ENHANCEMENT OF MODIFIED SOLAR STILL INTEGRATED WITH EXTERNAL CONDENSER USING NANOFLUIDS: AN EXPERIMENTAL APPROACH

A.E. Kabeel[1]*, Z.M. Omara*[2]*, and F.A. Essa*[3]

[1] *Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt, E-mail: kabeel6@hotmail.com*
[2] *Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, Egypt, E-mail: zm_omara@yahoo.com*
[3] *Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, Egypt, E-mail: fadlessa@eng.kfs.edu.eg*

ABSTRACT

The distilled water productivity of the single basin solar still is very limited. In this context, the design modification of a single basin solar still has been investigated to improve the solar still performance through increasing the productivity of distilled water. The experimental attempts are made to enhance the solar still productivity by using nanofluids and also by integrating the still basin with external condenser. The used nanofluid is the suspended nanosized solid particles of aluminum-oxide in water. Nanofluids change the transport properties, heat transfer characteristics and evaporative properties of the water. Nanofluids are expected to exhibit superior evaporation rate compared with conventional water. The effect of adding external condenser to the still basin is to decrease the heat loss by convection from water to glass as the condenser acts as an additional and effective heat and mass sink. So, the effect of drawn vapor at different speeds was investigated. The results show that integrating the solar still with external condenser increases the distillate water yield by about 53.2%. And using Nanofluids improves the solar still water productivity by about 116%, when the still integrated with the external condenser.

Keywords: Desalination, Basin solar still, Nanofluids, Vacuum, Condenser

1 INTRODUCTION

In the last 40 years, the problem of freshwater shortage has been one of the main challenges in the world. Potable water not only is important for life but also for industrial and agricultural purposes. So, the life without water will be impossible. The origin and continuation of mankind is based on water. Although more than 75% of the earth covered with water, only 0.014% of that can be used directly for the human being and other organisms. On the other hand, sea water constitutes 97.5% of global water, so it can be used for those purposes by converting it to distilled water (Kabeel, 2009). There are some techniques for water purification, which among them, solar water distillations is an attractive subject. A single basin solar still is a very simple solar device used for converting available brackish or waste water into potable water. The solar distillation systems are mainly classified into two categories: passive and active solar still. In passive solar stills, solar radiation is the only parameter which affects evaporation, but in active solar stills by using the additional device such as fan (Ali, 1991), pump (Tabrizi & Zolfaghari, 2010), sun tracking system (Abdallah & Badran, 2008) or solar collectors (Abdenacer & Nafila, 2007), (Bacha et al, 2007), and (Voropoulos et al, 2003), the temperature difference between evaporating and condensing area is increased, and consequently enhancement on productivity is achieved. Active solar stills also can use waste heat of other processes or devices to improve the evaporation rate of water. Productivity of such solar stills is very low. The efficiency of a conventional single-basin solar still is usually about 30–40% (Delyannis & Belessiotis 2001). This is because of the loss of the heat of condensation to the environment through the glass cover of the basin and some useful heat carried away by the warm condensate.

Many extensive studies have been carried out to the problem of enhancing productivity, effectiveness and efficiency of single-basin solar stills. Solar still with sponge cubes in basin is studied by Bassam & Hamzeh (2003). Hiroshi Tanaka (2009) constructed a basin type solar still with internal and external reflectors. Tiwari et al. (2003) used a multi wick solar still with electrical blower. Jim et al. (1981) used a multiple tray tilted still. John Ward (2003) designed a solar water purifier. Tiris et al. (1998) conducted experiments on two flat plate solar collectors integrated with a basin type solar still. Performance study on solar still with enhanced condensation was studied by Kumar & Kasturibai (2008). Hussaini & Smith (1995) studied the effect of applying vacuum inside the solar still. Gnanadason et al. (2012) use suspensions containing nanometer-sized particles in vacuum solar water still (nanofluids).

In this context, the attempts are also made to increase the productivity of water by integrating the still basin with external condenser and using the nanoparticle sized in solar still with conventional water. The fluids with solid-sized nanoparticles suspended in them are called nanofluids. The suspended metallic or nonmetallic nanoparticles change the transport properties, heat transfer characteristics and evaporative rate of the base fluid. These nanofluids are expected to exhibit superior heat transfer properties compared with conventional water in the solar still and hence the increase in the productivity and efficiency of the solar still (Assael et al, 2004).

2 EXPERIMENTAL SETUP

In this work, two basin stills were designed, fabricated and constructed to compare the performance of the solar desalination system. One of them is a conventional type and the other is the modified basin still as shown in Fig. 1. The conventional still has a basin area of 0.5 m^2 (1000 mm x 500 mm). High-side wall depth is 450 mm and the low-side wall height is 160 mm. The still is made from galvanized iron sheets (1.5 mm thick). The whole basin surfaces are coated with black paint from inside to increase their absorptivity. Also, the still is insulated from the bottom and side walls with wool to reduce the heat loss from the still to ambient. The basin is insulated from the bottom and side walls with low thermal conductivity fiber glass of 5.0 cm thick. The basin is covered with glass sheet of 3 mm thick inclined with nearly 30° on horizontal, which is the latitude of Kafrelsheikh city, Egypt. The gaps between the glass cover and the still box was filled by silicon to prevent any leakage from anywhere inside the basins to outside of them.

The modified basin still has the same dimensions and construction of conventional still. In addition, inside the still, there is the vacuum port to be able to measure the pressure inside the basin still by the pressure measurement instrument. Also, there is the vacuum fan and its output duct to the condenser as shown in Fig.1. The condensation unit consists of 3.0 m copper tubes with 3.81 cm diameter encased in polyethylene tank (40 x 40 x 50 cm) filled with cold water. The copper tube is terminated with graded container to collect the condensate water, as shown in Fig. 1. The used vacuum fan is of the axial-flow type. It has a blade diameter of 8 cm and was attached by a variable speed indicator on a screen to control the fan speed as shown in Fig. 1. The brushed DC electric motor was used to run the fan. It had a maximum rotational speed of 1440 rpm, power factor of 45°, and consumed 2 A and 12 V. The feed water tank is connected to the main line which is divided into two feed water lines. A flow control valve is integrated at each line inlet in order to regulate the flow rate of water as shown in Fig.1.

The experimental setup is suitably instrumented to measure the temperatures at different points of the still (brine, absorber and glass cover temperatures), total solar radiation and the amount of distillate water. The temperatures are measured by K-type thermocouples. The solar radiation intensity is measured instantaneously by a solarimeter. The digital air flow/volume meter is used to measure the wind velocity.

Figure 1. Photograph of experimental setup

3 EXPERIMENTAL PROCEDURE

Experiments are constructed and conducted at Faculty of Engineering Kafrelsheikh University, Egypt. The experiments were carried out at the period from 9 a.m. to the sunset, during April 2013 to July 2013. The solar radiation, atmospheric temperature, basin temperature, saline water temperature, glass temperature and distilled water productivity were measured every hour. However, the accumulated productivity during the 24 hours had also been measured in each test. The depth of the saline water in the solar stills is holding constant during the test manually by using a make-up saline water tank and control valve every hour. All measurements were performed to evaluate the performance of the conventional basin still and the modified basin still under the outdoors of Kafrelsheikh City conditions.

There are three groups of experiments; the first group was done with water depth of 10 mm in each of basin stills and with continuous running of fan speed from sunrise to sunset. The performance of the modified basin still is investigated with different running of fan speed of 90, 450, 900 and 1350 rpm. From this study, it can be reached to the optimum running speed of the fan which produces more distilled water. The second group of tests was done at constant water depth of 10 mm in each of basin stills and with corrupted running of fan speed of constant value of 1350 rpm through the period from 11:00 am to 3:00 pm. The performance of the modified basin still is investigated with different fan running time of 60, 45, 30, and 15 minutes in each hour through all of the period. In the third group of tests; the performance of the modified basin still was compared with the conventional one, but with mixing aluminum oxide nanoparticles in the feed water to the modified basin still with and without providing the reached optimum running of fan speed inside the modified basin still from the previous studied group of experiments, with as small as 0.2 % volumetric fraction of Al_2O_3 loading, the thermal conductivity of water is enhanced by 10.5 % (Shuying et al, 2009)

4 ERROR ANALYSIS

During the experiments, several parameters are measured in order to evaluate the system performance. The quantities needed to be measured are, the temperatures at different points of the stills (brine and glass cover temperatures), ambient temperature, total solar radiation, wind velocity and the amount of distillate. The temperatures have been measured using calibrated copper constantan type thermocouples (±1°C) which were connected to a digital temperature indicator. Total insolation was measured on the same level of stills glass covers with the help of a Data logging solar power meter ranged of 0-5000 W/m^2 with an accuracy of ±1 W/m^2. Wind speed was measured with the help of a van type anemometer, ranged of 0.4 - 30 m/s with an accuracy of ± 0.1 m/s. A flask of 2 liter capacity (an accuracy of 5 ml) was used to measure the hourly yield.

Based on the accuracy of each measuring instrument, an estimate of the uncertainty in measurements has been carried out following the procedure explained by Kline & McClintock (1953). It has been found out that the maximum uncertainty in the measurements is about 2 %.

5 RESULTS AND DISCUSSIONS

5.2 Effect of Condenser on the Performance of Solar Still

5.1.2 For the Case of Continuous Running Fan

The variation of solar radiation, atmospheric temperature, basin water temperature, and glass temperature of stills is shown in Fig. 2. It is clear that the profile of the solar radiation incident during the days of the testing has the same behavior. The solar radiation increases in the morning hours reaching its maximum values around midday and then decreases in the afternoon. Also, it can be observed from Fig. 2 that, the maximum temperature is obtained during the period from 11a.m. to 3 p.m. Also, it is observed that the temperatures at all points increase in the morning hours to reach maximum value around midday before it start to reduce late in the afternoon.

Comparisons between the hourly variations of freshwater productivity per unit area for the modified and the conventional solar stills are illustrated in Fig. 3. The amount of accumulated distillate water for the modified solar still is greater than that of conventional still. This is mainly due to the existence of the fan that caused higher evaporation rate inside the still. The fan creates an amount of turbulence of the water vapor content of the air above the saline water that can take evaporated water vapor away from the saline water surface. In addition, the fan takes the non-condensable gases away from the still to the condenser. Then the effect of non-condensable gases which reduce the rate of condensation is also avoided. The increase in the fresh water production is due to the circulation of the air inside the solar still and the absence of non-condensable gases and hence the evaporation rate that has been increased by the use of small power consumption fan. Measurements of accumulated distillate water for some different testing days are tabulated in Table 1. It can be observed from this table that, at constant operating time of fan during the day, it was found that the productivity is increased when the fan speeds of 90, 450, 900, and 1350 rpm are used approximately by 16.26 %, 21.65 %, 25.39 %, and 53.22 % respectively as compared to the conventional still, and the consumed power of the fan, which operated by photovoltaic solar panels, are 35.2, 52.8, 70.4, and 88 W.hr respectively.

In general, it can be seen from Fig. 3 that the hourly freshwater production increases during the day time as solar radiation intensity increases till it reaches the maximum value around midday, after that, in the afternoon, the decrease in temperature gradually reduces the production rate. Also, it is seen for the day time that the water temperature in the modified still is less than that of conventional still by 0.0 - 0.5 °C but the glass temperature in the modified still is less than that of conventional still by 1.5 - 3.0 °C. As a result of this difference, the ability of condensation, then the production rate in the modified still is more than that of conventional still, and for the night time the production rate of the modified and conventional stills is about the same quantity as there is no marked difference of temperatures in the stills. Also from the figure, it can be observed that, the water productions are increased from zero value in the morning and reached the maximum values in the afternoon. In addition, the maximum productivity occurs at maximum temperature of saline water (from 11a.m. to 3 p.m.).

Table 1. Accumulated productivity for some days of testing

Testing day	Operating Period (h)	Operating time per hour (minutes)	Fan operating speed (rpm)	$D_{modified}$ (ml)	$D_{conventional}$ (ml)	Increase in distillate (%)	Fan Consumed Power (W.hr)
For the case of continuous running of fan (constant operating time & variable speed)							
15/4/2013	9 am : 17	60	900	4840	3860	25.39	70.4
25/5/2013	9 am : 17	60	1350	4290	2800	53.22	88
27/5/2013	9 am : 17	60	90	4720	4060	16.26	35.2
28/5/2013	9 am : 17	60	450	4720	3880	21.65	52.8
For the case of corrupted running of fan (variable operating time & constant speed)							
16/6/2013	11 am : 3	30	1350	4400	3250	35.39	11
17/6/2013	11 am : 3	45	1350	6010	4100	46.59	22
19/6/2013	11 am : 3	15	1350	4870	3870	25.84	33
23/6/2013	11 am : 3	60	1350	6280	4180	50.24	44
For the case of using nanofluids with and without operating the fan (constant speed)							
3/7/2013	9 am : 17	60	1350	8390	3880	116	88
6/7/2013	9 am : 17	-	-	7920	4500	76	-

5.1.2 For the Case of Corrupted Running Fan

From the previous tested speeds, it can be reached the optimum operating fan speed and the effective operating period of the fan at all the day time. So, the fan consumed power and system costs can be reduced, and hence the system efficiency can be increased by operating the fan at corrupted periods through the effective fan operating period. From Fig. 4 it is concluded that the solar radiation behavior does not change. It has a maximum value around the midday and has small values in the morning and the afternoon. Also, the amount of accumulated distillate water for the modified solar still is greater than that of conventional still, as shown in Table 1. It can be observed from this table that, at constant operating fan speed of 1350 rpm (the optimum operating fan speed) and variable fan operating time during the effective fan operating period, it was found that the productivity is increased when the operating fan time of 15, 30, 45, and 60 minutes (corrupted operating) are tested approximately by 25.84%, 35.39%, 46.59%, and 50.24% respectively as compared to the conventional still, and the consumed power of the fan are 11, 22, 33, and 44 W.hr respectively. It can be seen from Fig. 5 that the hourly freshwater production has the same behavior almost as the previous tests. Also, it is seen for the day time that the water temperature in the modified still is less than that of conventional still by 0.0 - 0.5 °C after operating the fan and they have equal values before that. But the glass temperature in the modified still is less than that of conventional still by 1.5 - 3.0 °C after operating the fan. As a result of that, the ability of condensation, then the production rate in the modified still is more than that of conventional still and the fan consumed power is reduced. Also from the figure, it can be observed that, the water productions have equal values in the morning and reached the maximum values in the effective fan operating period.

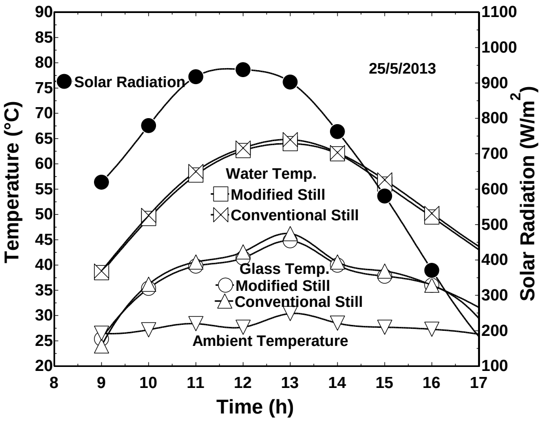

Figure 2. The hourly temperature variation and solar radiation for the modified and conventional solar still

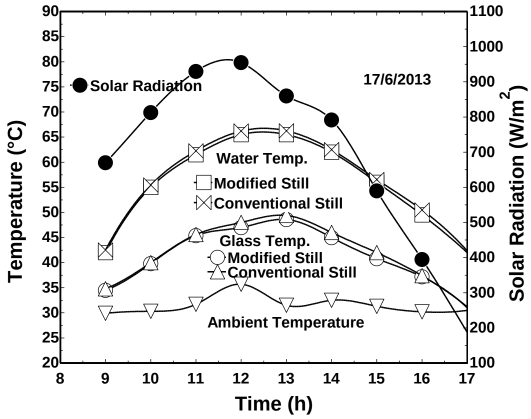

Figure 4. The hourly temperature variation and solar radiation for the modified and conventional still

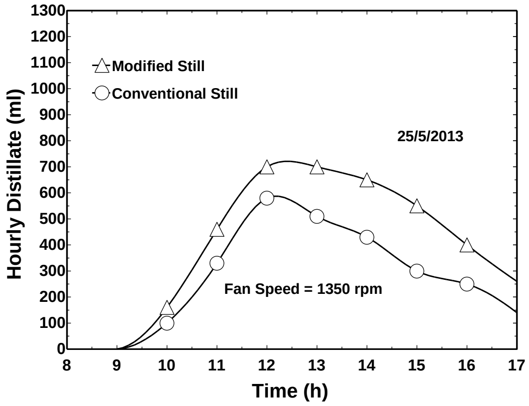

Figure 3. The variation of fresh water productivity for the modified and the conventional still

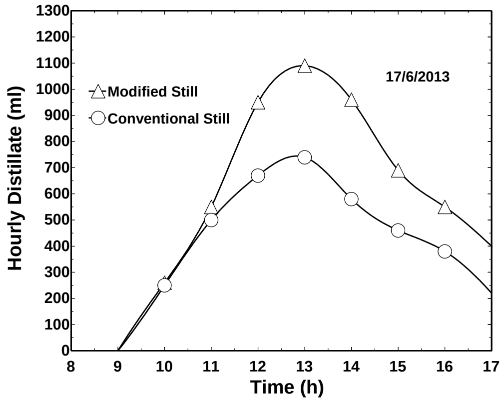

Figure 5. The variation of fresh water productivity for the modified and the conventional still

5.2 Effect of Nanofluids on the Performance of Solar Still

Effect of Nanofluids on the performance of solar still without external condenser is shown in Figs. 6 and 7. The solar radiation and temperature profiles have the same behavior for all the days of the testing as shown in Fig. 6. The only difference that can be seen from the figure is that the basin water temperature of the modified still is more than the water temperature of the conventional still by 2 - 5 °C.

The variations of hourly fresh water productivity per unit area for the modified and conventional solar stills are presented in Fig. 7. It is found from Table 1 that the amount of accumulated distillate water for the modified solar still is greater than that of conventional still. Addition of nanofluids in the basin surface increases the water temperature by increasing heat transfer rate and thereby increasing the evaporation rate. It can be observed from Table 1 that, at constant fan operating speed of 1350 rpm during the day, it was found that the productivity is increased when using the nanoparticles of aluminum oxide approximately by 116 % as compared to the conventional still. And when using the nanofluids without operating the fan, the productivity of the modified still is increased approximately by 76 % as compared to the conventional still.

It can be seen from Fig. 6 that the water temperature in the modified still is greater than that of conventional still by 2 - 5 °C. As a result of this big difference, the ability of evaporation, then the production rate in the modified still is more than that of conventional still. As shown in Fig. 7, it can be observed that, the water productions have the same behavior of the previous testing days.

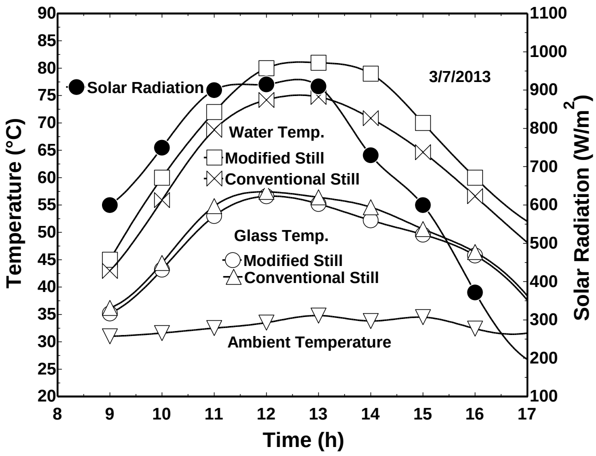

Figure 6. The hourly temperature variation and solar radiation for the modified and conventional still

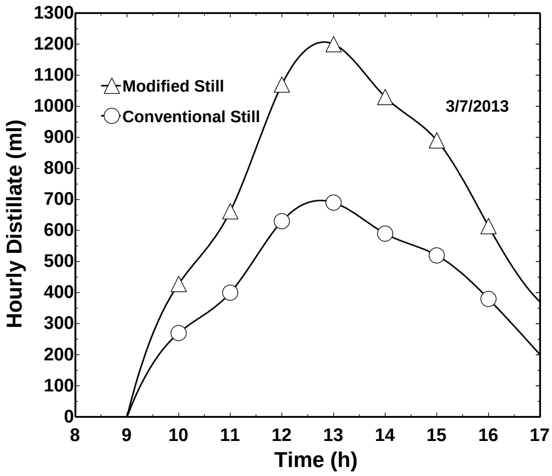

Figure 7. The variation of fresh water productivity for the modified and the conventional still

6 COST EVALUATION

The total fixed cost of conventional still is about F = 103 $. To obtain the average value of the cost of distillate output it is assumed: n is the expected still life time, V is the variable cost, C is the total cost, where, C = F + V. Assume variable cost V equals 0.3 F per year (Buongiorno et al, 2009), and for the expected still life 10 years, then C = 103 + 0.3 × 103 × 10 = 412 $ where the minimum average daily productivity can be estimated from the analysis of different experimental data, and it is assuming that 2.5 l/m^2 a day, Assume still operate 340 days in the year, where the sun rise along the year in Egypt. The total productivity during the still life =2.5x10x340=8500 l. Cost of litter from conventional still = 412/ 8500 = 0.048 $.

The total fixed cost of modified basin solar still, when applying vacuum fan only, is about F = 140 $. Assume the expected still life 10 years. Assume the variable cost V equals 0.3 F per year, then C = 140 + 0.3 × 140 × 10 = 560 $ where the minimum average daily productivity can be estimated 4.0 l/day. The total productivity during the still life = 4x10x340=13600 l. Cost of litter from modified still = 560/ 13600 = 0.041 $. When the nanomaterial is used in the modified basin still with providing vacuum; F = 260 $, V equals 0.3 F per year, then C = 260 + 0.3 × 260 × 10 = 1040 $ where the minimum average daily productivity can be estimated 6 l/day, Assume still operate 340 days in the year. The total productivity during the still life = 20400 l. Cost of litter from the modified still = 1040/ 20400 = 0.05 $.

7 CONCLUSIONS

In this work, the effect of integrating the still basin with external condenser and using nanofluids on the performance of modified solar still is investigated experimentally under outdoors of Kafrelsheikh City (north of Egypt) climatic conditions. It was found that using a small power consumption fan work with photovoltaic solar panels improves the evaporation and condensation rates by avoiding the effect of non-condensable gases and creating an amount of turbulence of the water vapor content of the air above the saline. The higher performance of modified still is achieved for continuous running fan of speed 1350 rpm through all the day time (53.22% higher than the productivity of the conventional still). The higher performance of modified still is achieved for corrupted running fan of speed 1350 rpm and with operating through all the effective fan operating period from 11 a.m. to 3 p.m. (50.24% higher than the productivity of the conventional still). The productivity of the basin solar still can be increased by mixing Nanofluids with water inside the still. Using Nanofluids improves the solar still water productivity by about 116% and 76% with and without operating the vacuum fan respectively.

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