An Experimental Study of Performance of a Pyramid Solar Still with Variation of Different System Parameters

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ABSTRACT

This study resents the effect of three different parameters: water depth, water type and absorber plate color on the system performance of the pyramid solar still for the weather conditions of April 23 to May 7 in Mandalay. The temperatures of the basin, water, glass cover and fresh water production of the solar still were experimentally and theoretically investigated. The depth of water was changed to 1.0 cm, 1.5 cm, 2.0 cm and the absorber plate color was changed to black, red-brown and white. Tap water and salt water were used to determine the effects of the water type. Then, theoretical calculations were also performed for verification and comparison with experimental data. The height solar heat flux of 819.17 W/m^2 is obtained at the mid-day. However, the trend of solar heat flux and the trend of temperature distribution of solar still do not coincide due to a delay to increase the water heat level. In the daily operation of a solar still, the temperature of basin is higher compared to the temperature of water and glass. The results reveal that there is a considerable effect of water depth on freshwater productivity in the morning hours. The maximum production of 2443.75 mL is achieved using normal tap water at 1 cm of water depth. The salt water has a higher freshwater productivity of 2718.75 mL compared to normal tap water. While investigating the effect of absorber plate color, the back color absorber plate shows the best performance for the pyramid solar still.

1. INTRODUCTION

Today, fresh water is an essential need for domestics, industries and hospitals. According to UN goal (SDG-6), it is important to reduce water pollution, reduce the proportion of untreated wastewater and increase recycling and safe reuse globally. In the future, everyone must have to access to safe drinking water. It suggests that the process of producing fresh and clean water from wastewater and/or untreated water (e.g., sea water) becomes important for both domestic and industrial applications. In rural areas where limited access to freshwater, solar water distillation is a popular way to produce fresh water with naturally harvested solar energy.

A typical solar water distillation system is shown in Figure 1. Its operation is based on the evaporation process and condensation process of working fluid. A typical solar water distillation system consists mainly of a painted basin that stores untreated water, a glass cover that serves as a solar collector, piping and buckets to collect the distilled water. Sometimes, an extra solar collector or other energy source is connected to the basin for pre-heating the working water. If there is no extra solar collector for pre-heating, it is called a passive system and if pre-heating is used, it is called an active system.

Indeed, the overall performance of a solar still is measured in regard to fresh water production, it produced in a given period of time. The solar still's performance is governed by many system parameters such as the weather condition, the depth of working fluid in the basin, the absorber color, the collector shape and size, the properties of the working water, the location of the system, the orientation of the system as well as the supply of extra energy.

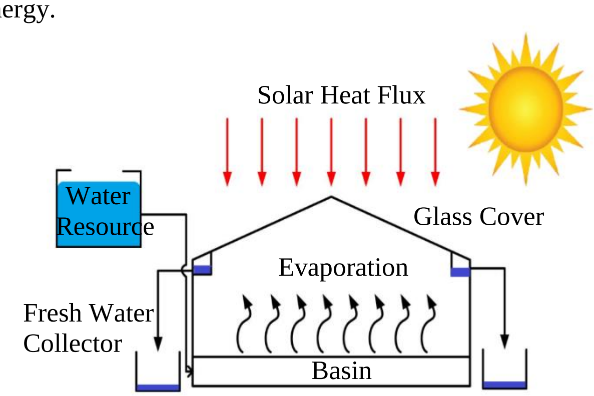

Fig.1. A typical solar distillation system.

It is important to understand the result of different parameters on solar still's performance. In this regard, there have been many studies that concerned with the solar still's

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performance with respect to different parameters such as structural parameters, climate parameters, and operation parameters.

In some previous works [1, 2, 3] the glass cover inclination effect was studied with different inclinations of 15˚, 25˚, 30˚, 35˚, 40° and 45˚. One common observation from these works was that a higher inclination angle can give a larger yield of fresh water. The optimum inclination angle should be between 30˚ and 45˚. The authors [1] studied the effect of thickness of glass cover on solar still performance. The authors observed that the higher the thickness of the glass cover, the lower the efficiency of the solar still [4].

The effect of basin shape (absorber shape) was studied in the research groups of the authors [5, 6]. The basin shapes tested were flat, concave and convex shapes. Here, it was concluded that convex shape basin can provide higher efficiency. The effect of water depth on solar still performance was investigated in some previous works. They all agreed that lower water depths can give higher efficiency to solar stills [1, 4, 6, 7].

The effect of wind speed was studied in previous works of [8, 9]. The authors of the first work said that wind speed can enhance efficiency, while the other reported that wind speed had no significant effect on the amount of fresh water produced. The solar stills' efficiency can also be improved by adding an external heat source.

The effect of external heat sources was studied in many researches [10, 11, 12, 13, 14, 15, 16, 17]. In their studies, the solar still was connected to an external heat source such as a flat plate collector, a parabolic trough collector and an evacuated tube collector. All of the authors concluded that a cooperative external heat source can enhance the solar stills' performance.

Concerning the performance of different collector shapes, many researchers have done many attempts in which performance of single-slope, double-slope, pyramid, spherical, hemispherical, step shape, double basin glass solar still, tubular solar stills were investigated and compared to single slope and double slope, the pyramid solar still showed the largest productivity. According to the literature review, the performance of hemispherical shape collector is slightly lower than flat plate collector [18, 19, 20, 21,22]. Interns of absorber plat material, the aluminum heat absorber showed the best performance [23].

Since it can give greater productivity compared to other shapes, the pyramid shape of the solar still was selected for this study. It is to give more attention to the effect of system parameters such as water level, absorber colors and water types in the pyramid shape solar still in Myanmar. Therefore, the objectives of this work are to experimentally measure and compare the temperature distribution and fresh water production in a pyramid solar still using different water levels, absorber colors and water types.

2. THEORETICAL CALCULATION

2.1. Thermal Analysis

The free-body diagram of a pyramid shape solar still is shown in Figure 2. The transient temperatures of the glass cover, water, basin absorber and fresh water productivity can be calculated using the following theoretical equations.

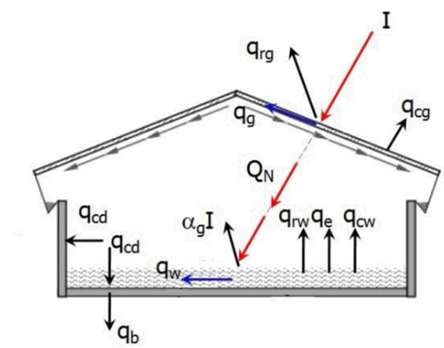


Fig.2. Free body diagram of solar stills.

$$m_g\, C_{pg}\frac{dT_g}{dt} = \alpha_g I\, A_{gp} + A_g\left[q_{rw} + q_{cw} + q_e - (q_{rg} + q_{cg})\right] \tag{1}$$

$$m_w C_{pw}\frac{dT_w}{dt} = A_w\left(I\tau_g\alpha_w - q_{rw} - q_{cw} - q_e - q_{cd}\right) \tag{2}$$

$$m_b\, C_{pb}\frac{dT_b}{dt} = A_b\left(I\tau_g\tau_w\alpha_b - q_{cd} - q_b\right) \tag{3}$$

where, I is direct heat flux (W/m^2), q_{rg} is radiation at glass (W/m^2), q_{cg} is convection at glass, q_g is the heat stored at glass (W/m^2), Q_N is the total heat (W/m^2), q_w is heat stored in water(W/m^2), q_{rw} is heat radiated of water (W/m^2), q_{cw} is heat convection of water (W/m^2), q_e is the heat loss by evaporation (W/m^2), q_{cd} is heat loss by conduction (W/m^2), α is absorption coefficient, τ is transmittance coefficient, q_b is heat loss to surrounding (W/m^2).

Heat transfers (W/m^2) by convection, evaporation and radiation from the still water to the glass can be analyzed by Eqs: [4-6].

$$q_{ew} = 16.276\times10^{-3}\times q_{cw}\frac{(p_w - p_g)}{T_w - T_g} \tag{4}$$

$$q_{cw} = 0.884\left[(T_w - T_g) + \frac{(p_w - p_g)(T_w + 273)}{268.9\times10^3 - p_w}\right]^{1/3}(T_w - T_g) \tag{5}$$

$$q_{rw} = \varepsilon_w\sigma\left[(T_w + 273)^4 - (T_g + 273)^4\right] \tag{6}$$

where, p_w is the partial pressure of water vapor (Pascal), p_g is the partial pressure of glass (Pascal), T_w and T_g are water temperature and glass temperature, σ is the Stefan-Boltzman constant (5.67× 10^{-8} JK^{-4}m^{-2}) and ε_w is the emission of water.

Convection, radiation and heat transfer of radiation from the glass to the ambient around the still (W/m^2) can be calculated by the following equation.

$$q_{cg} = (5.7 + 3.8V_{wind})(T_g - T_a) \tag{7}$$

$$q_{rg} = \varepsilon_g \sigma\left[\left(T_g + 273\right)^4 - \left(T_a + 273\right)^4\right] \quad (8)$$

where, ε_g is the emission of the glass.

Then, heat transfer convection from the distilled water to the absorbing surface of the basin (W/m^2) can be solved this equation.

$$q_{cd} = h_{wb}\left(T_w - T_b\right) \quad (9)$$

The basin to the surrounding area (W/m^2) of heat convection is calculated using the following equation:

$$q_b = h_{ba}\left(T_b - T_a\right) \quad (10)$$

$$\frac{1}{h_{ba}} = \frac{\delta_{in}}{k_{in}} + \frac{1}{h_a} \quad (11)$$

where, h_{wb} is heat transfer coefficient of water and h_{ba} is the total coefficient of the heat transfer from the basin to the air.

2.2 Water Production Rate

Then, the condensation mass flow rate can be analyzed by using Dunkle's relationship:

$$m_{the} = 16.273 \times 10^3\, h_{cw}\left(\frac{p_w - p_g}{L}\right) \quad (12)$$

$$L = 2.569 \times 10^5 \left(647.3 - T_w\right)^{0.38} \quad (13)$$

$$p_w = \exp\left(25.317 - \frac{5144}{273.15 + T_w}\right) \quad (14)$$

$$p_g = \exp\left(25.317 - \frac{5144}{273.15 + T_g}\right) \quad (15)$$

Temperature distribution and fresh water productivity are simulated using system parameters specifications shown in Table 1. The software is used the MATLAB software.

3. EXPERIMENTAL MEASUREMENTS

3.1. Setup and Apparatus

The experimental setup for measurements is shown in Figure 3. First, the pyramid shape solar still was constructed using steel and plywood as shown in Figure 3. The total glass cover area is 1.314 m^2. The thickness of the glass covers is 5 mm. The glass covers were tilted at 45°. The still was insulated using 5 mm thickness of plywood for reducing heat loss of the surrounding. The total width and length of the solar still with including wood insulation are 896 mm and 1210 mm respectively. The height from the basin base to the pyramid tip is 625 mm.

A steel basin was used in this experiment. The total volume of the basin is (896mm × 1210mm × 200 mm) 0.2154 m^3. The absorber was coated with three different red color, white color, and black color for three different experimental tests.

Table 1. Simulation parameters and material properties

Parameter	Specifications	
	Tap water	Sea water
Location (Latitude)	21.98˚	21.98˚
Month	23 April to 7 May	23 April to 7 May
Local time	9 a.m to 5 p.m	9 a.m to 5p.m
Wind speed (V)	1.3 m/s	1.3 m/s
Convection heat transfer coefficient of water (h_{wb})	50 W/m^{2}K	50 W/m^{2}K
Convection heat transfer coefficient of air (h_{ba})	45 W/m^{2}K	45 W/m^{2}K
Specific heat of glass (C_{pg})	649 J/kg	649 J/kg
Specific heat of water (C_{pg})	4187 J/kg	4187 J/kg
Specific heat of basin (C_{pb})	600 J/kg	600 kg

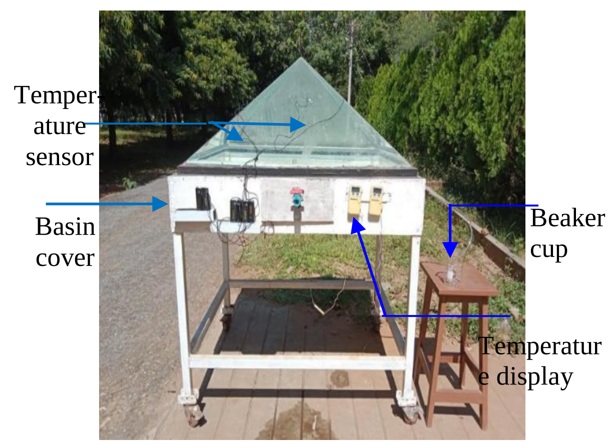


Fig. 3. Experimental setup of pyramid shape solar still.

The hourly solar heat flux was measured by means of a solar power meter as shown in Figure.4(a). The temperatures of the basin, water and glass were measured using thermometer temperature sensors and confirmed by measuring using the laser temperature sensor shown in Figure.4(b). Then, fresh water production was measured by beaker cup. Two thermometer temperature sensors were placed at the basin surface to measure the basin temperature.

A total of eight thermometer temperature sensors were used for measuring the glass temperature. Four thermometer temperature sensors were placed on the outer surfaces and another four thermometer temperature sensors were used on the inside surfaces of the glass covers. The beaker cup was connected to the water outlet of the solar still. The detailed specifications of the apparatus are described in Table 2.

(a) (b)

Fig. 4. (a) Solar power meter (b) Laser temperature sensor.

Table 2. Specifications for measuring tools

Parameter measured	Apparatus	Model/Specification	Scale/ Resolution
Soar heat flux	Solar power meter	Tenmars TM751	0.1 W/m^2
Temperature	Thermo meter	Digital Thermometer DS1	0.1 °C
	Laser temperature sensor	RayTek ITC-45	0.01 °C
Water production	Beaker cup	PO3EL BORO 3.3 (500 mL)	25 mL

3.2. Measuring Procedure

The experimental tests were conducted at Mandalay Technological University (MTU) in Mandalay, Myanmar. MTU is located at North Latitude of 21.996˚ and East Longitudinal is 96.1˚. The experimental tests and measurements were carried during from 23rd April to 7th May, 2022. The measurement procedure is as follows.

- First, working fluid (tap water or saltwater) was filled in the basin to obtain the required water level. The tap water was made at 1.0 cm, 1.5 cm and 2.0 cm depth respectively.

- Then, all temperature sensors were adjusted to the same level as the environment's temperature. around 7 a.m. in the morning, the environment temperature was 26 °C.

- Then, the measurements and recording of solar heat flux received, basin, water and glass temperatures were carried out starting at 9 a.m. in the morning and continuing every one hour.

- The drinking pure water productivity by the solar still was collected in the beaker cup and measured at every hour to obtain hourly production. Then it was accumulated until the end of the experiment. At the end of the day, the total volume of fresh water was measured to obtain the daily output.

4. RESULTS AND DISCUSSION

4.1. Solar Heat Flux

The hourly measured solar heat flux is shown in Figure 5. The solar heat flux was measured for three days. It was also theoretically calculated for comparison and verification. The weather is clear during these days. The heat flux measurements were carried out from 9 a.m. to 5 p.m. in the evening. It can be observed that the solar heat flux is increased from 9 a.m. to 12 noon. Start from 1 p.m., it decreased back. After the peak at noon, the declination in the afternoon is steeper compared to the trend in the morning. Also, one can see that both experimental and theoretical results showed a good agreement in both trend and value.

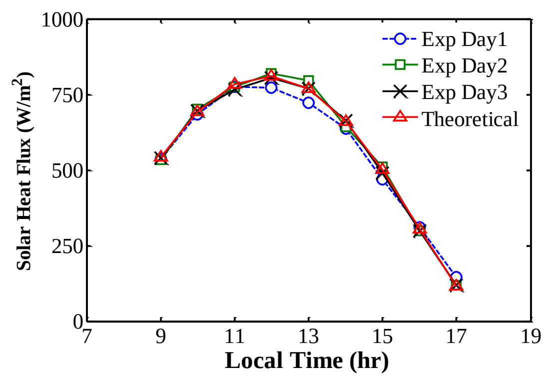


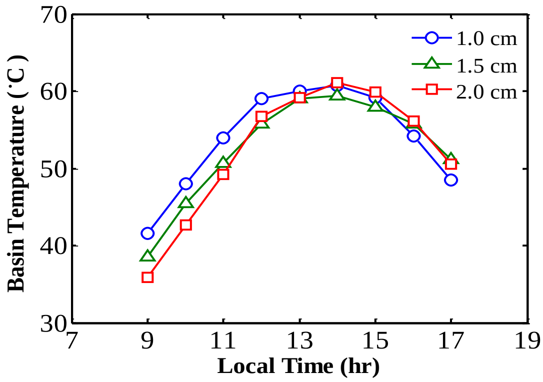
Fig. 5. Variation of solar heat flux.

4.2 Effect of Depth of Water on Temperature Distribution and Fresh Water Production

The comparisons of basin temperature, water temperature, glass temperature as well as fresh water production for every water depth are shown in Figure 6. The water depth in the basin was varied as 1.0 cm, 1.5 cm and 2.0 cm. The water is the tap water.

First, it can be observed that the operation temperature of solar still shows a delayed trend compared to solar heat flux. Thus, the experimentally measured temperatures show a delay trend compared to theoretical values. The water temperature increases from 9 a.m until 2 p.m and it decreases again after 2 p.m. The experimental measure ments of the temperature of basin, water and glass show the same trend. Here, the basin temperature and water temperature reach up to 60 °C and the glass temperature is 55°C as maximum. Here, the effect of water depth is clear in the morning hours. It finds that the operating temperature is higher when the water depth is smaller in the morning hours. However, in the afternoon, the effect of water depth is not obvious because the water temperature is approxi mately the same. The reason is that when water depth is thicker, it needs more heat amount to evaporate the water.

Thus, it takes more time for evaporating lager water volume.



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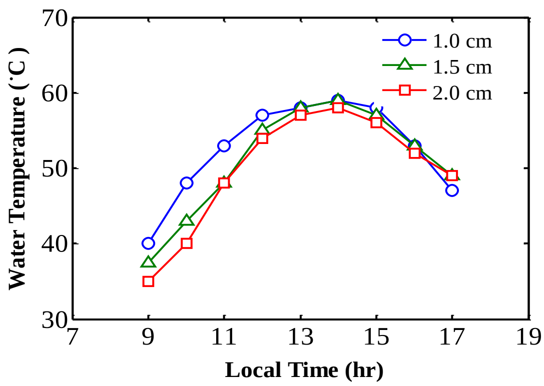

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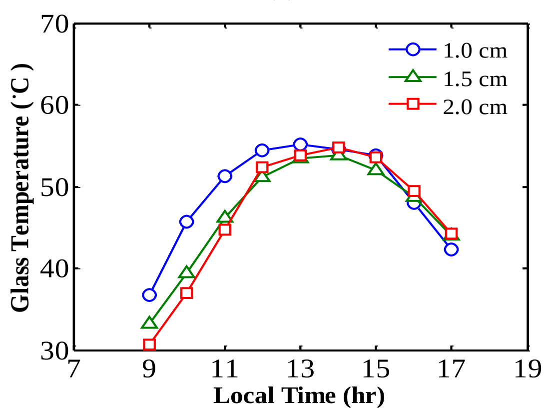

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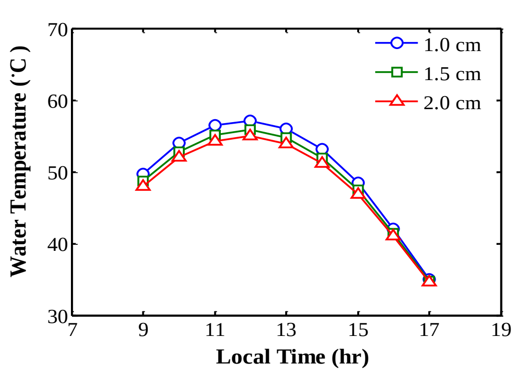

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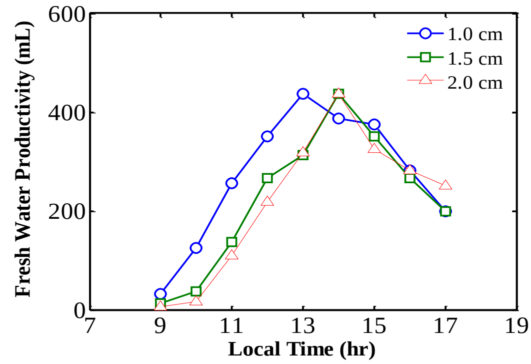


(e)

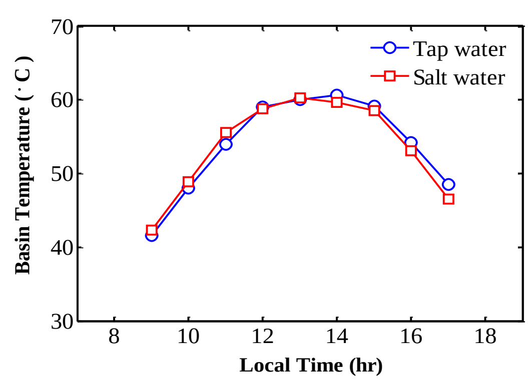
Fig. 6. Temperature distribution in solar still at different water depths. (a) Temperature of basin (b) Temperature of water (c) Temperature of glass (d) Theoretical water temperature (e) Fresh productivity water.

Consequently, the fresh water productivity is lager when the water depth is smaller. The total water productivity is 2443.5 mL, 2021.25 mL and 1962.5 mL at water depth of 1.0 cm, 1.5 cm and 2.0 cm respectively. At water depth of 1.0 cm, the fresh water productivity is obviously higher compared to the water production rates at 1.5 cm and 2 cm.

4.3 Effect of Water Type on Temperature Distribution and Productivity

To know the effect of water type, experiments were conducted using tap water and salt water. The salt water was created by well mixing 0.035 kg of salt in 1 liter of tap water to obtain approximately the same properties as sea water. The water depth was 1 cm. The experiments were conducted at the same location. The results are shown in Figure7.

It can be observed that the operating temperature except from glass temperature is slightly higher when salt water is used. Indeed, the glass temperature of is less dependent of water type. Thus, water productivity is also slightly higher when using salt water compared to tap water. At the same condition, the fresh water productivity for the whole day for salt water is 2718.75 mL while it is 2443.5 mL for tap water.



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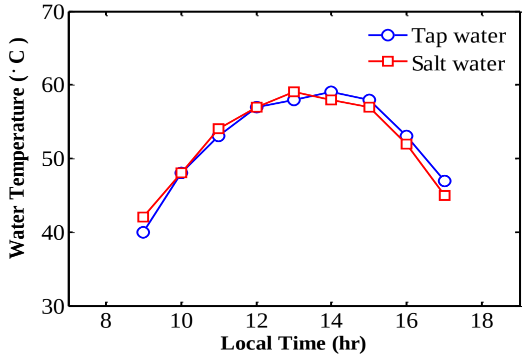

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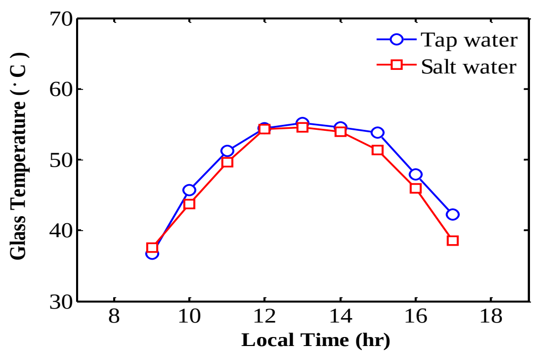

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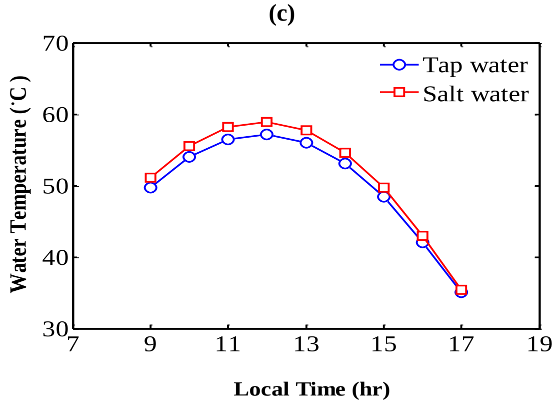

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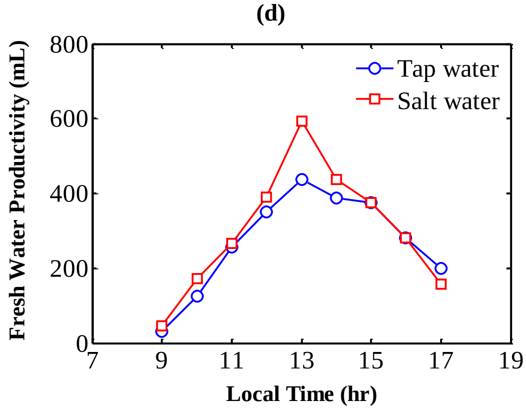


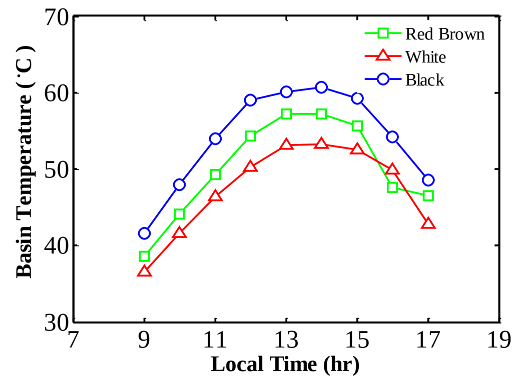
(e)

Fig. 7. Temperature distribution in solar still using tap water and salt water. Basin temperature (b) Water temperature (c) Glass temperature(d) Theoretical water temperature (e) Fresh water productivity.

4.4. Effect of Absorber Plate Colors on Temperature Distribution and Productivity

For observing the effect of absorber plate color, three different colors were used in the experiment.

The colors applied are black, red-brown and white. The experimental and theoretical results are shown in Figure 8. The results show that the difference in operating temperatures was significant for different absorber plate colors.



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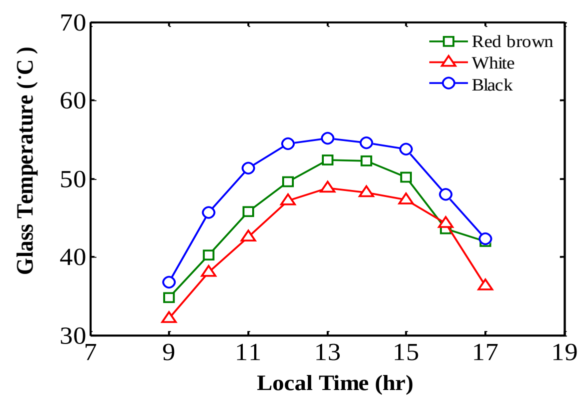

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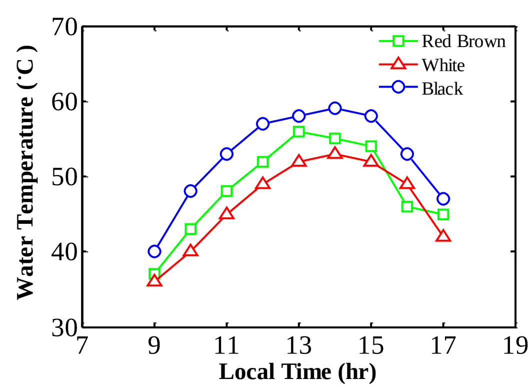

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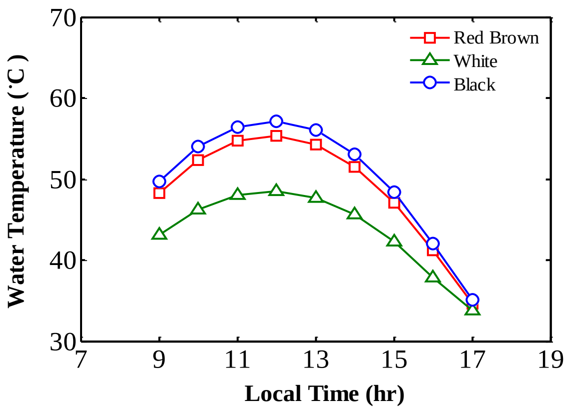

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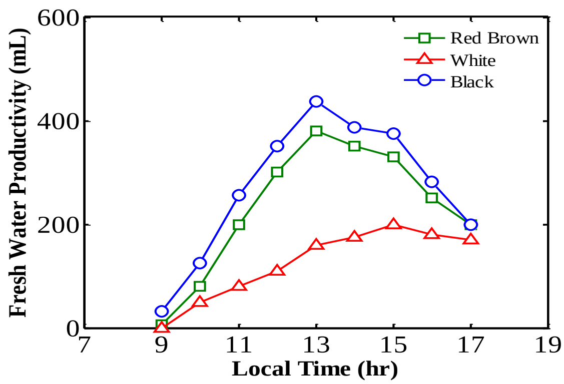

(e)

Fig. 8. Temperature distribution in solar still using absorber plate colours. Basin temperature (b) Water temperature (c) Glass temperature(d) Theoretical water temperature (e) Fresh water productivity.

It can be seen that the black absorber plate can create the highest operating temperature and water productivity while the white absorber plate shows the lowest performance. The red-brown absorber plate shows the second highest performance. The reason is that black color has the highest absorptivity while white has the lowest one which affects the amount of heat absorbed and stored in the absorber plate. The theoretically calculated temperatures also show good agreement with experimental data.

5. CONCLUSION

In this research, the effect of different parameters (water depth, water type, absorber plate colours) on the performance of a pyramid shape solar still was experimentally and theoretically investigated. The pyramid shape solar still was constructed with glass collectors which have a tilt angle of 45 °C. The thermal analysis is conducted for the weather from 23 April to 7 May in Mandalay. The experiments and theoretical calculations were conducted with the variations in water depths, water types and absorber plate colours. The following system parameters can be drawn based on the observations in this study.

- The water depth effect is obvious in the morning hours due to the fact that it requires more heat to evaporate the water when the water depth is larger. Thus, it consequently affects the water production of the solar still.

- Water type has a slight effect on the fresh water product. Salt water can produce more fresh water amount compared to tap water.

- The colors of the absorber plate have a significant effect on the operating temperature of a solar still. The black color can give the highest operating temperature compared to the red-brown color and white color.

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