the productivity, between the ambient temperature and the productivity, and between the productivity and water-cover temperature difference. The production rate of the still is higher than the conventional one. An improved simulation model is proposed to estimate the productivity of the still as some previous simulation models cannot estimate the productivity of the solar still precisely. A few new factors are incorporated in the new model as these factors affect the distillate output of the solar still.

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Nomenclature

B	Width of trough (m)
D_v	molecular diffusion coefficient of water vapor (m^2/s)
g	Gravitational acceleration (9.807 m/s^2)
h_{ew}	Evaporative mass transfer coefficient from water to humid air (m/s)
K_o	Diffusion coefficient of the water vapor (kg/m.s. Pa)
m	mass (kg)
$\dot{m}_{ew}$Hourly productivity (kg)P	Hourly productivity (kg)PHourly production mass flux (kg/m^2/hr)
R_s	Solar radiation flux (W/m^2)
R_v	Specific gas constant of the water vapor (461.5 J/kg.K)
RH	Relative humidity (%)
t	time (s)
T	Temperature (K)
T_c	Cover temperature (°C)
T_a	Ambient temperature (°C)
T_{ha}	Humid air temperature (°C)
T_g	Glass temperature (°C)
T_w	Water temperature (°C)
W_h	Hourly evaporation mass flux (kg/m^2.hr)

1. Introduction

Potable water crisis is a common in remote, coastal and arid regions [1]. Therefore, desalination technologies are applied to get pure water from seawater. Solar distillation is categorized as active distillation and passive distillation. In passive distillation, the still only gets direct sunlight as heat energy and it shows that the water production is less. A huge number of passive solar still designs are reported, e.g. basin type double slope [2], hemispherical [3,4], tubular [5], pyramid [6], triangular solar stills [7] and cascade [8]. To increase the efficiency of a still, many active solar still designs are reported as well, e.g. solar still using PCM [9], photovoltaic system [10], asymmetrical still with different insulations [11] evacuated tubular collector integrated still [12], still with sun tracking arrangement [13], still integrated with external PVC pipe solar heater and internal separated condenser [14] and still with rubber scraper to enhance condensation rate [15].

Generally, three factors affect the production: climate, design and operating conditions. In climate, sunlight, wind and ambient temperature are the main factors. The design condition factor includes water depth, inclination of cover, selection of materials, insulation, the coating material and type of solar still, while operational condition mainly includes surfactant additives, water color & flow, and salt concentrations [16].

A number of researchers, e.g. Refs. [17–21] conducted experiments to monitor the effects of initial water levels in trough to the productivity of different designs (passive and active) of solar still. The distillate output increases with the decreasing the initial water level in trough. In active still, the productivity is higher than the passive one as the temperature difference between water and cover is high. If sunlight is absent then the productivity in still is almost halted [22].

The main design parameters affecting the productivity of a basic still in Suez Gulf area are investigated by Ref. [23]. In Bou Ismail, Algeria [24], observed that the distillate output of a double-slope plane solar still mainly depends on the sunlight heat energy. Many researchers (e.g. Refs. [25–27] studied on the effect of the sunlight heat energy on the distillate output of solar still. It is revealed that the main parameter affecting the production is the solar heat [28]. Many researchers concluded that the distillate output is proportional to sunlight heat energy. In addition, the productivity may depend on the temperature difference of cover-atmospheric and of water-cover [29,30]. [31] studied on still performance in different temperatures. However, the measured temperatures of cover and water are higher than the ambient temperature [32]. It is concluded that a bulk amount of pure water production with affordable cost is an issue. The water production cost of a complicated system is expensive and need to monitor consistently [33].

Due to the low cost and variety of output data, numerical studies are important. A few numerical analyses were studied on the evaporation and production rates of solar stills. In solar still [34], first proposed the basic heat and mass transfers theory [35]. The further theoretical improvements are made by many researchers (e.g. Refs. [2,35] and Ahsan and Fukuhara, 2010) to estimate the distillate output of solar stills. To determine the film coefficient [36], studied on numerical modelling of a single slope solar still. The findings were seen to be in good agreement with earlier research. Nanoparticles were used in a numerical study by Ref. [37] to examine the output of still. They applied the response surface methodology to assess sensitivity. Numerical and experimental research on the effects of partitioning on the functionality of solar stills were carried out by Ref. [38]. The vortexes' magnitude was reduced, their number was raised, and the mass and heat exchanges were improved by partitioning, which improves the overall efficiency of the still.

Various parameters were integrated in a CFD solar still model for stepped solar still by Ref. [39]. They examined the effects of the number of steps, the depth of the water, the cover angle, and the water-cover distance on the productivity of the still [40]. experimented in Khuzestan, Iran on single slope passive solar still and studied on numerical analysis of the evaporation and production rates

Table 1
Specifications of PHTSS.

	Items	PHTSS
Cover	Material	Polythene (thickness = 0.15 mm)
	Length (m)	2.00
	Width (m)	0.83
Trough	Material	Perspex (thickness = 10 mm)
	Length (m)	0.8
	Width (m)	0.2
	Height (m)	0.10
Frame	Material	PVC pipe (diameter = 15 mm)
	Length (m)	1.0
	Base length (m)	0.5
	Height (m)	0.43
	Material	PVC pipe & rope
	Assemble and setup of TSS	Easy
	Internal angle	60°
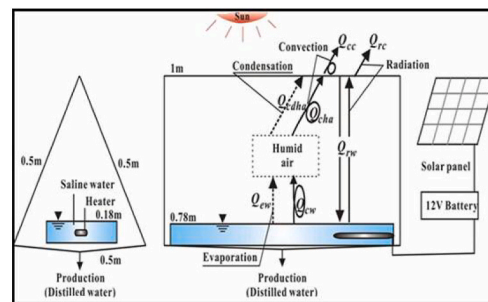
(a)
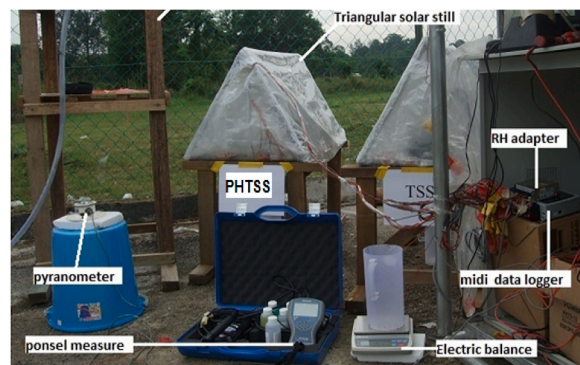
(b)

Fig. 1. Details of PHTSS (a) Schematic of PHTSS and (b) Photograph of PHTSS at field.

due to the high evaporation rate and drinking water requirements. The efficiency of the still and evaporation rates were influenced by a variety of variables, including wind speed, ambient temperature, solar heat energy, frame and insulator materials and geographic location. Therefore, based on the meteorological and geographic characteristics, the study numerically explored the impacts of wind velocity on the efficiency of still. In order to forecast the water production of various designs of solar stills, an integrated multi-layer perceptrons model with an artificial rabbits optimizer is formulated by Ref. [41]; where conventional, stepped, pyramidal and tubular stills were analyzed.

However, modifications in physical structure to obtain higher distillate output and in numerical modelling (of earlier models) are required to predict precisely the distillate output of newly designed panel heater triangular solar still (PHTSS).

In this study, a triangular shape solar distillation system is fabricated for the first time by incorporating two heat energy inputs to increase the water production rate, i.e. i) direct solar radiation and ii) direct current (DC) water heater connected to a solar PV panel system. A few factors that affect the productivity are observed. The observed data is then compared with the simulated results (by earlier and proposed models) to obtain the precision of the models. The simulation models developed earlier, however, could not able
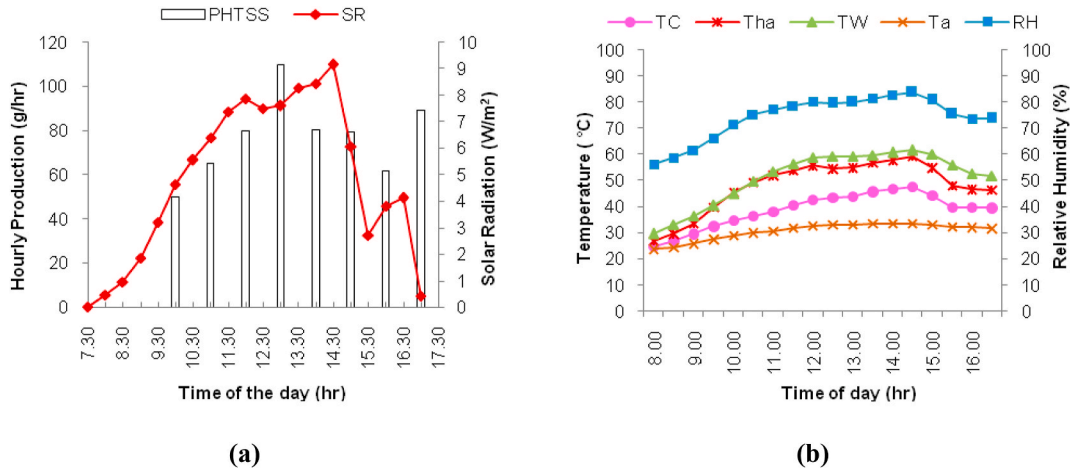
Fig. 2. Hourly variations of (a) production and solar radiation and (b) temperature and relative humidity on 20th July.

to predict the productivity precisely of PHTSS. Therefore, a further improvement in modelling is proposed here to estimate the distillate accurately.

2. Methodology

A new triangular solar still was fabricated using locally available materials by integrating with solar PV panel connected to DC water heater. This active solar still was tested in sunny days to produce potable water from salty water using solar heat energy directly (to heat salty water) and indirectly (through water heater to heat salty water). Then, a few simulation models are applied to estimate the hourly and daily distillate output of the still. Finally, the proposed model is defined by incorporating the findings of the present study. Fig. A1 shows the flow chart of research activities of this study in Appendix.

2.1. Design, fabrication and testing

A primary structure of PHTSS was designed using lightweight, cheap and available materials. The PHTSS consisted of a trough, frame, polythene film, heater and solar panel. The evaporation rate for PHTSS was enhanced due to the use of a DC water heater connected to the solar panel. Consequently, the efficiency and throughput of PHTSS was improved. A highly durable polythene film warranted for 3 years was used as a cover. Table 1 shows the overview of specifications of PHTSS. Fig. 1 presents the schematic and photograph of the PHTSS.

Eight thermocouples were placed inside of the still for taking measurement of temperature in various places. Thermocouples were positioned in the cover (inside and outside), bottom of the trough, humid air and in the water surface. The ambient temperature of the surrounding environment and the relative humidity of the humid air were measured. A pyranometer was located outside to obtain the concentration of solar heat energy.

2.2. Numerical analysis

In this study, the simulation models of [2,34] and Ahsan and Fukuhara (2008) are applied to estimate the hourly and daily distillate output of the still. The evaporation mass flux (W_h) can be estimated by Eq. (1) as derived by Ref. [34].

$$W_h = \frac{3600 q_{ew}}{L} = \frac{51.787(P_w - P_{ci})\left[(T_w - T_{ci}) + \frac{(P_w - P_{ci})(T_w + 273)}{(268900 - P_w)}\right]^{\frac{1}{3}}}{L} \qquad (1)$$

In addition, W_h is defined by Eqs. (2) and (3) as derived by Ahsan and Fukuhara (2008). Some common parameters used in modelling of solar still are given in Appendix.

$$W_h = 3600 h_{ew}(\rho_{vw} - \rho_{vha}) \qquad (2)$$

where, the evaporative mass transfer coefficient, h_{ew}, can be obtained by Eq. (3) as follows.

$$h_{ew} = [0.123 + 0.012(T_w - T_c)]\left[\frac{g\beta}{\vartheta D}\right]^{\frac{1}{3}} K_{\circ} R T^{*} \qquad (3)$$

The daily yield, m_w, can be estimated by Eq. (4) as derived by Ref. [2]; where temperatures of air, glass and water are the three factors.
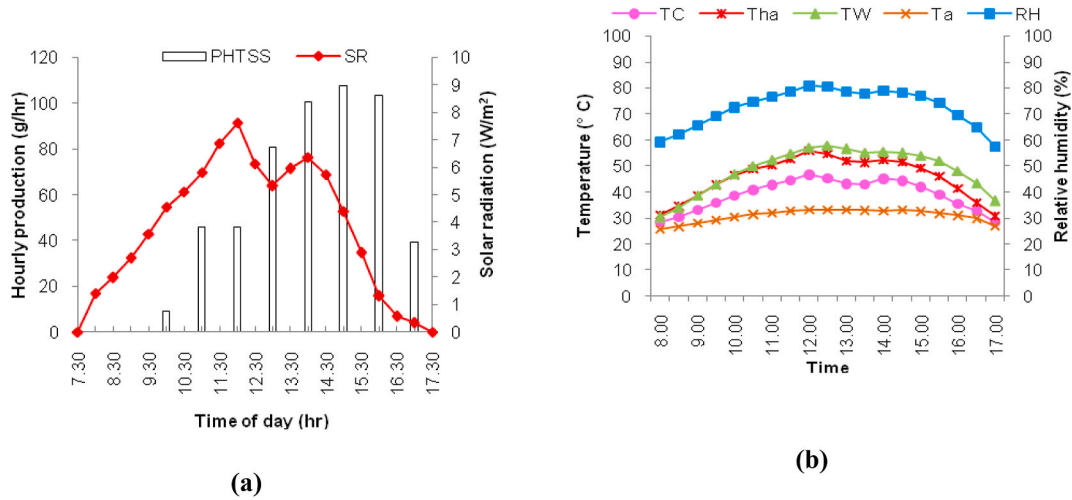
(a)

(b)

Fig. 3. Hourly variations of (a) production and solar radiation and (b) temperature and relative humidity on 1st October.
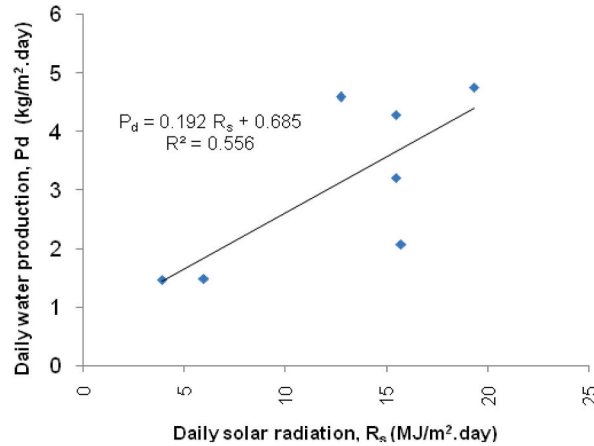

Fig. 4. Relationship between total sunlight heat energy and daily distillate output ($P_d = 0.192 \, R + 0.685$ when $2 \leq R_s \geq 25 \, W/m^2$).

$$m_w = 0.012\left(T_w - T_g\right)\left(T_g - T_a\right) - 0.003737 T_w - 0.005144 T_g\left(T_g - T_a\right) + 0.005365\left(T_g - T_a\right)^2 + 0.0212\left(T_g - T_a\right) - 0.003828 T_w\left(T_w - T_g\right)$$
$$- 0.005015 T_g$$

$$(4)$$

3. Results and discussion

3.1. Diurnal variations of temperatures, relative humidity and production

During the experiment, the data of production (P_h), solar radiation (R_S), the relative humidity of the humid air (RH) and temperatures at various locations were recorded, e.g. temperatures of water (T_w), of humid air inside the still (T_{ha}), of ambient air outside the still (T_a) and of cover (T_c). These parameters were recorded to analyze the effect on the production.

Fig. 2(a) and (b) presents the diurnal variations of P_h and R_S, and RH, T_c, T_{ha}, T_w and T_a on July 20, respectively. The production for stills begins at 10:00 a.m. with 50 g/h. The highest distillate output was 109.6 g/h at 1:00 p.m. As the solar intensity declined afterwards (after 2:00 p.m.), the distillate output was lesser. The distillate output was 3.8 kg/m^2 in sunshine period (7:30 a.m.–5:00 p. m.). The daily distillate was 4.75 kg/m2 including the distillate at nighttime (0.95 kg/m^2 as considered). The hourly variation of solar radiation implied that the highest was 9.15 W/m2 at 2:30 p.m. and lowest was 0.42 W/m2 at 5:00 p.m. The trends of hourly variations of various temperatures implied that the order was $T_w > T_{ha} > T_c > T_a$ almost throughout the daytime. The highest and lowest RH values were 83.8% at 2:30 p.m. and 56.3% at 8:00 a.m., respectively.

Fig. 3(a) and (b) presents the diurnal variations of P_h and R_S, and RH, T_c, T_{ha}, T_w and T_a on October 1, respectively. The production for stills begins at 10:00 a.m. with 9.3 g/h. The highest output was 107.6 g/h at 3:00 p.m. As the solar intensity declined afterwards (after 3:00 p.m.), the output was lesser. The output was 3.33 kg/m^2 in sunshine period (7:30 a.m.–5:00 p.m.). The daily distillate was
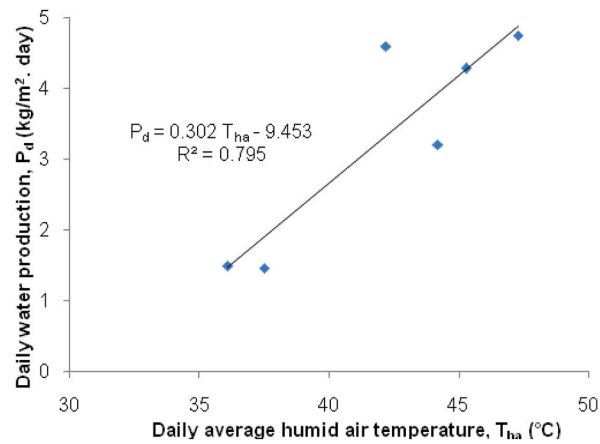
Fig. 5. Relationship between daily average humid air temperature and daily distillate output.
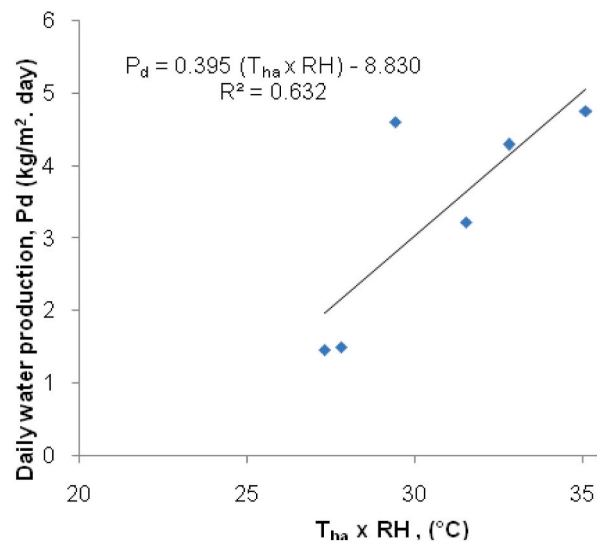

Fig. 6. Relationship between daily average humid air temperature times relative humidity and daily distillate output.
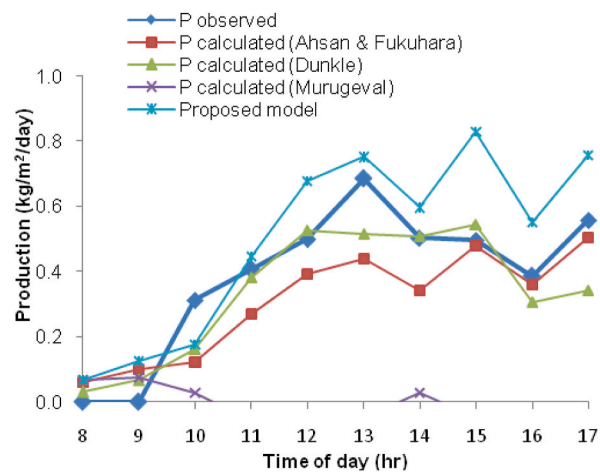

Fig. 7. Comparison of calculated hourly production flux with the observed value on 20th July.
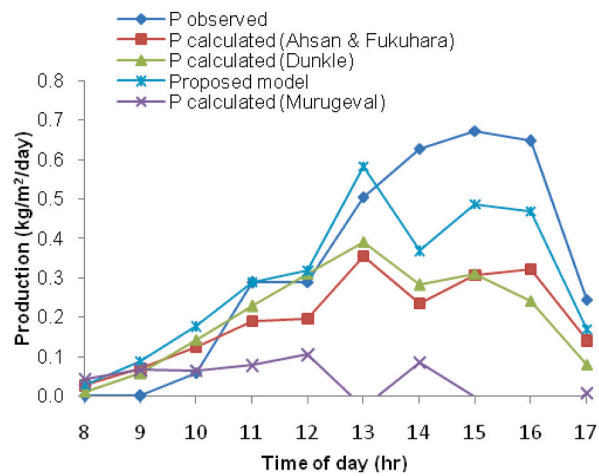
Fig. 8. Comparison of calculated hourly production flux with the observed value on 1st July.
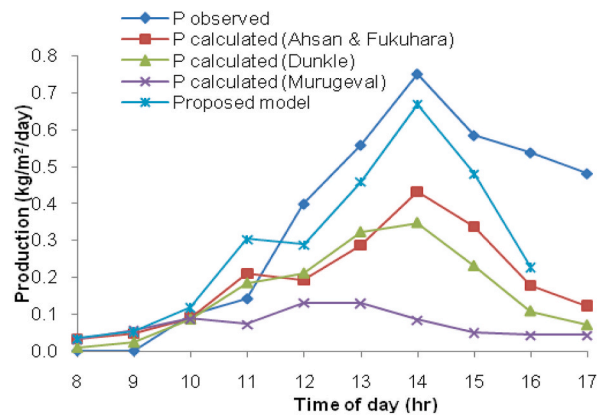

Fig. 9. Comparison of calculated hourly production flux with the observed value on 20th September.
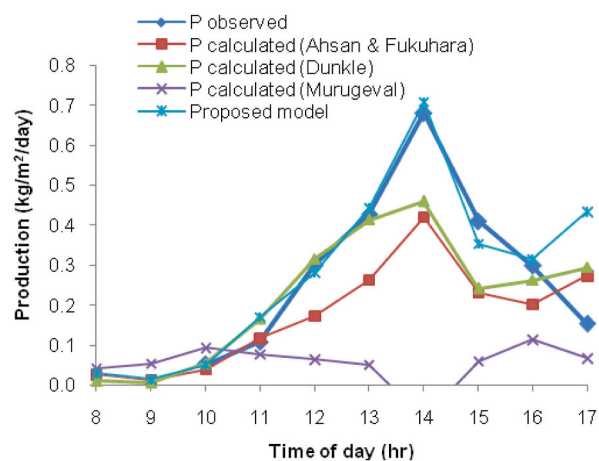

Fig. 10. Comparison of calculated hourly production flux with the observed value on 24th September.

Table 2
Comparison of RMSE values between developed calculated and observed values of daily water production.

Salt concentration (%)	RMSE values			
	Dunkle	Murugeval et al.	Ahsan and Fukuhara	Proposed model
1	0.107	0.486	0.129	0.043
2	0.217	0.416	0.213	0.129
3	0.271	0.387	0.234	0.147
5	0.101	0.309	0.129	0.089

4.28 kg/m2 including the distillate at nighttime (0.9 kg/m^2 as considered). The hourly variation of solar radiation implied that the highest was 7.62 W/m2 at 12:00 p.m. and lowest was 0.34 W/m2 at 5:30 p.m. The trends of hourly variations of various temperatures implied that the order was $T_w > T_{ha} > T_c > T_a$ almost throughout the daytime. The highest and lowest RH values were 80.9% at 12:00 p.m. and 57% at 5:00 p.m., respectively.

3.2. Various relationships

3.2.1. Solar heat and yield
The relation between R_s and P_d is shown in Fig. 4, where the relationship between them is nearly proportional. Since the regression coefficient, $R^2 > 0.5$, the relationship between P_d and R_s is acceptable.

3.2.2. Humid air temperature and yield
Fig. 5 presents the relation between P_d and T_{ha}. It implies that of P_d has nearly proportional relationship with T_{ha} and the regression is $P_d = 0.302\ T_{ha}$ - 9.453 when $35 \leq T_{ha} \geq 50$ °C.

3.2.3. Humid air temperature times relative humidity and yield
Fig. 6 presents the relation between P_d and $T_{ha} \times$ RH. It implies that Pd is nearly proportional to $T_{ha} \times$ RH and the regression is $P_d = 0.395\ (T_{ha} \times$ RH$)$ - 8.830 when $25 \leq T_{ha} \times$ RH ≥ 40 °C.

3.3. Comparison of predictive models

Figs. 7–10 present the comparison between the calculated the observed hourly production fluxes of PHTSS. It shows that the Murugeval's model is not applicable as it underpredicts the yield of still highly. Similarly, two other models namely, Dunkle's and Ahsan and Fukuhara models, are not suitable as well as it underpredicts the yield of still slightly. Consequently, a new model is developed by modifying the model of Ahsan and Fukuhara (2008) to estimate the productivity of the still precisely. As Fig. 6 implies that the RH and T_{ha} are the important two parameters affect the productivity of the still, therefore, these parameters are incorporated in the proposed model (Eq. (5)). Note that Eq. (3) is replaced by Eq. (5) and then, the hourly distillate is calculated by Eq. (2).

$$h_{ew} = [0.123 + 0.0001\ (T_w - T_c)]T_{ha}RH \left[\frac{g\beta}{\vartheta D}\right]^{1/3} K_oR_vT^* \tag{5}$$

Table 2 presents the root mean squared error (RMSE) between the experimental distillate yield of the still and the predicted one. Murugeval et al. model results show the highest error and the proposed model presents the smallest error.

4. Conclusions

The PHTSS is experimented to produce potable water using sunlight heat energy. The PHTSS is a potential device for coastal and arid regions because the fabrication materials are cheap, available, lighter and durable. From the experimental results, it is observed that the efficiency of PHTSS depends on numerous parameters such as sunlight heat energy, water temperature and water-cover temperature difference. The highest water production for PHTSS during the experiment is 4.75 L/m^2. day. The relationships between yield and total solar heat, between yield and water temperature, and between yield and humid air temperature, and between yield and water-cover temperature difference present a positive linear relation. The relation between yield and ambient air temperature presents a very weak relationship. The proposed model can calculate the water productivity precisely; however, some previous models cannot reproduce well the water productivity of the PHTSS. Therefore, the new model can be applied to other designs of solar still in any weather conditions.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Acknowledgements

Appendix

Some common parameters used in modelling of solar still can be expressed as:

$$D = 0.241 \times 10^{-4} \left(\frac{Tha + 273}{288}\right)^{1.75}; \quad K_o = \frac{0.263 \times^{-5}. \ T_{ha}^{0.75}}{101325}; \quad \vartheta = 0.0535 + 0.0015 \ T_{ha};$$

$$\beta = \frac{1}{(T_{ha} + 273)}; \quad R_v = 461.5 \text{ J} \Big/ \text{kg.K}; \quad g = 9.807 \text{ m} \Big/ \text{s}^2; \quad T^* = \overline{T}\Delta T^n; \quad \overline{T} = \frac{T_w + T_{ha}}{2}; \quad \Delta T^n = (T_w - T_c)^n; \quad n = \frac{1}{3}$$

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            Start
              ↓
     Fabrication of PHTSS
              ↓
    Experimentation of PHTSS
              ↓
        Data analysis
              ↓
      Numerical analysis
              ↓
  Comparison of present and
   proposed numerical models
              ↓
             End
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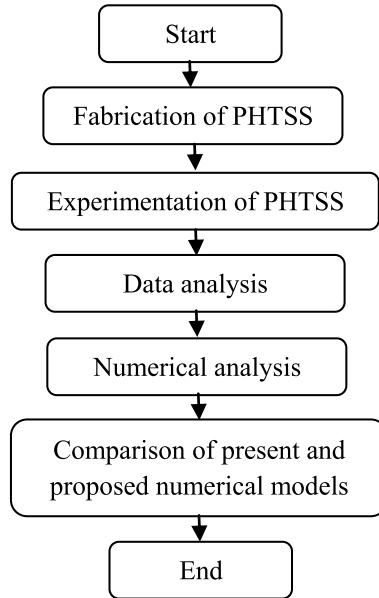
Fig. A1. Flow chart of research activities of this study

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