Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 6 Issue 4, April - 2019

Studies on Solar-Powered Water Purification with PCM Energy Storage

Wayne E. Aydt, Emmanuel C. Nsofor*
Department of Mechanical Engineering & Energy Processes, Southern Illinois University, Carbondale, IL, USA
*Corresponding Author: Email: nsofor@siu.edu

***Abstract*— This paper is on the development of a solar powered water purification system with Phase Change Material (PCM) energy storage and experimental studies done on the system. It has applications in many societies that lack adequate clean water. These societies also often lack the energy resources such as electricity that can be used for water purification. Water distillation was achieved in this study and analyses were performed on the effects of weather conditions on distillate production. Since solar systems are affected by limited sunshine that occurs only during daylight hours, a second part of the study involved adding a PCM heat exchanger to the system to extend distillation beyond daylight hours. Evaluation of the distillate production with respect to outdoor conditions such as temperature, wind speed, and use of the PCM heat exchanger were done to investigate performance of the system. Results show that high daytime temperatures and clear atmospheric conditions yield greater distillate production. Incorporation of the PCM heat exchanger added more time for distillate production beyond daylight hours, but overall, it resulted in lower daily production compared to when it was bypassed. The most definite indicator for distillate production was the temperature differential between the water entering the solar still and the outdoor temperature.**

Keywords—: distillation, energy storage, phase change material, PCM, solar, still, water purification

I. INTRODUCTION

The purpose of this study is to contribute a solution to the lack of adequate energy and clean water which is a problem that spans many areas of the globe. Accessibility to clean water is necessary for a healthy lifestyle. Many societies find it difficult to access clean water necessary for sustaining life. Addressing the problem calls for studies such as this to be conducted to identify robust new methods of purifying water at a lower cost and with less energy, while at the same time minimizing the use of chemicals and impact on the environment [1].

There are four general categories of drinking water contaminates: physical, biological, chemical and radiological.[2] This research focuses on the removal of biological and chemical contaminates using a solar still. Solar stills utilize the free energy from the Sun and the natural process of evaporation to capture purified water. Since evaporation is the mechanism of purification, this technology is effective for the complete removal of all chemical, organic, and biological contaminants within the feed water [3]. A simple solar still consists of a basin of raw water enclosed with a tilted glass cover. Solar radiation transfers heat to the inside of the still through the glass surface. The water vapor density of the air within the still increases due to evaporation from the water surface. Water condenses on the inner surface of the glass cover forming droplets which trickle down the tilted glass cover due to gravity. The condensed water is then collected [3, 4].

Solar distillation has been implemented for many years. However, there are difficulties that has limited the production of distilled water. The most common one has to do with the Sun not being available round the clock, primarily in the night. Other methods to heat the water during these times must be found. Following recent developments and advances in the application of Phase Change Materials (PCMs) in solar energy system [5-7], this study used a PCM for energy storage for that purpose.

The objective of this research was to develop a solar powered water purification system with PCM energy storage and to study the effects of weather on the distillate production based on a variety of parameters such as ambient temperature, wind speed, and atmospheric conditions. The study evaluated the effects of using PCM as a thermal energy storage (TES) device by comparing distillate production when using the PCM heat exchanger against distillate production when bypassing the PCM heat exchanger

II. DESIGN AND SELECTION OF SUBSYSTEMS

The basic design of a solar still relies on the natural process of evaporation that creates a miniature replica of the water cycle. Research on solar still design has resulted in improved performance by modifying the basic design.[4, 8, 9] It has been determined that in a basin still, the water depth is inversely proportional to the productivity of the still. Tripathia[10] determined through thermal modeling that “the internal convective heat transfer coefficient decreases with the increase of water depth in the basin due to a decrease in water temperature.” Because previous research results of the effects of water depth on still performance had been inconsistent, Khalifa[11] summarized several studies on brine depth effect with the primary goal to determine the effects of water depth on still performance. The study concluded that “the shallower the basin layer, the higher is the productivity. A thin layer of water attains higher temperatures compared to a deep layer because of its lower capacity. The study validated the decreasing trend in productivity with the increase of brine depth and showed that still productivity could be influenced by the brine depth by up to 48%.

It can be difficult to maintain a shallow level of water during the distillation process. Sharon et al.[12] reported on a study using a “wick”. A fabric wick is placed in the basin of the still retaining a minimal amount of water. As evaporation from the wick occurs, additional water is absorbed into the wick on a continuous basis. The advantage of the wick is to maintain a shallow depth of water while avoiding dry spots. A variety of wick materials have been tested, as well as different colors. Omara[13] concluded that “a still with light black cotton cloth was the most effective wick material.” Aybar[14] determined, that “the fresh water generation increased two to three times when wicks were used instead of bare plate.”

Another method for creating a thin layer of water is to use a tilted still. Water enters the top of the still and runs down a tilted backplane, creating a continuous shallow flow of water.[15] A tilted still requires continuous water flow and method to transport the water to the highest point of the still.

Several related options were considered for the design of the solar still system for this project.[3, 4, 6-9, 12-18] Some of the key design factors that were considered included: the source of power for the system which must be solar; the system must be able to evaporate water

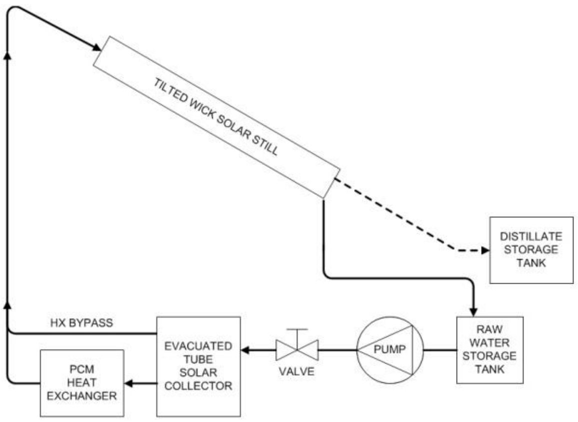


Fig.1. Diagram of System Components

inside the still and provide a means for separation of the distillate from the raw water; the design should maximize solar radiation through the condensing surface; and the system should minimize heat energy losses.

Figure 1 is a schematic representation of the system components and the flow of water through the system. The basic design involved a tilted wick solar still with a circulation pump for continuous water flow; a preheat device was installed for increased energy absorption; and a PCM heat exchanger was used for thermal energy storage.

The system has two water storage containers, one for the raw water and a second one for the distillate. Raw water was pumped from a storage tank through a preheat device. A pump was installed to drive the raw water through the system. A photovoltaic solar panel charge controller, and deep cycle battery shown in Figure 2 were used to provide power for the pump. A manual ball valve was inserted after the pump to control the flow rate of raw water through the system.

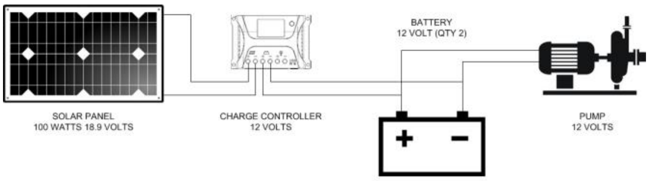


Fig. 2. Diagram of Electric Components

An Evacuated Tube Solar Collector (ETSC) was used as the preheat device. The ETSC preheats the raw water prior to entering the still. By preheating the water, the amount of additional heat required by the still to achieve evaporation is reduced.

A heat exchanger filled with the PCM was installed between the ETSC and the still. The PCM gains heat during daylight hours and melts. As it melts it stores latent energy in its liquid form. Water is distilled “normally” during daylight hours but as the sun goes down, there is less energy available and the raw water cools. The cooler water continues to be circulated through the system and the heat exchanger. Latent heat from the PCM is transferred back into the water, allowing distillate production to continue into the later hours of the day. A bypass line was installed to allow flow to bypass the heat exchanger providing ability to make a comparison between distillate production with or without the heat exchanger in the loop.

The heat exchanger is a shell and tube design built using a 6” PVC pipe, with end caps, as the shell and ¾” fin tube element for the tube as shown in Figure 3.

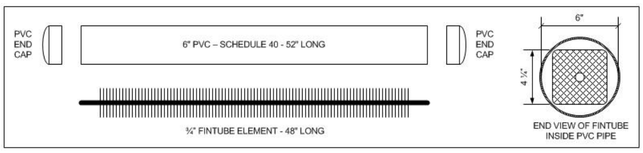


Fig. 3. Detail of Heat Exchanger Components

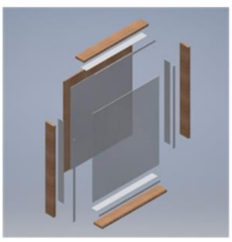
A fin tube element with small diameter tube was selected as the “tube” in lieu of a large diameter pipe. Previous studies[19, 20] determined that as the PCM solidifies around a pipe, it can create a barrier for the heat transfer into the rest of the fluid. The fin tube element allows the heat to be distributed more effectively through the PCM and displaces less volume within the heat exchanger.

A PCM is a material that has a high heat of fusion. By melting and solidifying at a precise temperature, it is capable of storing and releasing large amounts of energy. When selecting a PCM, the melting point of the PCM is the most important factor, so that it transitions between the solid and liquid states at the desired temperatures. PCMs that can be used for thermal energy storage applications include salt hydrate, paraffin waxes, fatty acids and sugar alcohols. The properties of PCMs that enhance thermal energy storage include possession of high latent heat of fusion and high specific heat. Other desired advantages are being chemically stable, non-toxic, and non-corrosive. The main disadvantages are, low thermal conductivity, toxicity, flammability, high cost, etc.

For the solar still component, a single slope, tilted wick design was used with fleece cloth as the wick material to cover the back plane from the top to the bottom of the still. The water that flows into the still wets and saturates the wick serving two purposes; it reduces the “depth” of the water in the still, which has been shown to improve performance, and also it eliminates “dry spots” within the still as evaporation occurs.

Energy loss reduction requires that the still be very well insulated. The shell of the still was constructed of plywood, which has low thermal conductivity. A one-inch layer of polystyrene foam insulation was sandwiched between the plywood and the aluminum “tub” that forms the primary still compartment as illustrated in Figures 4 and 5.

Glass was selected as the condensing surface because it allows solar radiation into the still, while preventing radiation from leaving the still. An aluminum rod was attached to the glass above the distillate trough to provide a barrier and collection point for the condensate. The condensate gathers on the aluminum rod allowing it to drip down into the distillate trough where it flows to the distillate storage tank. Raw water that has not evaporated enters the raw water trough and returns to the raw water storage tank



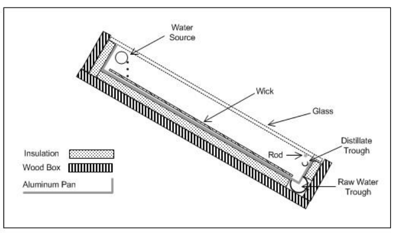


Fig. 4. Exploded View of Still   Fig. 5. Side View of Still Design

For data acquisition, four thermocouple sensors, labeled T1 thru T4 in Figure 6, were installed to record the water temperature at various points in the system. Distillate production was measured by using a tipping bucket meter, labeled F1 in Figure 6. Ambient temperature, wind speed, and atmospheric conditions were recorded and used to study the effects of weather on distillate production. Raw water flow was manually switched to flow through either the bypass or the PCM heat exchanger so that the effects of thermal energy storage on distillate production could be determined.

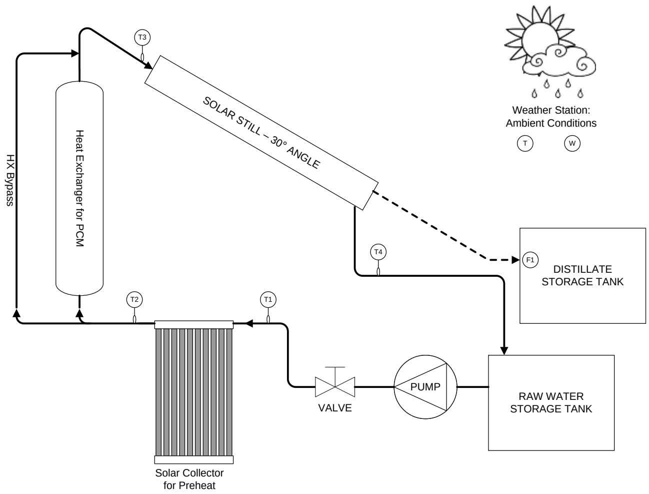


Fig. 6. Schematic of System Components

A weather station located at the site of the still, was used to record the ambient temperature and wind speed. Atmospheric conditions were obtained from the local airport records. Raw water was obtained from a rain water harvesting tank.

The solar components face due south at an angle 30° above the horizontal to provide optimum solar absorption for the site in Southern Illinois where the still is located.[21] The thermal solar collector sits in front of the solar still with the photovoltaic solar panel mounted “above” the solar still as shown in Figure 7. The weather station, circled in the figure is adjacent to the still.

Fig. 7. Solar Still System (Side View)

The solar still sits atop a frame designed to house other components. The frame has two sections within the base. The lower section houses the batteries, pump, valve, solar charger, and distillate container while the upper section contains the raw water tank, which allows gravity to feed the raw water to the pump in the lower section. The heat exchanger and bypass line were mounted to the side of the still frame.

Since sustainability is one of the focal points of this project, there was the need to use a PCM that is stable, non-toxic, non-flammable, renewable and biodegradable. The PCM used in this project is Puretemp 23 [22] that is solid at room temperature but has a relatively low melting temperature. It is a patented natural vegetable-based phase change material derived from 100% renewable resources. It is stable, biodegradable, non-toxic and non-flammable. Thermophysical properties of the PCM are shown in Table1. More technical data on it are shown in Figure 8.

TABLE 1: PURE TEMP 23 TECHNICAL INFORMATION

Property	Value
Appearance	clear liquid, waxy solid
Melting Point	23°C
Heat Storage Capacity	227 J/g
Thermal Conductivity (liquid)	0.15 W/m K
Thermal Conductivity (solid)	0.25 W/m K
Density (liquid)	0.83 g/mL
Density (solid)	0.91 g/mL
Specific Heat (liquid)	1.99 J/g K
Specific Heat (solid)	1.84 J/g K

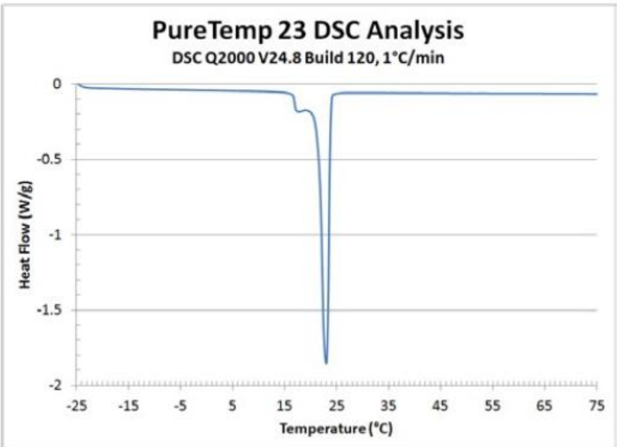


Fig. 8. PureTemp 23 Technical Data

The latent heat of the PCM is a representation of how much energy can be stored in the PCM. Using the mass of the material (m_{pcm}) and the latent heat value (Q_{latent}), the amount of energy needed to melt the PCM (Q_{pcm}) was calculated using Equation 1:

$$Q_{pcm} = m_{pcm} \, x \, Q_{latent} \quad (1)$$

The mass of the PCM was calculated using the volume of the heat exchanger and the density of the PCM in its liquid state. Equation 2 was used to calculate the volume of the PCM in the heat exchanger.

$$V_{PCM} = L_{HX} \cdot \frac{\pi(D_{shell}^2 - D_{tube}^2)}{4} \quad (2)$$

The fin tube is 123 cm (48 inches) long, so the heat exchanger shell was cut to 132 cm (52 inches), allowing adequate space for pipe extensions to be soldered to the fin tube.

$$V_{PCM} = 52 \cdot \frac{\pi(6.0^2 - 0.75^2)}{4} = 1400 \, in^3 \approx 23000 \, cm^3 = 23000 \, mL$$

The density of the PCM is 0.83 g/mL (liquid) gave the mass of the PCM as 19000 g. The heat storage capacity of the PCM is 227 J/g. Using Equation 1, Q_{PCM} was obtained as 4.3 kJ. Since the heat to be stored in the PCM is equal to the amount of heat to be transferred from the water, this energy can be stored in the heat exchanger.

The velocity of the raw water passing through the fin tube was obtained as

$$Velocity \; of \; Flow = \frac{Rate \; of \; Flow}{Area \; of \; Fin \, Tube}$$
(3)

$$Area \; of \; Fin \; Tube = \frac{\pi(D_{tube})^2}{4} = \frac{\pi(0.75)^2}{4} = 0.4418 \, in^2$$

$$Velocity \; of \; Flow = \left[\frac{\left(0.5 \, \frac{gallon}{minute}\right) \cdot \left(\frac{231 \, in^3}{gallon}\right) \cdot \left(\frac{1 \, minute}{60 \, seconds}\right)}{0.4418 \, in^2} \right] = 4.36 \, \frac{in}{sec} \approx 11 \, \frac{cm}{sec}$$

The Fin Tube element has a rating of 776 BTU/hr./foot at a flow rate of 3 ft/sec and 150°F.[23] The Fin Tube element is 4 feet in length.

$$776 \frac{BTU}{hr \cdot ft} \cdot 4 \, ft = 3104 \frac{BTU}{hr}$$

$$\left(3104 \frac{BTU}{hr}\right) \cdot \left(\frac{1 \, Watt}{3.413 \, \frac{BTU}{hr}}\right) = 909 \, W = 909 \frac{J}{s}$$

Thermal Energy Storage of the PCM is 200 J/g and the Density = 0.91 g/ml. This implies that

$$23000 \, mL \cdot 0.91 \frac{g}{mL} = 20930 \; grams \; of \; PCM \; (solid)$$

$$(20930 \, g) \cdot \left(200 \frac{J}{g}\right) = 4186000 \, J$$

$$4186000 \, J \div 909 \frac{J}{s} = 4605 \; seconds = 77 \; minutes$$

$$4186000 \, J \div 909 \frac{J}{s} = 4605 \; seconds = 77 \; minutes$$

The PCM should be able to maximize its thermal energy absorption within the afternoon hours allowing for optimum performance of the heat exchanger.

III. RESULTS AND ANALYSIS

The system was operated between July and December. The four water temperature sensors recorded values every two minutes. The weather station recorded data every twelve minutes. The wind speed was averaged over the twelve minute period by the weather station. The tipping bucket meter creates an "event", "0" or "1", each time the bucket tips. Daily distillate production was divided by the total tips per day yielding an average of 1.50 mL of distillate per tip. The distillate produced each hour was calculated and compared to the hourly averages of the other parameters.

Several factors can affect the performance of the system, so it was necessary to study the effects individually. The performance of the still was studied first with water allowed to flow through the heat exchanger and then with the water bypassing the heat exchanger. The other factors studied that affect the performance of the system are atmospheric conditions including cloud cover, wind speed, and the ambient temperature. For each case, data set was obtained for the best performance of the system. Recommendations for improvement of the performance of the system were made based on the results.

The results on the distillate production for July/August is illustrated in Figure 9. The tipping bucket meter was used to measure the distillate production and the total volume for each hour was obtained. The bar graph shows the distillate production when the flow is through the PCM heat exchanger compared to when the flow bypasses the heat exchanger.

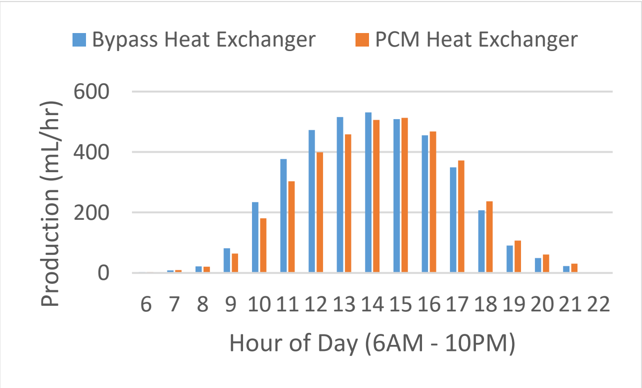


Fig. 9. July/August Distillate Production – Bypass vs PCM Heat Exchanger

During the morning hours, distillate production is observed to be higher when the flow bypasses the heat exchanger, but during the evening hours, distillate production is observed to be greater when flow goes through the PCM heat exchanger.

Figure 10 illustrates the results for the months of November and December. Figures 9 and 10 show that there is drastic reduction in distillate production between the July/August months and the November/December months. Figure 10 shows that like the summer months, during the morning hours, distillate production is greater when the flow bypasses the heat exchanger compared to when it goes through the heat exchanger but during

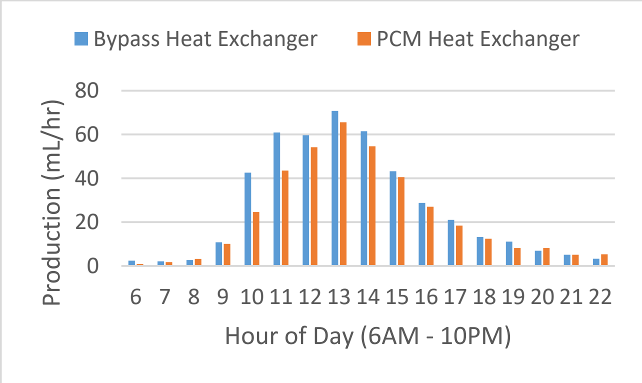


Fig. 10. November/December Distillate Production – Bypass vs PCM Heat Exchanger

the evening hours, distillate production is observed to be about the same for both.

Some of the results seen in Figures 9 and 10 can be explained by the fact that in the system, raw water flow from the solar collector passed through the PCM heat exchanger prior to entering the solar still allowing the PCM to extract and store energy from the water prior to reaching the solar still. Since the peak production hours of the solar still were between 10:00 and 14:00, distillate production was reduced during the peak hours when the flow was going through the PCM heat exchanger. Although better production was seen in the afternoon and evening hours when using the PCM heat exchanger compared to the bypass, the overall daily distillate production was observed to be lower when using the PCM heat exchanger.

Atmospheric conditions were obtained from the local airport. The different conditions studied include clear sky, partly cloudy sky, mostly cloudy sky, light rain, thunderstorms, overcast, fog, etc. For the analysis, the conditions were reduced to four categories, namely, clear, partly cloudy, mostly cloudy, and overcast. Each category was given a numerical value as shown in Table 2. Clear skies were given the highest value since "clear" provided the best distillate production.

TABLE 2: ATMOSPHERIC CONDITIONS (NUMERICAL VALUES)

Skies	Value
Clear	4
Partly Cloudy	3
Mostly Cloudy	2
Overcast	1

Figure 11 is a scatter chart of the daily average atmospheric conditions versus distillate production for the months of July, August, September, and a

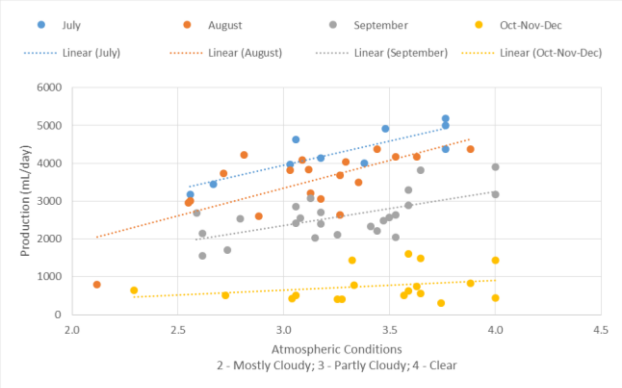


Fig. 11. Atmospheric Conditions vs Production

combination of October thru December. Daily average was calculated and comparison was made with the overall distillate production for that day. Daily average was for the hours of 6:00 to 22:00. The hours the still was not producing were excluded. The days when the PCM heat exchanger was used were excluded here because the PCM had a negative effect on the daily distillate production. The still was run on days when the forecast was for partly cloudy skies or better.

Table 3 shows the linear trend line for each set of data. It indicates an increase in distillate production with respect to clear atmospheric conditions. The regression (R^2) values vary from the highest at 0.8584 in September, 0.7205 for July, to 0.5113 in August. The R^2 value for Oct thru Dec, is the lowest at 0.1831, possibly due to low distillate production during those months.

TABLE 3: ATMOSPHERIC CONDITIONS VS PRODUCTION – BEST FIT LINE AND REGRESSION ANALYSIS

Description	Best Fit Line	R^2	R
ATMOSPHERIC CONDITIONS vs PRODUCTION (July)	y = 1270.4x+133.58	0.7205	0.8488
ATMOSPHERIC CONDITIONS vs PRODUCTION (AUGUST)	y = 1428.3x - 944.07	0.5113	0.7151
ATMOSPHERIC CONDITIONS vs PRODUCTION (SEPTEMBER)	y = 1388x - 1635.9	0.8584	0.9265
ATMOSPHERIC CONDITIONS vs PRODUCTION (OCT-DEC)	y = 413.21x - 468.19	0.1831	0.4279

Table 4 shows the comparison between atmospheric conditions and distillate production for the period of August 8th through August 24th.

TABLE 4: VARIATION OF DISTILLATE PRODUCTION WITH ATMOSPHERIC CONDITIONS

Date	Atmospheric Conditions	Distillate Production
8/8/2017	3.5	4170 mL
8/9/2017	3.3	4040 mL
8/10/2017	3.2	3050 mL
8/11/2017	2.1	800 mL
8/12/2017	2.7	3740 mL
8/13/2017	3.1	4080 mL
8/18/2017	3.4	3500 mL
8/19/2017	3.6	4180 mL
8/20/2017	3.3	2640 mL
8/21/2017	3.1	3210 mL
8/23/2017	3.4	4370 mL
8/24/2017	3.9	4370 mL

The largest distillate production of 4370 mL occurred on August 24th, when the average atmospheric condition was the greatest at 3.9. The lowest distillate production of 800 mL, occurred on August 11th, corresponding to the date with the lowest average atmospheric conditions of 2.1. August 8th, 9th, 13th, 19th, and 23rd follow accordingly with distillate production above 4000 mL corresponding to average atmospheric conditions of between 3.1 and 3.6. August 10th, 12th, 18th, and 21st has distillate productions of 3050 mL, 3740 mL, 3500 mL, and 3210 mL respectively, corresponding to average atmospheric conditions of 3.2, 2.7, 3.4 and 3.1. For the most part, the data represent a positive relationship to the fact that clearer skies result in greater distillate production.

Figure 12 displays the effect of wind speed on distillate production. It displays the comparison between the average wind speed and distillate production for the seven day period of August 18th thru August 24th, when the still was run in the bypass mode. August 21st results show a large dip in the wind speed and distillate production at midday. However, compared to the other days' results, such as August 19th and 24th, similar reactions to the wind speed were not seen.

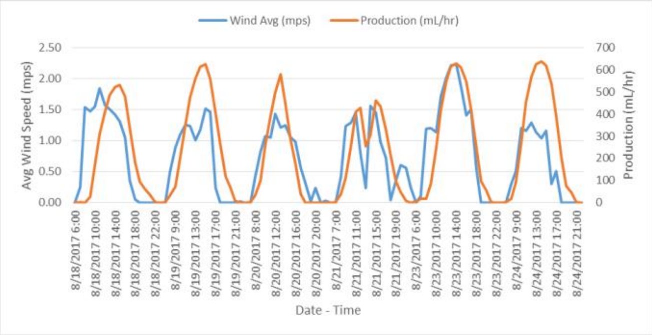


Fig. 12. Comparison of Average Wind Speed with Production

Figure 13 displays a scatter plot representation of average wind speed versus distillate production. Although a positive linear relationship exists, it is not a well-defined line with R^2 regression value of 0.5288. From these two figures, it can be deduced that there does not seem to be a significant relationship between the wind speed and distillate production.

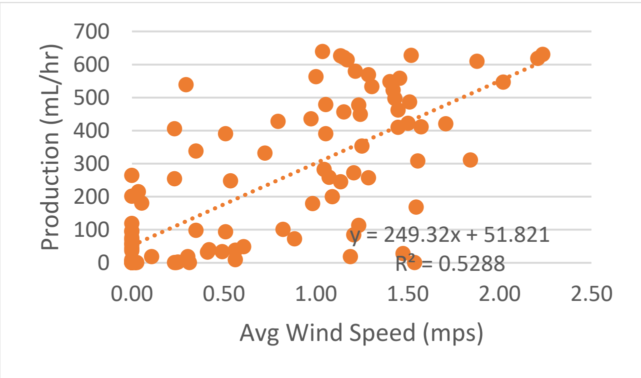


Fig. 13. Average Wind Speed vs Production

Comparison of the ambient temperature versus distillate production is shown in Figure 14. Reviewing Figures 9, 10, and 12, a pattern can be seen showing that distillate production peaks at midday when ambient temperatures and solar insolation are typically at their highest. From Figure 10, it can be seen that overall production in the months of November and December was much lower than the production displayed in Figure 9 for the months of July and August, strengthening the conclusion that ambient temperature has a significant effect on distillate production.

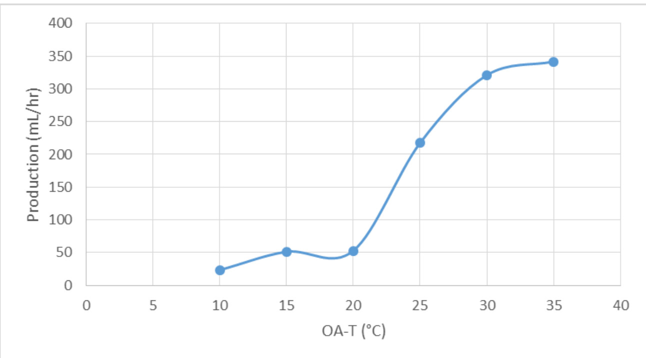


Fig. 14. Ambient Temperature vs Production

Figure 15 is a surface chart of hourly distillate production compared to both outside air temperature and atmospheric conditions. The results show the combined effects of ambient temperature and other ambient conditions on distillate production. When high ambient temperatures coincide with clear skies, the greatest hourly distillate production are shown to occur.

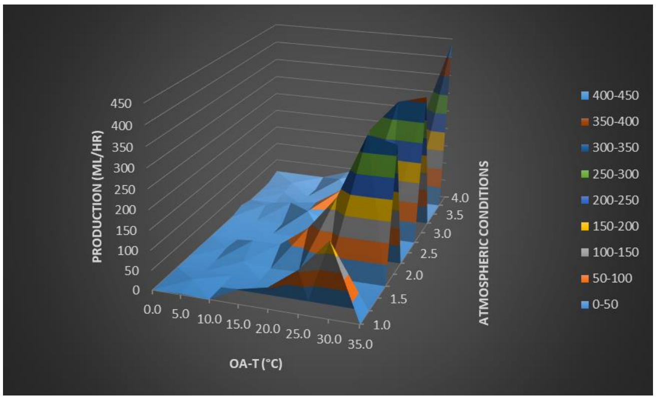


Fig. 15. Ambient Temperature and Atmospheric Conditions vs Production

The parameter that was found to be the best indicator of distillate production is the temperature difference between the raw water and the ambient conditions. Figure 16 shows the effects of this temperature difference on the distillate production. It demonstrates a strong linear relationship between the temperature differential of the raw water as it leaves the still and the ambient air temperature on the distillate production. The results shown in the figure are inclusive of all scenarios for which the system was run. The only exclusion was when the temperature differential was less than 10°C.

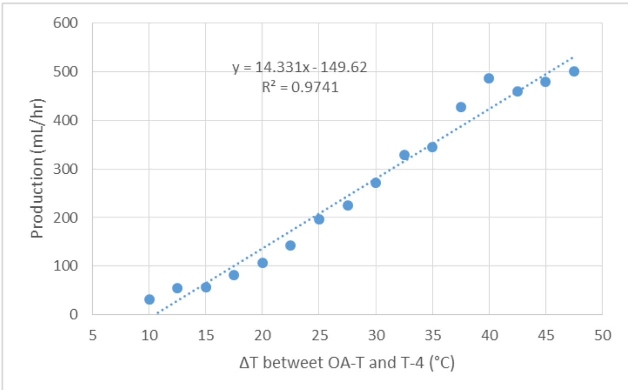


Fig. 16. ΔT Between Water and Ambient Temperature vs Production

The results confirm the expectations. Distillate production is dependent upon evaporation, leading to high relative humidity within the still, followed by condensation on the glass. The greater the differential between temperature of the glass and the dew point of the air within the still, the greater is the condensation which results in larger distillate production.

The R^2 value of 0.9741 represents a strong correlation between the temperature difference and distillate production. To increase distillate production, the temperature differential needs to remain high. This is an important factor that should be taken into consideration in the design and improvement of this system.

IV SUMMARY AND CONCLUSIONS

One of the conclusions reached is that the system achieved the aim of demonstrating energy storage and water purification together. Based on the scale of this system, projections show that it can be extended to home building applications. The study also shows that distillate production is affected by a number of factors. Distillate production peaked when the ambient temperature increased along with atmospheric conditions that were clear or mostly clear as can be seen in Table 1. Under these conditions, the temperature of the raw water entering the still was maximized by the preheat device and there was increased solar insolation on the still. These circumstances resulted in the highest yield of distillate production. When atmospheric conditions were mostly cloudy or overcast, distillate production decreased, but that could also be related to the lower ambient temperatures that correspond to the cloud cover. The study of wind effects on distillate production showed that there was not a strong correlation between wind speed and distillate production. Distillate production decreased as the season advanced from summer to fall, which correspond to shorter days, lower solar insolation, and cooler ambient temperatures. Even on days in fall, when atmospheric conditions were clear the results still showed low distillate production.

On the effects of energy storage using the PCM heat exchanger together with distillation production, results show that the heat exchanger absorbed heat in the morning hours, and released it into the system in the evening, as desired. However, the overall performance of the solar still declined when the heat exchanger was in use as thermal energy was transferred from the raw water prior to entering the still. This led to reduction in distillate production between the peak production hours of 11:00 and 14:00. This had a greater negative effect that could not be overcome when production was increased later in the day using the energy stored. A study will need to be done to determine the appropriate times and conditions for bypassing the PCM heat exchanger for energy storage in order to achieve maximum distillate production.

Another significant conclusion reached in this study is that a strong linear relationship exists between the temperature differential of the raw water as it leaves the solar still and the ambient air temperature on the distillate production.

ACKNOWLEDGEMENTS

The authors are very grateful to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) for funding received, to Entropy Solutions, LLC for donating PCM and to Tim Attig, Sulaiman Alareefi, Mary Sophie Hall, Braden Hull, and Austin Peterson for valuable contributions during the development and construction of the system.

REFERENCES

1. M. A. Shannon, P. W. Bohn, M. Elimelech, J. G. Georgiadis, B. J. Mariñas, and A. M. Mayes, ‘Science and Technology for Water Purification in the Coming Decades‘, Nature, vol. 452: p. 301-310, 2008.

2. https://www.epa.gov/ccl/types-drinking-water-contaminants. Types of Drinking Water Contaminants. [Cited 2017 September 20].

3. C. Ray, and R. Jain, “Drinking Water Treatment: Focusing on Appropriate Technology and Sustainability”, Springer. vol. 260, 2011.

4. T. Arunkumar, K. Vinothkumar, A. Ahsan, R. Jayaprakash, and S. Kumar, “Experimental Study on Various Solar Still Designs”, ISRN Renewable Energy, pp. 10, 2012.

5. A. K. Pandey, M. S. Hossain, V. V. Tyagi, N. A. Rahim, Jeyraj A. L. Selvaraj and A. Sari, “Novel approaches and recent developments on potential applications of phase change materials in solar energy”, Renewable & Sustainable Energy Reviews, vol. 82, p. 281-323, February 2018.

6. A. Shukla, K. Kant, and A. Sharma, “Solar still with latent heat energy storage: A review”, Innovative Food Science & Emerging Technologies, vol. 41, pp. 34-36, June 2017).

7. A. E. Kabeel, and M. Abdelgaied, “Improving the performance of solar still by using PCM as a thermal storage medium under Egyptian conditions”. Desalination, vol. 383: pp. 22-28, 2016.

8. S. Manikandan, G. Mohanraj, M. Nandhakumar, P. Neelamanikandan, M. Selvaraj, B. S. Gandhi, and N. Balakrishnan, “Design of Solar Stills on Water Distillation”, IJARIIE-ISSN(O)-2395-4396, vol. 3, 2017.

9. A. J. N. Khalifa, A.S. Al-Jubouri, and M.K. Abed, “An experimental study on modified simple solar stills”. Energy Conversion & Management, vol. 40 pp. 1835-1847, 1999.

10. R. Tripathi and G.N. Tiwari, “Thermal modeling of passive and active solar stills for different depths of water by using the concept of solar fraction”. Sol Energy, vol. 80: pp. 956-967, 2006.

11. A. J. N. Khalifa and A. M. Hamood, “On the verification of the effect of water depth on the performance of basin type solar stills”, Solar Energy, vol. 83: pp. 1312-1321, 2009.

12. H. Sharon, K. S. Reddy, D. Krithika, and L. Philip, "Experimental performance investigation of tilted solar still with basin and wick for distillate quality and enviro-economic aspects". Desalination, vol. 410, pp. 30-54, 2017.

13. Z. M. Omara, M. A. Eltawil, and E.A. ElNashar, "A new hybrid desalination system using wicks/solar still and evacuated solar water heater" Desalination, vol. 325: pp. 56-64, 2013.

14. H. S. Aybar, F. Egeliofglu, and U. Atikol, "An experimental study on an inclined solar water distillation system", Desalination, vol. 180, pp. 285-289, 2005.

15. S. A. El-Agouz, "Experimental investigation of stepped solar still with continuous water circulation", Energy Conversion and Management, vol. 86, pp. 186-193, 2014.

16. K. Selvaraj and A. Natarajan, "Factors influencing the performance and productivity of solar stills - A review", Desalination, vol. 435, 1 June 2018.

17. A. E. Kabeel, T. Arunkumar, D. C. Denkenberger, and R. Sathyamurthy, "Performance enhancement of solar still through efficient heat exchange mechanism – A review". Applied Thermal Engineering, vol. 114, pp. 815-836, 2017.

18. M. Al-harahsheh, M. Abu-Arabi, H. Mousa, and Z. Alzghoul, "Solar desalination using solar still enhanced by external solar collector and PCM, Applied Thermal Engineering, vol. 128: pp. 1030-1040, 2018.

19. A. Shinde, S. Arpit, P. K. M. Peddy, V C. Rao and S. K. Saha, "Heat Transfer Characterization and Optimization of Latent Heat Thermal Storage System Using Fins for Medium Temperature Solar Applications" Journal of Solar Energy Engineering - Transactions of the ASME, vol. 139(3), 2017.

20. A. Abdulateef, S. Mat, J. Abdulateef, K. Sopian, A. A. Al-Abidi, "Geometric and design parameters of fins employed for enhancing thermal energy storage systems: a review", Renewable & Sustainable Energy Reviews, vol. 82, pp. 1620-1635, 2018.

21. http://solarelectricityhandbook.com/. Solar Irradiance. [Website] 2009-2017 [cited 2018 February 18].

22. http://www.puretemp.com/. PureTemp 23 technical data sheet. 2018 [cited 2017 March 12].

23. http://www.slantfin.com/. Fin Tube / Bare Element C-340. 2017 [cited 2017 February 21].