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Research Article

EVALUATION OF DOUBLE TILTED-GLASSED COVER DISTILLATION SYSTEM USING METALLOID-TYPED DOUBLE HEAT ABSORBER

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ABSTRACT:
Experiment in this research was conducted to evaluate the competent of double tiled-glassed cover distillation system (DTGD) in production of distilled water. The main parameter investigated was the heat absorber's size as a percentage based on the water surface inside the distillation unit. The amount of distilled water, total solar flux, and temperature inside the DTGD were monitored throughout the day. These data were stored and analyzed via an engineering equation solver (EES) to obtain the efficiency of different sizes of heat absorber from 10% to 90% of the water surface area. The total amount of distilled water produced from 10% aluminum was 1.6 liter per day. The volume of distilled water was monitored to calculate the efficiency of the distillation unit. Results showed the highest distilled volume of 1.6 liter per day. An increase in area to 90% caused the efficiency of the DTGD to drop from 26% to 17%, while the rate of distillation decreased to 0.98 liter per day. Efficiency reduction from an increase in heat absorber's area was due to the inaccessibility of solar radiation through the heat absorber.

Keywords: *Heat absorber, double tiled-glassed cover distillation system, mathematic modeling*

1. INTRODUCTION

Production of clean water is essential for rural communities in Thailand. In location that does not have access to electricity it is important for the communities to design facility for clean water production that does not required electricity. Solar-based distillation is an alternative method that can solve this problem at an inexpensive cost. For high BOD content water it is very important to install a reverse osmosis device in the treatment process [1]. However, for seawater or groundwater with low BOD content it is possible to install only a distillation unit to produce a clean source of water. The geometry of the heat absorber in distillation unit is a significant parameter that effect the efficiency of the clean water production system. One method that have been employed to improve the absorption of heat is the origami technique which focus on the shape and the material used for the heat absorber [2].

Over the years there have been many kind of developments and prototype for the distillation process for the production of clean water. Some of the successful model included indirect desalination, humidification-dehumidification and basin distillation. For the humidification–dehumidification technique dry air was used to create atmosphere that favor evaporation of the water. The indirect desalination process is completely different. A normal

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indirect desalination model consisted of solar receiver and heat exchanger system [3]. Basin distillation is similar to indirect desalination, however the basin type included absorption of solar radiation that penetrated through the glass screen to the heat absorber [4]. Compared with others models of distillation unit, the basin distillation type is inexpensive and the most feasible model for rural areas in Thailand. Unfortunately, the basic distillation model is not as effective as the other two types. Many researches have been conducted to overcome the disadvantages feature of the basin distillation. For instance it was documented that clean water productivity can be increased by using a double layered basin distillation unit [5]. An increase in the number of hot water outlet per area was found to be an efficiency technique to improve the productivity of treated water. Implementation of fins on condenser walls was also found to be an effective way to improve water yield from 11% to 14% [6]. Another important advancement in the field of solar-distillation prototype is the implementation of underground solar distillation unit that can generate over 3 kg of distilled water per m3 of solar receiver [7].

Addition of nanoparticles in untreated water was also found to have a positive effect on the production of distilled water. For instance gold and silver nanoparticles was found to improve the thermal efficiency by approximately 6.7% and 4.8% [8]. Apart from these two precious metals, titanium nitrate was used with membrane technology to increase thermal efficiency and heat flux [9]. An increase in efficiency occurred due to the increase in thermal conductivity of the untreated water after nanoparticles were added [10]. Despite the usefulness of nanoparticles, these are rare and precious metals which are expensive and difficult to find

This research aimed to develop and evaluate the distilled water productivity of the double-tilted distillation unit. In this research, the area of heat absorber as percentage base on the area of water surface was varied (10% to 90%). Data of solar intensity and temperature in different section of the double-tilted distillation unit were monitored over the day from morning to evening.

2. METHODOLOGY

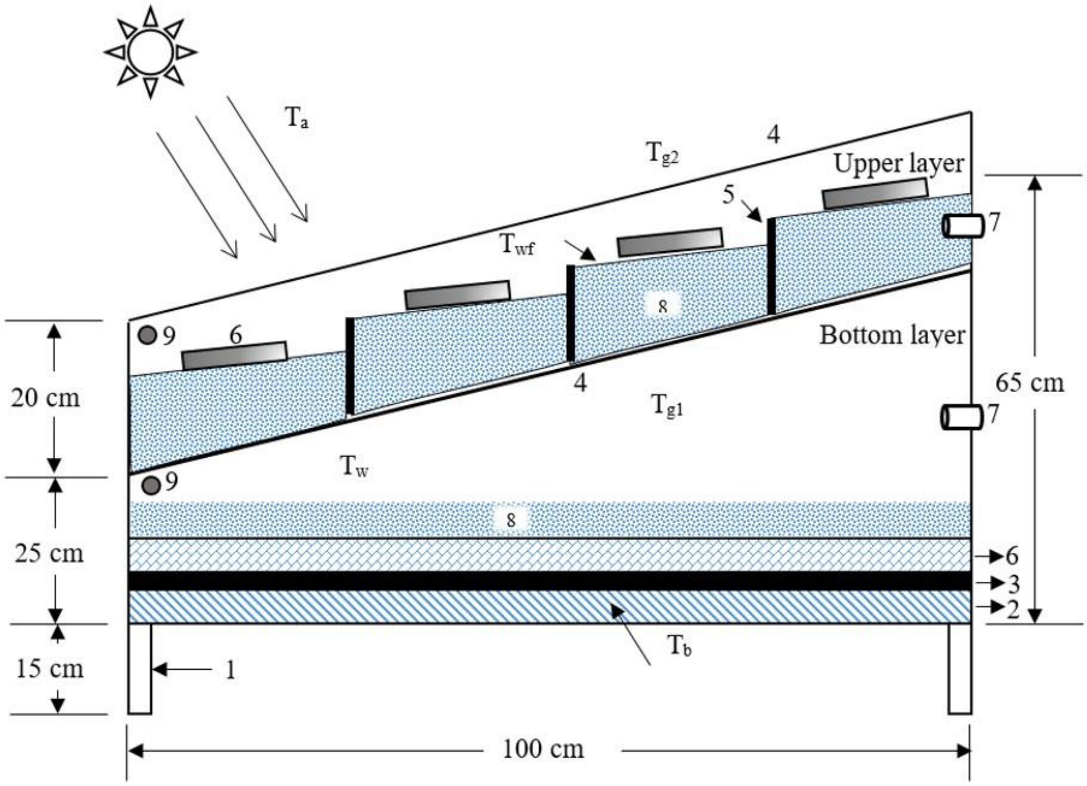
2.1 Experimental setup

This experiment investigated the double-tilted distillation unit with glass layer. As shown in Fig. 1 the distillation unit is divided into two layers with a 14 degree slope for both layers. Each layer contained a glass screen and the base area of 150 x 100 cm. The height of the distillation unit was 20 cm. The bottom and upper layer of the distillation unit contained an inlet and outlet port for untreated water to enter. The multistep along the length of the distillation unit are added in order to increase the efficiency through repeated water condensation mechanisms. The slope of the distillation unit is necessary because it help deliver condensed water into the horizontal gutter installed in the upper layer of the distillation unit. The dimension and function inside the distillation unit was derived from another research [11].

Solar intensity and the amount of collected distilled water was observed, recorded and used to calculate efficiency of the distillation process. These data were added to the engineer equation solver (EES) program to calculate the efficiency of the distillation unit. Heat absorber's area was varied from 10% to 90% of the water surface area at the bottom layer. Temperature inside the distillation unit was monitored at five different locations including the temperature of the insulator (T_b), upper layer's glass screen (T_{g2}), upper layer body of water (T_{wf}), bottom layer's glass screen (T_{g1}), bottom layer's body of water (T_w). The upper layer can contained 24 mL of water, while the bottom layer can contained 75 mL of water. These data were collected at an interval of 1 hour.

2.2 Mechanism in heat transfer

Heat transfer mechanism inside the distillation unit included solar penetration from the atmosphere through the glass screen into the body of water, adsorption of heat by the wall of the still and the insulator. Due to the presence of heat, water inside the distillation unit will be transformed to water vapor which floated upward to the glass screen and returned to the outlet gutter to be collected as treated distilled water. Evaporation of water was promoted by an increase in the pressure of water vapor above the equilibrium point.



a)

b)

Fig. 1. a) Experimental setup for the double slanted-glass distillation unit: 1. Stand for the distillation unit, 2. Compressed wood partition, 3. Insulator, 4. Glass screen, 5. Glass partition for upper gutter, 6. Heat absorber, 7. Inlet water, 8. water inside the upper and bottom layer and 9. Outlet for distilled water. b) Photograph captured of the solar-based distllation unit employed in the experment.

2.3 Calculation for heat transfer through radiation

The accumulation of solar radiation recorded per day can be multiplied by the rate of solar accumulation per hour (H) to obtain the degree of solar radiation per hour (I).

$$I = Hr_t \tag{1}$$

$$r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - (\frac{2\pi\omega_s}{360})\cos\omega_s} \tag{2}$$

The coefficient and constant used to calculate the rate of solar radiation can be obtained by the equations; $a = a_1 + a_2\sin(\omega_s - 60)$, $b = b_1 + b_2\sin(\omega_s - 60)$ and ω_s which represent the angle of solar incidence relative to the area of exposure. These constant depend mainly on the location of the distillation unit setup. This research used the constant for Ubonratchathani station which are a_1= 0.76, a_2= -0.031, b_1= 0.207 and b_2= 0.238.

2.4 Heat transmission mechanism

Most of the heat transmission was loss from the system which resulted in the reduction the efficiency of the distillation system. Part of this heat loss is due to the reflection of radiation from different sections of the distillation unit. First solar radiation is absorbed by the glass screen ($Q_{S.AG}$). A percentage of solar radiation penetrated through the protective cover (Q_{TR}) and it was absorbed by the body of water in the upper layer ($Q_{S.AW}$). Additionally, heat transfer in convection mode was obviously occurred from glass screen to the atmosphere (Q_{co}) and water surface to the glass screen (Q_{CI}). Heat loss from the bottom and the top of the unit was also considered (Q_L). Evaporation and heat loss during condensation was also included into the equation (Q_E and $Q_{distill}$).

Energy balance at different location inside the solar-based distillation unit are shown in equation 3 to 8.

a. Energy balance for the insulator

$$m_b C_{pb}\frac{dT_b}{dt} = I(t)A_b - q_{cbw} - q_{loss} \tag{3}$$

b. Energy balance for water in the upper still container (level 1)

$$m_w C_{pw}\frac{dT_w}{dt} = I(t)A_w + q_{cbw} - q_{rwg1} - q_{cwg1} - q_{ewg1} \tag{4}$$

c. Energy balance for glass surface (level 1)

$$m_g C_{pg}\frac{dT_{g1}}{dt} = I(t)A_{g1} + q_{rwg1} + q_{cwg1} + q_{ewg1} - q_{cg1wf} \tag{5}$$

d. Energy balance for water in the lower still container (level 2)

$$m_{wf} C_{pw}\frac{dT_{wf}}{dt} = I(t)A_{wf} + q_{cg1wf} - q_{cwfg2} - q_{rwfg2} - q_{ewfg2} + q_{absorber} \tag{6}$$

e. Energy balance for glass surface (level 2)

$$m_g C_{pg}\frac{dT_{g2}}{dt} = I(t)A_{g2} + q_{cwfg2} + q_{rwfg2} + q_{ewfg2} - q_{rg2,sky} - q_{cg2,a} \tag{7}$$

f. Condensation for the two levels inside distillation unit

$$\frac{dm_c}{dt} = h_{ewg1}\frac{(T_w - T_{g1})}{h_{fg@T_W}} + h_{ewfg2}\frac{(T_{wf} - T_{g2})}{h_{fg@T_{wf}}} \tag{8}$$

The atmosphere temperature was assumed to be 25 $^{\circ}$C. The value of other constants are shown in Table 1.

Table 1: Operating conditions during distillation simulation and experiment throughout the day [12].

Operating conditions	Value	Unit
Glass screen weight (m_g)	6	kg
Insulator weight (m_b)	10	kg
Heat capacity for glass material (C_{pg})	840	J/(kg°C)
Heat capacity for water (C_{pw})	4,184	J/(kg°C)
Water emissivity (ε_w)	0.96	-
Glass emissivity ($\mathcal{E}_g$)	0.88	-
Radiation absorbed by the glass screen (α_g)	0.0475	-
Radiation absorbed by water (α_w)	0.05	-
Glass reflectivity (ρ_g)	0.0735	kg/cm^3
Overall heat transfer coefficient (U_b)	14	W/(m^{2}K)
h_{cg1wf}	25	W/(m^{2}K)
h_{bw}	135	W/(m^{2}K)

2.5 Absorption of heat by material inside the unit

Absorption of heat by material inside the distillation unit can be calculated by using equation 9 as shown below.

$$q_{absorber} = \alpha(I_b\tau_{wb} + I_d\tau_{wd}) \quad (9)$$

For this equation α is the coefficient of radiation absorption which is different for different type of material. I_b is the quantity of radiation per hour, τ_{wb} is radiation that is delivered into the atmosphere via hot steam and τ_{wd} is solar radiation that is delivered into the atmosphere via scattering.

2.5 Calculation of the distillation unit's efficiency using Engineering Equation Solver

The distillation unit's efficiency (η) in term of heat transfer inside the distillation unit can be found using equation 10.

$$\eta = \frac{\sum m_c \dot{h}_{fg}}{\sum I \times A_o} \quad (10)$$

For this equation $\dot{m}_c$ is the rate of distillation, h_{fg} is the latent heat, I represent solar radiation intensity, and Ao is the area of the heat absorber.

An Engineering Equation Solver (EES) software was developed and employed to resolve the efficiency of the solar based double-tilted distillation unit. First the distillation variables were calculated by using equation 3 to 8, which also give the temperature of different sections inside the unit including T_b, T_w, T_{gl}, T_{wf} and T_{g2}. These values were then stored in the software and then used to calculate latent heat (h_{fg}) in the bottom and upper layer of the distillation unit. The distillation rate and efficiency are then calculated using equation 10. The logical steps applied in the EES software are shown in Fig. 2.

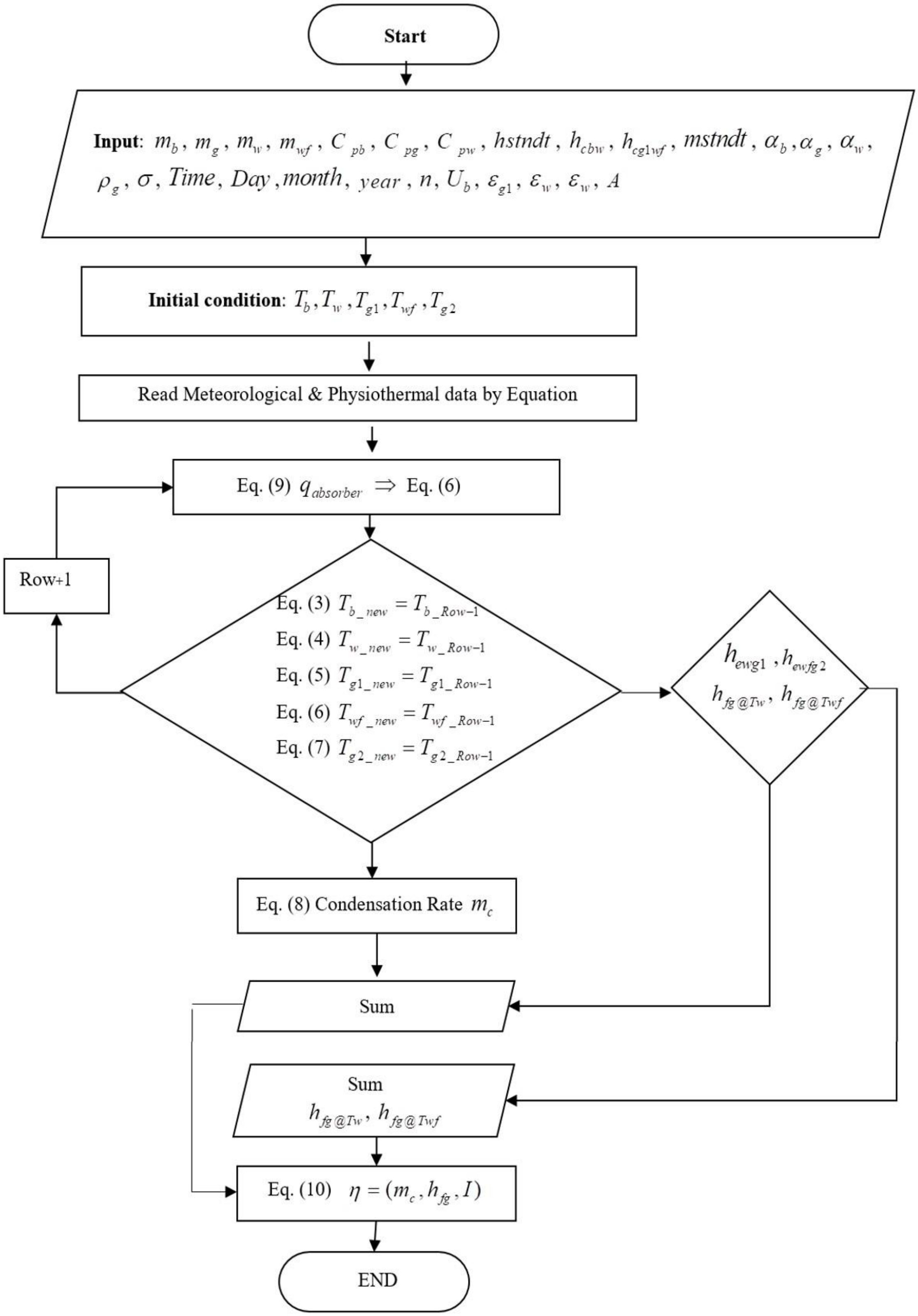


Fig. 2 Logical diagram used for the EES software to solve for efficiency of the distillation unit

3. RESULTS AND DISCUSSION

3.1 Solar intensity of the distillation unit

Area of the heat absorber was varied from 10 to 90 % of water surface. Solar intensity is one of the significant parameters investigated in this experiment. According to Fig. 3, the maximum solar flux recorded at around 12:30 in the afternoon was approximately 700 W/m^2. The average solar intensity throughout the whole day was 393.80 W/m^2 and reached a maximum of 708.33 W/m^2. Compared with other researches the total solar intensity produce in this distillation unit is relatively smaller than that of other researches. For instance, distillation results in term of solar intensity obtained in India gave similar data compared with this experiment [1].

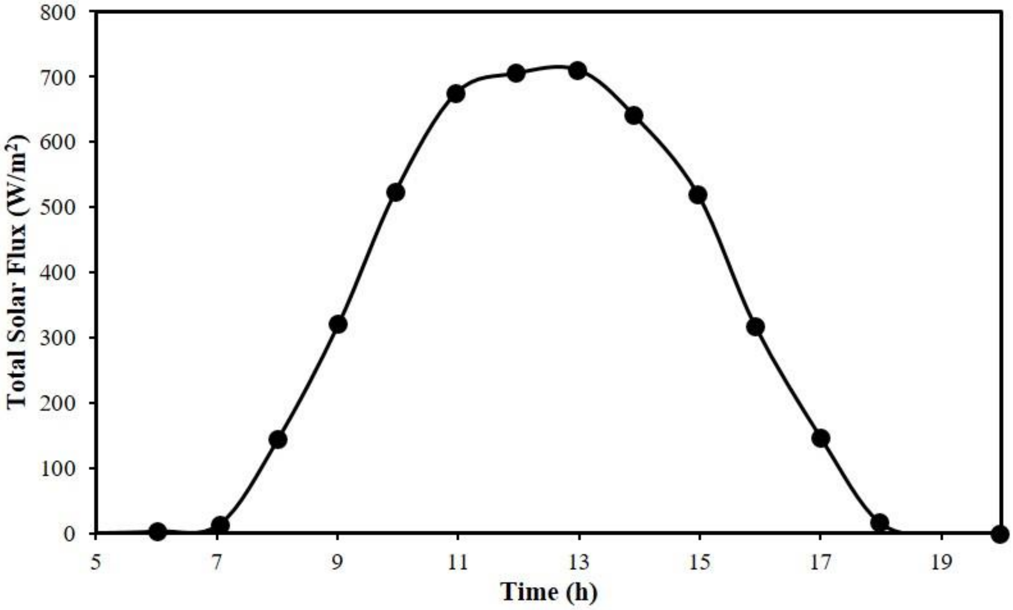


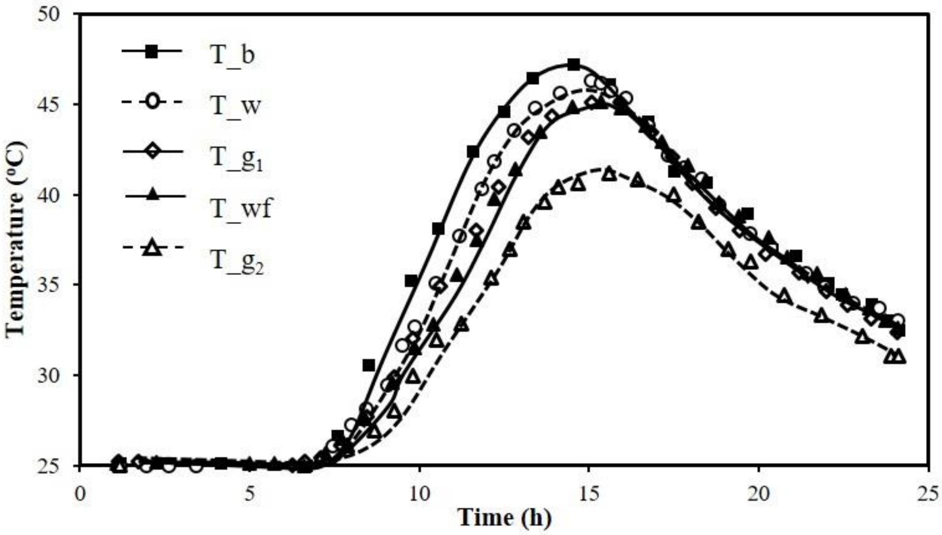
Fig. 3 Recorded solar intensity from Monitoring solar flux from 7:00 A.M. to 19:00 P.M. aluminum heat absorber size 10%

3.2 Distribution of temperature inside the distillation unit

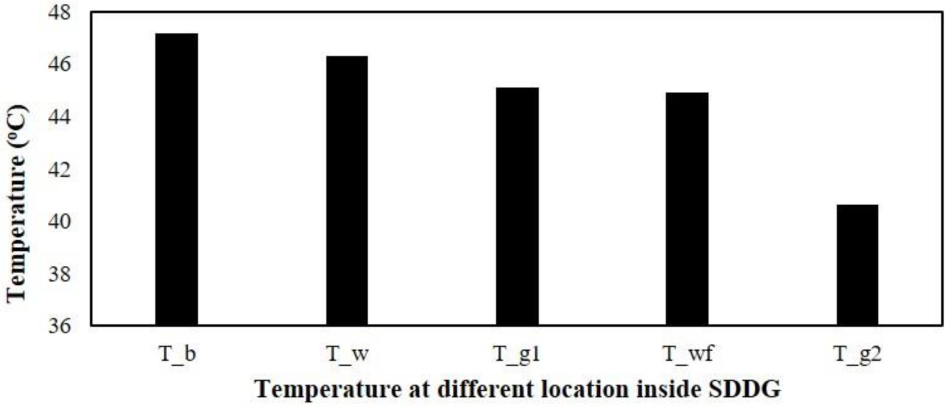
According to Fig. 4, temperature inside the distillation unit at different time during the day varied from 25 to 47.2 ˚C. It can be observed that the difference in temperature between glass screen and the water in upper layer of the distillation unit was relatively higher compared with the glass screen and the water in the bottom layer of the distillation unit. The thermal environment inside the distillation unit peaked approximately at 15:00 P.M. giving the highest insulator temperature of 47.2 ˚C. Difference in temperature between glass screen and water in the upper layer was 1.67 ˚C, while temperature different between glass screen and water in the bottom layer was 1.37 ˚C. This results suggested that the condensation process inside the upper layer is more effective compared with the bottom layer.

3.3 Accumulated water condensation ratio

Water productivity or the amount of distilled water produced per hour was demonstrated in Fig. 5. It was observed that the rate of distillation or condensation in the upper and bottom layer were 0.51 l/m^2 and 0.92 l/m^2. Additionally, distillation activities took place clearly after 9:00 AM in the morning. In order for condensation to occur it is important for the heat inside the unit to be higher than the latent heat necessary for the transformation of liquid water to vapor. The productivity of the distillation unit increased dramatically between 11:00 AM to 13:00 PM in the afternoon. According to Fig. 5 the total productivity, productivity from upper layer and bottom layer after 24 hours of operation were 1.43 L, 0.89 L and 0.58 L.



(a)



(b)

Fig. 4 The temperature at different location inside the distillation unit containing a) aluminum and b) temperature inside the distillation unit 15 hours after the start of operation.

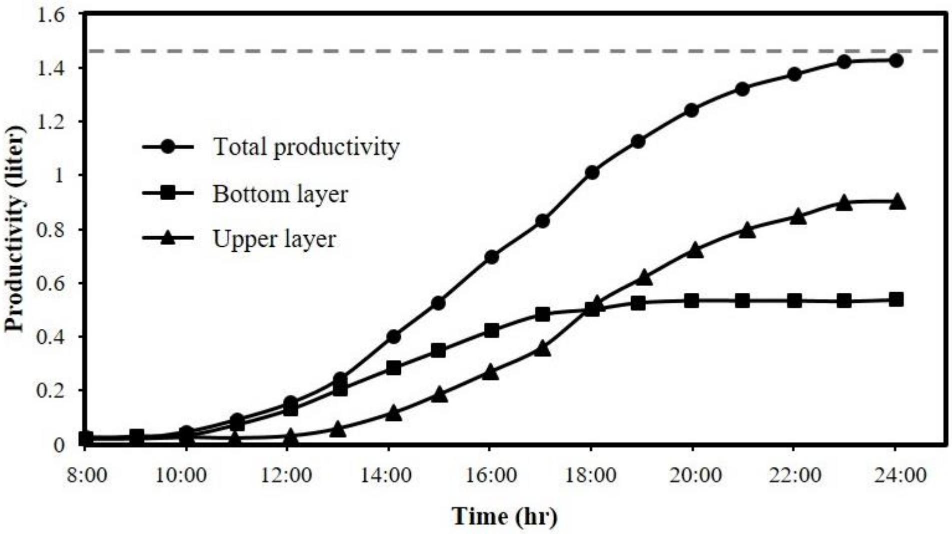


Fig. 5 Distilled water productivity measured from 8:00 AM to 24:00 PM from the distillation unit with built-in 10% by size of aluminum heat absorber

A mathematical model of the distilled water productivity was formulated based on the polynomial equations as shown in Eq. 11. Prediction of the distilled water productivity using equation 11 resulted in R^2 very close to 1. This was the main reason why the sixth order polynomial was employed. On the other hand the efficiency

$$\text{Productivity (liter)} = 4E\text{-}07t^6 - 3E\text{-}05t^5 + 0.0008t^4 - 0.0096t^3 + 0.0528t^2 - 0.1245t + 0.1111 \quad (11)$$
$R^2 = 0.9997$

$$\text{Efficiency (\%)} = -0.0005x^6 + 0.0178x^5 - 0.2175x^4 + 1.2487x^3 - 3.4599x^2 + 3.2071x + 24.919 \quad (12)$$
$R^2 = 0.9979$

Where t represents the operating time of the distillation unit and x represents the size of the heat absorber.

Variation of the size of heat absorber from 10% to 90% was observed based on the outcome of the distillation unit. As shown in Fig. 6 a decrease in the efficiency unit, derived from the EES process, resulted from an increase in the size of the heat absorber. Efficiency of the aluminum heat absorber decreased by approximately 5% when the size of heat absorber increase from 10% to 90%. The distillation unit demonstrated an average efficiency of 26%.

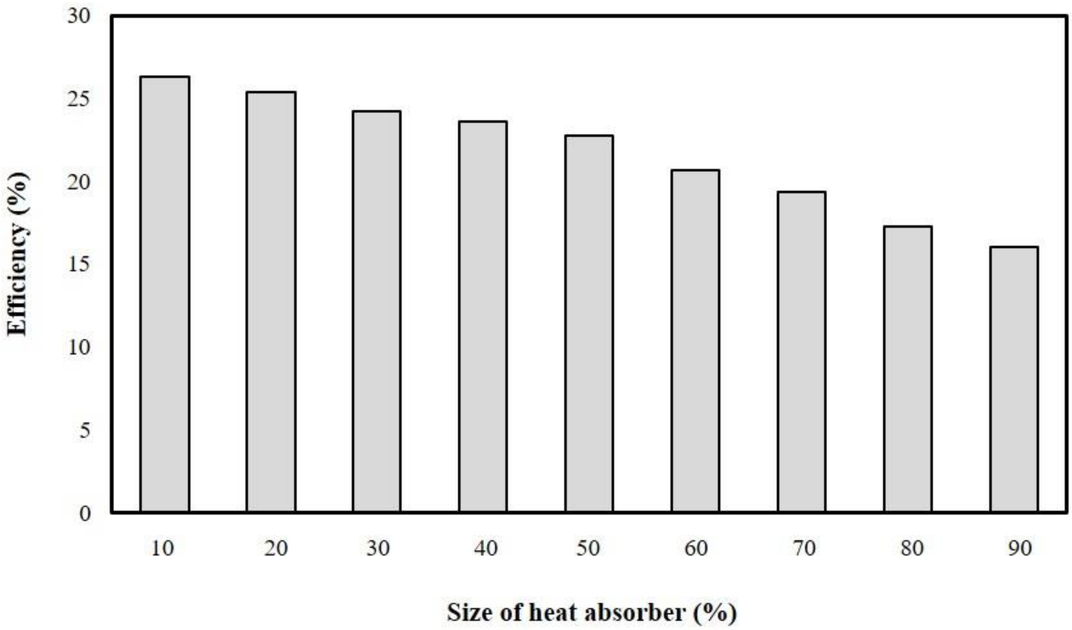


Fig. 6 Influence the size of heat absorber on the efficiency of the distillation unit

Table 2 demonstrated the characteristic of the distillation unit based on the average solar intensity, the amount of produced distilled water after 8 hours of operation, and efficiency. As heat absorber size increased the efficiency decreased significantly. The highest efficiency of 26.3% was observed when the 10% by size aluminum was used. The efficiency reduced to 17.3% when the heat absorber size was increase to 90%. A hybrid-type distillation in another study was found to give similar solar intensity [13]. Another experiment developed a chimney-type distillation unit which provide relatively high solar intensity of 982 W/m^2 [14] compared with our work. Additionally, another tubular type distillation unit was employed to give relatively higher solar intensity of 1000 W/m^2 [15]. The reason these two experiments provide higher solar intensity. The reason this distillation unit can absorbed lower solar intensity is because the size of the distillation unit in this work is significantly smaller than the chimney and tubular type distillation unit. Furthermore, these distillation units were tested in different location causing the result to differ slightly. The solar intensity of each type of distillation unit recorded after 13 hours of operation were illustrated in Fig. 7.

Table 2: Average solar intensity, the amount of distilled water and efficiency for different aluminum heat absorber.

No.	Heat absorber size (%)	Average solar intensity (W/m^2)	Amount of distilled water per day (8 h) (Liter)	Efficiency (%)
1	10%	393.80	1.60	26.34
2	20%	395.39	1.44	24.94
3	30%	393.87	1.42	24.36
4	40%	390.53	1.37	24.07
5	50%	377.89	1.32	23.24
6	60%	391.94	1.19	21.59
7	70%	404.10	1.13	20.22
8	80%	432.22	1.08	18.73
9	90%	438.03	0.98	17.29

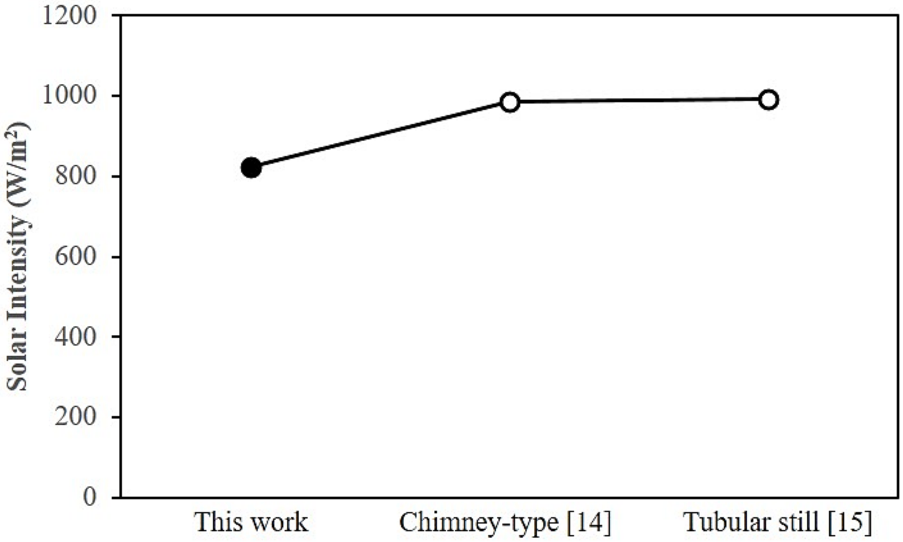


Fig. 7 Solar intensity comparison between distillation units developed in this work and the other two models

4. CONCLUSION

This research aimed to evaluate and model the performance of aluminum material as heat absorber for the double tiled-glassed cover distillation system (DTGD). The distillation efficiency was found to reduce as the surface area of the heat absorber increases. This is because an increase in heat absorber area causes sunlight to be reflected instead being transfer to untreated water inside the distillation still. A reduction in the efficiency of the distillation activity also resulted in a decline in the production of distilled water. Accumulation of approximately 1.6 liter of distilled water (efficiency of 26.3%) was recorded when the heat absorber with 10% surface area was installed in the distillation unit. However, when the heat absorber area increase to 90% the productivity decline to 0.98 liter (efficiency of 17.3%). Temperature difference was an important driven force that promotes heat transfer between layers and sections inside the distillation unit. It was observed that the temperature difference between glass screen and water surface (1.4 °C) in bottom layer was significantly lower than that of the upper layer (1.8%). Furthermore, experimental data were correlated with a polynomial mathematical model to predict productivity and efficiency based on operating time and the size of heat absorber. Simulated results were found to be very close to the experimental data with R^2 close to 1. Results from this research will support sustainable development of inexpensive water treatment system for rural areas in Thailand.

NOMENCLATURE

m_g	Glass screen weight, kg
m_b	Insulator weight, kg
C_{pg}	Heat capacity for glass material, J/kg°C
C_{pw}	Heat capacity for water, J/kg°C
ε_g	Glass emissivity
ε_w	Water emissivity
α_g	Radiation absorbed by the glass screen
α_w	Radiation absorbed
ρ_g	Glass reflectivity, kg/cm^3
U_b	Overall heat transfer coefficient, W/(m^{2}K)
T_b	Temperature for the insulator, °C
T_{g1}	Temperature for the glass screen in the bottom layer, °C
T_{g2}	Temperature for the glass screen in the upper layer, °C
T_w	Temperature for water surface in the bottom layer, °C
T_{wf}	Temperature for water surface in the upper layer, °C

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