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Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
ISSN (online): 2289-7879 | Vol. 15, No. 1. Pages 17-27, 2015

Efficient Water Recycling through Solar Distillation

K. Shehabuddeen[*,a], *H. H. Al Katyiem*[b] *and H. Mazhanash*[c]

Universiti Teknologi Petronas, 32610 Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia
[a,*]*kamashe@petronas.com.my*, [b]*hussain_kayiem@petronas.com.my*, [c]*haziqasiad@gmail.com*

Abstract – *The supply of clean water that can be used to meet human demands is very limited, where only less than one percent is available. Water scarcity faced by several countries in the world such as in Saudi Arabia, African countries and India has become worse each year due to the impacts of global warming thus limiting the clean water supply for their domestic use. The use of oil/diesel generators to purify and recycle used water or brackish water is very expensive and non-environment friendly; hence a need of developing a renewable energy water recycling method is to be addressed, as such provided by this project. A pyramid shape cascade solar still model is chosen from the several conceptual designs proposed. This model is the results from improvements of the previous designs to create a better efficient model. In this project, experiments and CFD simulations are conducted to determine the highest rate of fresh water production yielded by the solar still. The experiment is conducted using pre-heated tap water via solar heaters to increase the inlet water temperature that promotes efficiency of fresh water production from the solar still. From the experiment, a maximum rate of fresh water production of 0.47 kg/m2.hr is yielded which results a significant 57% increase in productivity when compared to a single slope cascade solar still model and 27% increase compared with an inclined solar still model. The CFD simulation predictions and the experimental results are agreeable with a percentage deviation ranging from 7.8% – 15.7% by comparing the rate of fresh water production from both types of analysis.*

Keywords: Solar still, Distillation system, CFD, Efficient water recycling

1.0 INTRODUCTION

The need for a clean water supply all over the globe has reached its limit where advancement in distillation and recycling technology to obtain clean water is needed. Taking an example of occurrence in Malaysia in the year of 2014 where several states; mainly Selangor faced critical water crisis due to the excessive and wasteful use of water by the people and developers in that respective area. According to reports by The Star, the water supply in peninsular Malaysia in 2050 will decrease approximately by 3000 m3 per year [1]. This assumption is based on the study that showed Malaysians use 226 litres of water per person on a daily basis which makes it among the highest among Southeast Asia countries. Other than resolving the present problem, long term consequences from the present action must be hugely considered. One method that can help resolves the water crisis and save the environment is by using water distillation processes powered by renewable energy sources, preferably solar. Solar distillation simply means using direct solar radiation to purify the salt water or the brackish water. The system works by heating the water till the evaporation point where water vapor will be formed and condensed on the inner surface of the glass and collected into the distillate tank. Solar distillation technology has been changed and improved by the researchers since the first solar distillation was developed in 1872 by Carlos Wilson, the creator of the first modern sun-powered desalination plant. By using solar energy for the water treatment, significant negative impacts to the environment can be reduced.

In this paper, the overall analysis focuses on maximizing the amount of fresh water production by the solar still. Each of the regions around the globe has different amounts of solar radiation per year and the suitability of the solar still design to be implemented is crucial in assuring a high fresh water production. The solar radiation vaporizes water from the sea and lakes, condenses it as a cloud and return to the earth as rainwater. Basin-type solar still replicate these concepts in a smaller scale and are the most common type of still system used for water distillation. Comparing basin-type solar still with basin-type solar wick still, the presence of the wick on the surface plate significantly affects the amount of distillate water being produced at the end of the day. Additionally, the wick has the ability to be tilted according to the orientation of the sun makes the basin-type wick still much preferable than the basin-type solar still. With that, Hikmet S. Aybar has conducted an experiment to determine the amount of distillate water being produced by varying the type of plate used where the evaporation of water takes place [2]. A bare plate painted to form a matt black surface, a black cloth wick and a black fleece wick were used as the variables in the experiment where the presence of wick helps in increasing the distillate production due to increase in residential time of the water flowing down the plate. Based on the theoretical and experimental result, an addition of the wick is the leading and economically preferred option for the distillation process [3].

A different study conducted by A. S. Nafey, they concluded that the presence of surfactants additives can enhance the boiling heat transfer of the water [4]. The surfactants reduce the surface tension of the water thus promote better evaporation efficiencies, however limited up to 300 – 400 ppm of surfactants concentration due to formation of foam once the concentration level reaches 500 ppm. Other than the additional of additives, Tiwari and Yadav had conducted a study on a multi-wick with the objective to increase the rate of evaporation of the brine [5]. The production of multi-wick is higher than that of the basin type due to the negligible heat capacity of the water mass. This type of still is only applicable in a medium scale application due to its complexity in design and maintenance. Experiment conducted by Minasian and al-Karaghouli showed that a combination of wick and basin still increases the productivity for about 85% more than basin still and 43% more than wick still [6]. The hot brine from the wick still will flow inside the basin still that is covered by a jute wick. The jute wick is soaked in cooling water to increase the temperature difference of the wick and the basin to promote the evaporation process.

Another study conducted by Fatemeh Bakhtiari Ziabiri used a stairs-like or cascade design for the still as the basic design which was modified throughout her study [7]. A significant increase of 26% of the fresh water production was recorded when compared to the initial site's unit. By including additional cotton black absorbers on top of each step for the cascade still, an increase in productivity up to 53% was recorded when compared to the conventional solar still [8]. One of the major concerns is the temperature difference inside the cavity. The higher the temperature difference, the higher the rate of evaporation by the water. Hence, Moustafa M. Elsayed has proposed a design together that incorporates a cover cooling [9]. The design will keep the glass cover cool to make sure there is huge temperature difference between the glass cover and the absorber plate. In this method, the evaporation rate increases alongside the productivity.

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
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Zeinab S. Abdel Rahim had proposed a design by using a packed layer of glass balls that act as the thermal storage for the still [10]. The glass ball with a diameter of 13.5 mm each was packed in one layer and placed at the bottom of the still to absorb heat and allow the model to be used during less solar radiation, or during the night. Another type of thermal storage that can be implemented is charcoal particles. Mona M. Naim proposed that by using charcoal, the productivity can be increased up to 15% when compared with the wick-type model [11]. This is due to the nature of charcoal that functions as the heat absorber and at the same time as a wick for the stills. The charcoal will absorb the required heat for the evaporation to occur after sunset and also acts as the wick where the coarse charcoal yields a high productivity when high flow rate of water entering the still was applied. Finer charcoal particles will also yield higher productivity but with a moderate flow rate due to water diffusion between the tiny particles which may result in a low rate of heat transfer. The low rate of heat transfer is due to the consequent temperature drop between the inside and outside of the particle.Skip a line space of 10 pts to start a new sub section.

Al-Karaghouli has proposed another method in his other study which is using a floated jute wick [12]. The jute wick will float with the help of a polystyrene sheet. It has been found that this method produces more distillate than the tilted wick design and basin type design. By using the floating wick, the dry areas on the wick can be avoided with the presence of goof capillarity of the floating wick fibers. The floating wick type is capable of increasing the productivity up to the range of 72% when compared to the simple basin type.

2.0 METHODOLOGY

By cooperating existing designs with new models from the research studies, 4 conceptual designs have been developed. The final design is selected is used for the CFD analysis by ANSYS FLUENT and experimental analysis using a working prototype is conducted to identify the potential of the design to yield high amount of fresh water. A CFD simulation of the design with respect to the boundary conditions of the real surrounding were carried out to analyze the flow of water and varying in temperature of the whole still. The accuracy of this simulation will be validated by the experiments.

The experimental setup for the experiment will be based on the pyramid shape still as in Figure 1. The bottom plate has an area of 504 x 504 mm^2 and followed by the first step with a height of 30 mm but with a much smaller area of 400 x 400 mm^2. Each step will have a width of 50 mm with a 4 mm weir to ensure an evenly water distribution from each tray to the subsequent tray below. Each tray plate will be painted black to enhance the absorptivity of solar radiation and also be filled with a charcoal granules which functioning as absorber medium to increase the rate of evaporation of the water to produce distillate. Each tray will be made from Perspex sheet with 4 mm thickness due to low cost and ease the fabrication works. 4 triangular Perspex of 4 mm thickness is being glued together with an epoxy and silicon glue and fitted on the top of the still to receive the solar radiation. The distillate will condensed on the inner surface of the glass and flowing down straight into the glass gutter which will channel the collected distillate into the distillate tank. The supply of water will come from the supply tank. The flow rate and quantity of the water inlet will be control by a ball valve attached at the end of flexible rubber hose at the brine inlet. A tap water will be directly used as the source for the feed water.

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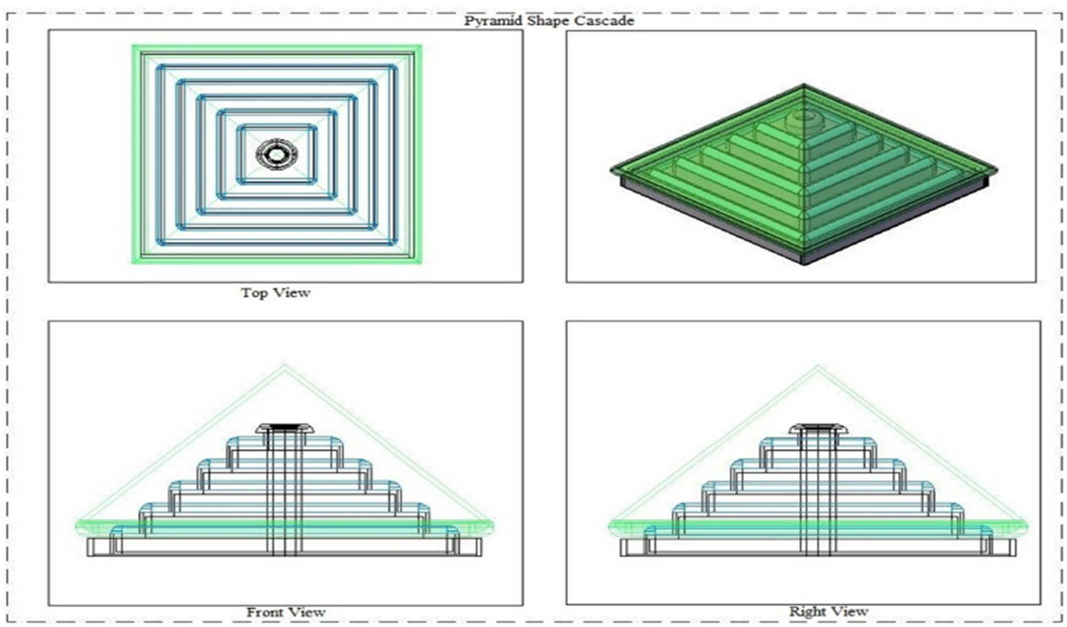

Figure 1: Isomeric drawing of the pyramid shape solar still

Figure 2 shows the setup of the experiment. The feed water will come from the inlet situated at the top of the still, siphon from the feed water container. The water will then moisture up the charcoal which is placed at each tray. The water will overflow to the next subsequent tray one after another until the water being eject at the bottom of the still through the outlet point.

Figure 2: The setup of the experiment

The water will undergoes evaporation while overflowing from one tray to another due to the temperature difference inside the still between the tray that contain the charcoal and the glass

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cover on top of the still. Type K thermocouples are placed at certain areas where the temperature of the water or surface need to be recorded for numerical analysis later. One thermocouple is placed at the base plate of the solar still to monitor the change in temperature of the water on the solar still, and another one thermocouple is placed on the surface of the glass cover to monitor the change in temperature for the glass cover. These two temperatures will determine the rate of evaporation occur inside the solar still, and the rate of fresh water production from the solar still.

2.1 Numerical Analysis

The mass flow rate of the distillate being produce is given by [13],

$$\dot{m} = \frac{q_{ew} A_b}{L} \tag{1}$$

The rate of evaporation of water is given by,

$$q_{ew} = h_{ew}(T_w - T_g) \tag{2}$$

The evaporative heat transfer coefficient is given by,

$$h_{ew} = (16.273 \times 10^{-3}).h_{cw}.\frac{P_w - P_g}{T_w - T_g} \tag{3}$$

Since temperature range is from 25°C to 60°C, Dunkle's relation can be use where [14],

$$h_{cw} = 0.884\sqrt[3]{\left[T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{(268.9 \times 10^3) - P_w}\right]} \tag{4}$$

With partial vapor pressure of water, P_w and glass cover P_g is found by relation,

$$P_w = \exp\left(25.317 - \frac{5144}{T_w + 273}\right) \tag{5}$$

$$P_g = \exp\left(25.317 - \frac{5144}{T_g + 273}\right) \tag{6}$$

3.0 RESULTS AND DISCUSSION

The CFD simulation is carried out to simulate the change in temperature between the glass cover and the water. A higher difference in temperature will ensure a high rate of evaporation to occur inside the still. From the rate of evaporation, the rate of fresh water production can be obtain by calculating the mass flow rate of distillate being produce with respect to time. Figure 3 shows the variation in change of temperature of the glass cover and the water in 9 different positions on the solar still.

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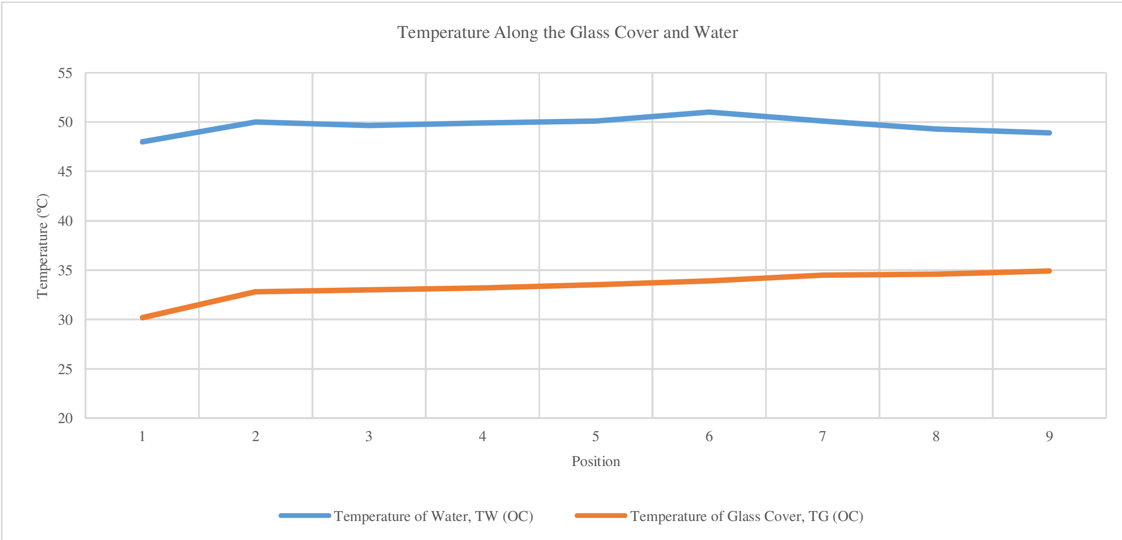

Figure 3: Temperature along the glass cover and water

From both of this temperature, the rate of fresh water production is calculated by conducting the numerical analysis. From the calculation, the rate of fresh water production obtained at different positions on the solar still is illustrated by Figure 4.

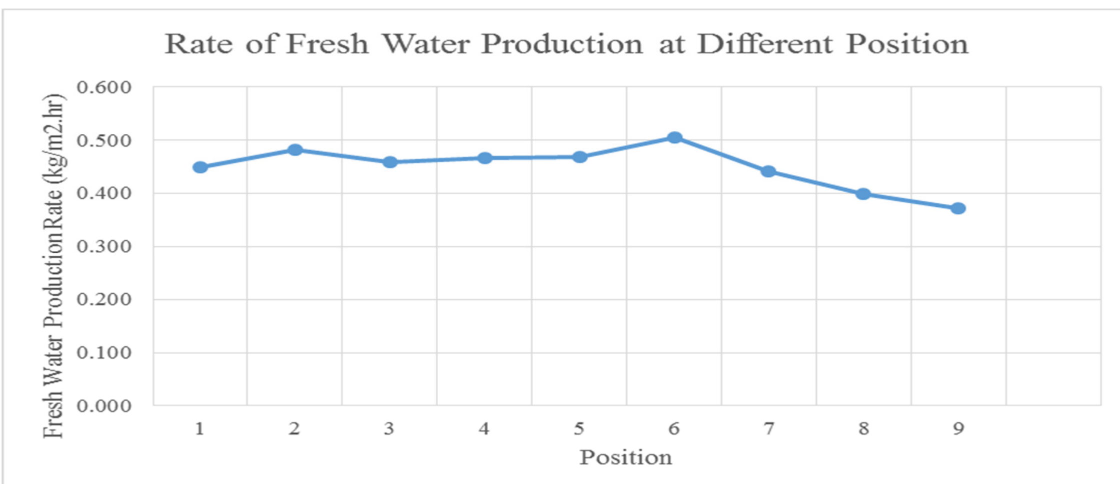

Figure 4: Rate of fresh water production from CFD simulation

The maximum rate of fresh water production predicted by the CFD simulation will be compared with experimental results obtained from the experiment conducted with working prototype. The experiment is conducted at Universiti Teknologi PETRONAS, Perak, Malaysia in the month of April for a duration of one week in total. The variation of results obtained from the experimental analysis starting from day 1 until day 7 can be refer from Figure 5 to Figure 11.

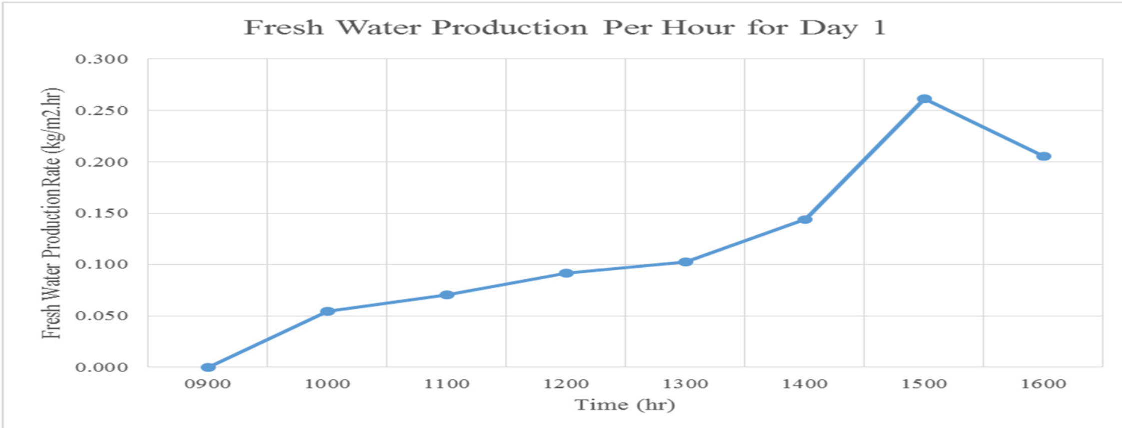

Figure 5: Rate of fresh water production on day 1

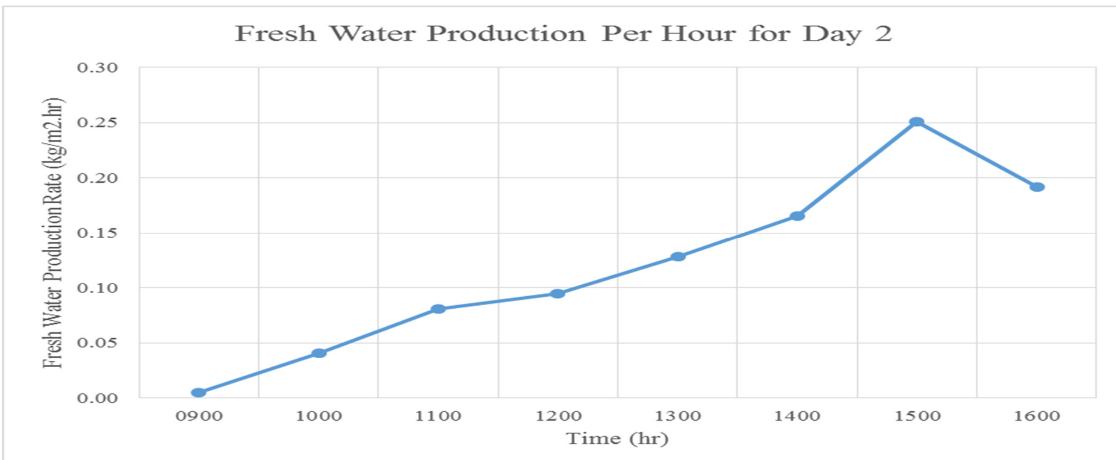

Figure 6: Rate of fresh water production day 2

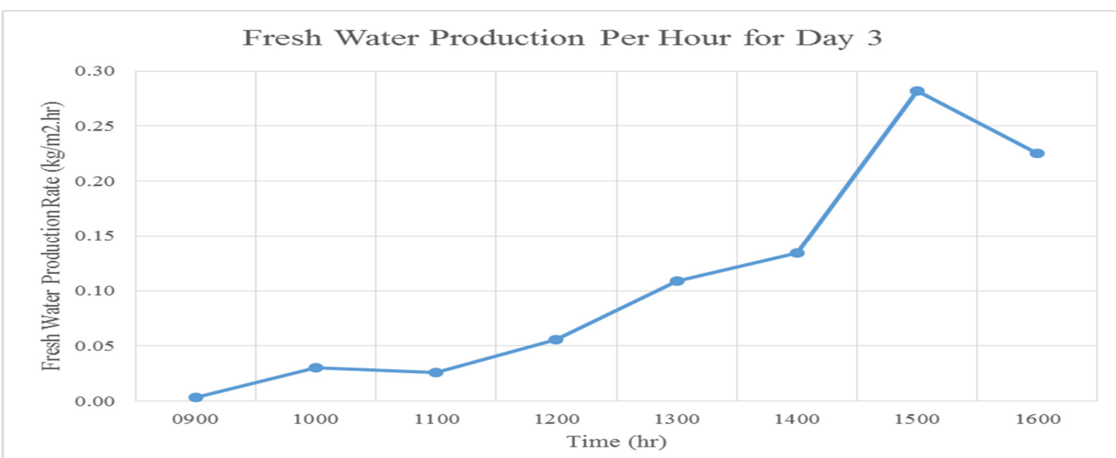

Figure 7: Rate of fresh water production day 3

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From the plotted graph observed in Figure 5 to 11, the rate of fresh water production increases slowly compared with results from day 5 until day 7 of the experiment. This is due to the weather conditions of the respective location of where the experiment is conducted. The Meteorological Department of Malaysia also stated that it is particularly intermittent to get one full day with a completely clear sky even during drought season [15]. An unclear sky blocks the sun's radiation from reaching the base plate, thus reducing the rate of evaporation that occurs inside the solar still.

Based on the following results, the pattern of the fresh water production for each day are closely similar. The maximum peak of the rate of fresh water production is between 1300 hours to 1500 hours where during this time the solar still acquire the maximum amount of solar radiation from the sun.

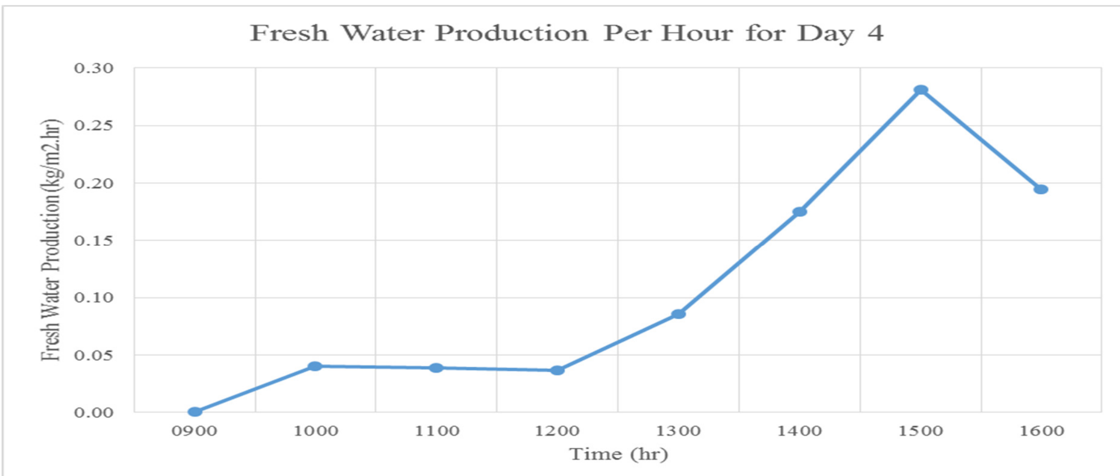

Figure 8: Rate of fresh water production day 4

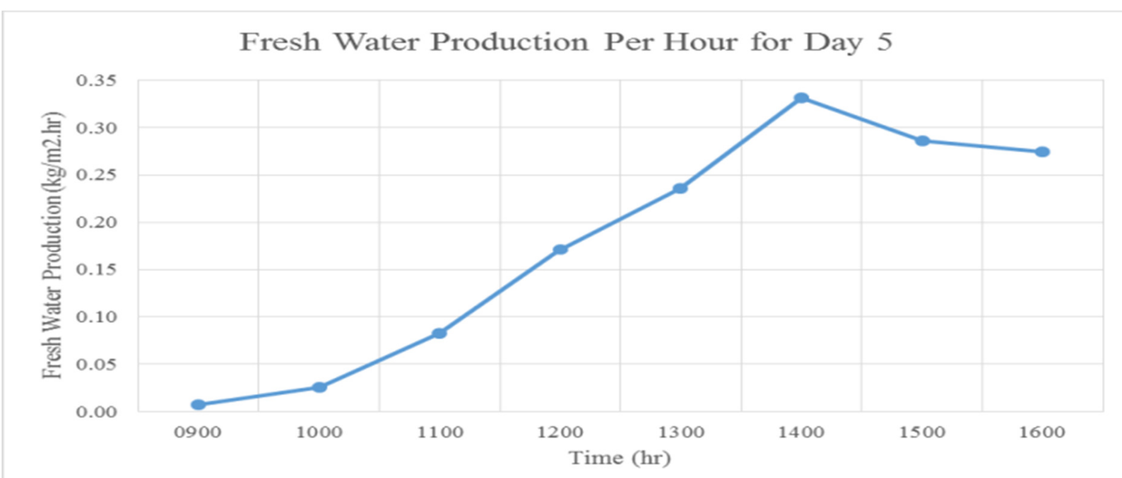

Figure 9: Rate of fresh water production day 5

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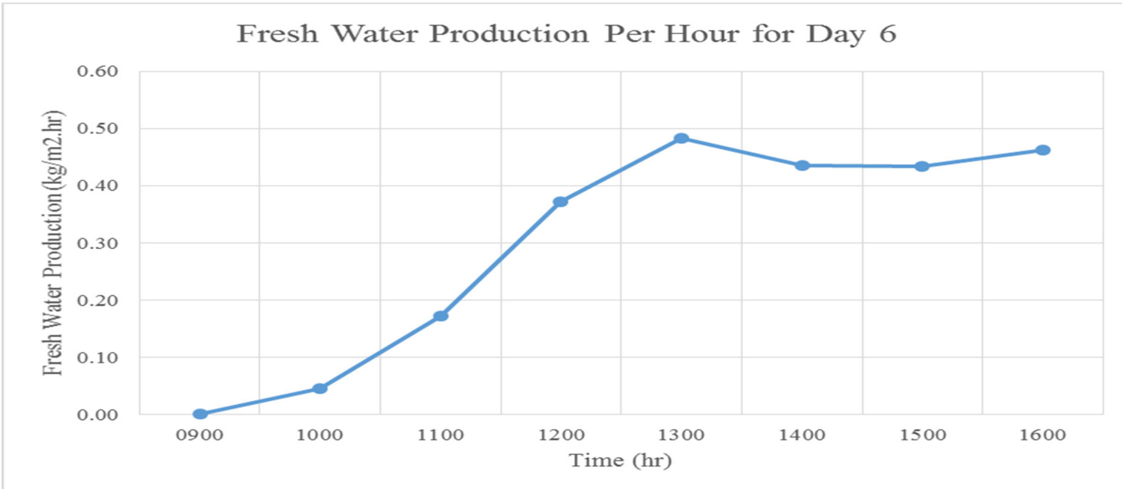

Figure 10: Rate of fresh water production day 6

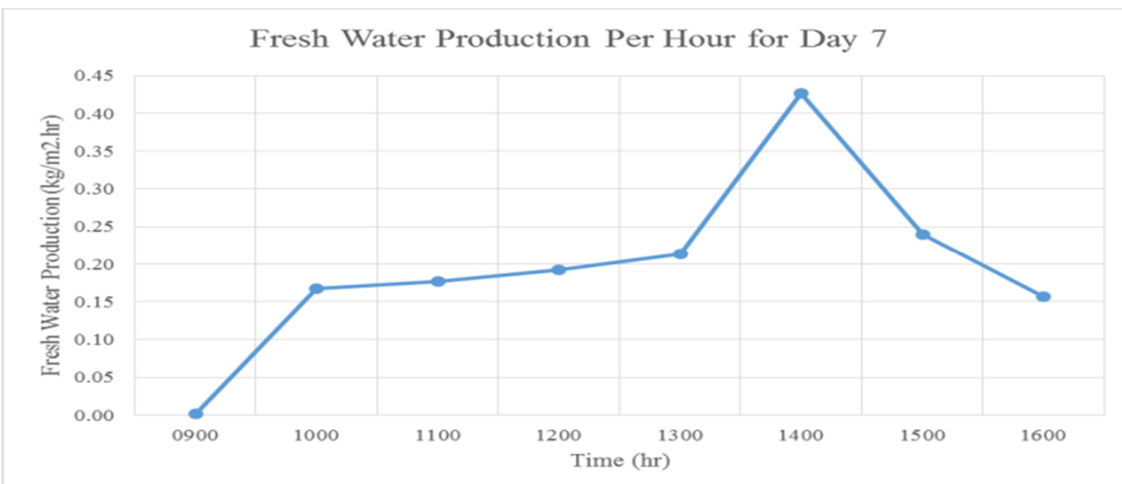

Figure 11: Rate of fresh water production day 7

Due to inconsistency of the weather during the experiment, the point for the fresh water production rate starts to increase differs for each day. From all seven (7) days of the experiment, the maximum rate for fresh water production peaked at 0.47 $kg/m^2.hr$ on the 6th day of the experiment.

By comparing the experiment analysis and the simulation analysis results, both results tally with one another. Since the CFD simulation only considered and simulate under the ideal condition of weather, the predicted results from the simulation is quite high when compared to the experimental analysis. From the CFD simulation, the highest production rate recorded is 0.51 $kg/m^2.hr$ while from the experiment results, day 6 shows the closest results with the simulation with a rate of 0.47 $kg/m^2.hr$, 0.47 $kg/m^2.hr$ and 0.43 $kg/m^2.hr$. This is due to the consistent weather conditions for the evaporation to occur. The three highest reading from the results for day 6 of the experiment is taken and compared with the maximum reading from simulation results in Table 1.

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Table 1: Comparison of CFD simulation results with experimental results

Results	**CFD Simulation Result (Max. Reading)**	**Experimental Results Day 6**		
		1st Reading	**2nd Reading**	**3rd Reading**
Temperature of water (°C)	51.00	51.40	51.50	51.00
Temperature of glass cover (°C)	33.90	35.40	36.30	36.30
Fresh water production rate (kg/m^{2}hr)	0.51	0.47	0.47	0.43
Deviation of results from CFD Simulation (%)		7.8	7.8	15.7

The percentage of deviation for the simulation result and the experiment results is calculated to be 7.8%, 7.8% and 15.7%. From both results, it clearly shows that pyramid shape cascade solar still shows a substantial increase in productivity when compared to other existing models even though being conducted in an equatorial climate. The pyramid shape cascade solar still manage to have a 57% increase in productivity when compared to single slope cascade still by Fatemeh Bakhtiari that only have 0.3 kg/m^2.hr of fresh water production rate and a 27% increase in productivity when compared to Hikmet inclined solar still with black fleece model that only have a 0.37 kg/m^2.hr rate of fresh water production.

4.0 CONCLUSSION

As the CFD simulation and experimental analysis is completed, it can be observed that the higher the rate of evaporation of water inside the solar still, the higher the rate of fresh water production. The temperature difference between the glass cover and the water inside the solar still will significantly affect the rate of evaporation that takes place. The higher the temperature difference results in a higher the rate of evaporation. The highest rate of fresh water production by the pyramid shape cascade solar still recorded during the experiment is 0.47 kg/m^2.hr, which shows an increase of 57% in productivity when compared to a single slope cascade solar still by Fatemeh Bakhtiari and a 27% increase when compared to an inclined solar still with black fleece model by Hikmet. In terms of fresh water production rate, the CFD simulation results are agreeable with the experimental results. Since the CFD simulation are simulated under the ideal condition of a weather, the predicted rate of fresh water production from the CFD simulation is 0.51 kg/m^2.hr, which has a percentage deviation of 7.8% to 15.7% when compared with the experimental results.

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