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EXPERIMENTAL INVESTIGATION OF SOLAR STILLS INTEGRATED WITH SOLAR WATER HEATING COLLECTORS

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Abstract: Solar still is a more practical way of obtaining clean water. In this study, we aimed to improve the efficiency of solar still systems and obtain distilled water at the same time. For this purpose, 5 different solar still systems were designed. Type 1; conventional solar still, Type 2; conventional solar still integrated with solar water heating collector and run via natural convection, Type 3; conventional solar still integrated with solar water heating collector and tubular heat exchanger and run via natural convection, Type 4; conventional solar still placed with plate heat exchanger and integrated with solar water heating collector and run via natural convection, Type 5; conventional solar still placed with plate heat exchanger and integrated with solar water heating collector and run via forced convection. In this study, the experiments were carried out on the parameters influencing the performance, the amount of distilled water obtained, and the efficiency of experiment settings designed in different types; and finally the results were presented. The amount of distilled water and efficiency of conventional solar still were 2389 ml and 51.47%, respectively. Maximum total amount of water and efficiency from natural convection systems were obtained from Type 4, and the values calculated were found as to be 5788 ml and 55.91%. Maximum amount of distilled water and the efficiency were obtained by utilizing forced convection system were found as to be 6068 ml and 58.99%, respectively.
Keywords: Solar water heater, Solar water distillation, Efficiency.

GÜNEŞ ENERJİLİ SU ISITICI KOLLEKTÖRLERLE BİRLEŞTİRİLMİŞ GÜNEŞ ENERJİLİ DAMITICILARIN DENEYSEL İNCELENMESİ

Özet: Güneş enerjili damıtıcı temiz su elde etmenin daha pratik bir yöntemidir. Bu çalışmada, güneş enerjili damıtıcı sistemlerin verimini arttırmayı ve aynı anda damıtılmış su elde etmeyi amaçladık. Bu amaçla 5 farklı güneş enerjili damıtıcı sistem tasarlandı. Tip 1; geleneksel güneş enerjili damıtıcı, Tip 2; doğal taşınım yoluyla çalıştırılan ve güneş enerjili sıcak su kollektörü ile birleştirilmiş geleneksel güneş enerjili damıtıcı Tip 3;doğal taşınım yoluyla çalıştırılan, boru tipi ısı değiştirgeci ve güneş enerjili sıcak su kollektörü ile birleştirilmiş geleneksel güneş enerjili damıtıcı, Tip 4; doğal taşınım yoluyla çalışan, plaka tipi ısı değiştirgeci ve güneş enerjili sıcak su kollektörü ile birleştirilmiş geleneksel güneş enerjili damıtıcı, Tip 5; zorlanmış taşınımla çalışan plaka tipi ısı değiştirgeci ve güneş enerjili sıcak su kollektörü ile birleştirilmiş geleneksel güneş enerjili damıtıcı. Bu çalışmada deneyler, farklı tiplerde tasarlanan deney düzeneklerinin performansı etkileyen parametreler, elde edilen damıtık su miktarları ve verimleri ile ilgili yürütüldü. Ve nihayetinde sonuçlar sunuldu. Geleneksel güneş enerjili damıtıcının damıtılmış su miktarı ve verimi sırasıyla 2389 ml ve %51.47 ’dir. Doğal taşınım sistemlerde, maksimum toplam damıtık su eldesi ve verim Tip 4’te elde edildi ve hesaplanan değerler 5788 ml ve %55.91 olarak bulundu. Maksimum damıtık su miktarı ve verim zorlanmış taşınım sisteminden faydalanarak elde edilmiş sırasıyla 60698 ml ve %58.99 olarak bulunmuştur.
Anahtar Kelimeler: Güneş enerjili su ısıtıcısı, Güneş enerjili su damıtma, Verim.

NOMENCLATURE

h	Heat transfer coefficient [W/m$^{2\circ}$C]
I	Total solar energy [W/m^2]
L	Water’s heat of vaporization [J/g]
P	Vapor pressure [kPa]
m	The amount of distilled water [ml]
T	Temperature [$^\circ$C]
V	Wind speed [m/s]
Wp	Consumed electric power [W]
ε_{eff}	Effective permittivity
η	Efficiency
σ	Stefan-Boltzmann constant

Subscripts

e	evaporation
w	water
g	glass
r	radiation
c	convection

s	surrounding
b	bottom
v	vapor
ig	internal surface of glass
og	outer surface of glass

INTRODUCTION

Since the fresh surface waters sources cannot sufficiently meet the water requirement, many researches are being carried out on alternative solutions. For instance; within the scope of use of underground waters, the studies are carried out on using the precipitation waters and recycling waste waters. The insufficient time for preventing the irreversible depletion of natural resources forces humans to develop and utilize the technologies in order to protect and save these resources.

It is a very old method to obtain potable water by distilling saltwater and underground and aboveground waters containing excessive level of minerals (Sampathkumar, at al, 2010). The process of obtaining clean water is divided into 2 main categories based on the type of energy used. These are energy-supported methods and mechanically-supported methods. The main input of thermal energy-supported distillation is the thermal energy, while the reverse-osmosis and electrolysis methods require mechanical or electrical energy. Since the reverse osmosis and electrolysis methods are the processes requiring high level energy, it is essential to establish large systems in order to utilize them effectively. On the other hand, the small-scaled thermal systems are also very suitable for the places, where the central water mains cannot be reached, or if it is not possible to make investment for central water main.

The places, where clean water is needed mostly, are also the places receiving the most intense solar energy. For this reason, the solar energy distillation method is the most effective method to be implemented. The production of clean water via distillation is a simple, effective, and also a reliable method. This process requires energy, and solar energy can be used as a very effective source of heat in this process. During this process; firstly, water vaporizes, and the matters it includes are separated, and then potable water condenses. Solar energy distillation pools remove salt and heavy metals from the water and prevent water-related diseases. The potable waters obtained from these systems are much healthier than great many bottled waters.

In general, constructing and operating the solar energy distillation systems are not too expensive. However, their most important disadvantage is low productivity. For this reason, large surfaces are required for achieving successful results. This significantly increases the initial investment costs. The scientists carrying out research on this topic have designed various types of distillation systems in order to achieve better efficiency values. As a result, various models of solar energy distillation systems have been introduced.

Rajaseenivasan et al. (2014) examined the performance of conventional solar still by pre-heating saltwater via integrated flat plate solar collector. They examined the system by using various water depths, wick and energy storage equipment. Under the same conditions, they achieved 60% higher distillation than the classic distillers. The maximum productivity of conventional solar and integrated system were 3.62 and 5.82 $kg/m^2 \cdot day$, respectively.

Xiong et al. (2013) designed a new-type solar distiller system via increased condensation surface. In this system, heating was performed with both vacuum-piped collected at bottom and the coating at the top of tank. The trays placed inside the tank were wrinkled in order to decrease the condensation resistance. In that system, they have examined the temperature changes and fresh water efficiency. As a result of their study, they reached fresh water productivity up to 40%.

Morad et al., (2015) performed thermal analyses via energy balance equations by using internal and external heat transfers in order to estimate the performance of bilateral solar distiller system with integrated glass cover cooler. They utilized active and passive distillers for thermal analyses. For both distiller systems, the performance was found to be the function of change in glass coverage thickness and pool depth under cooled and non-cooled conditions.

Appadurai and Velmurugan (2015) performed experimental analysis and theoretical performance examination of flapped-type solar pool integrated with solar distiller, flapped-type solar distiller and classic solar distiller. In order to improve the performance of classic solar distiller, the flaps were placed into the distiller. Then the same operation was also performed in the pool. With using a larger surface for solar radiation, 50% higher productivity was achieved than the conventional solar still.

Alaudeen et al., (2014) utilized a multi-stage solar distiller in order to improve the productivity of solar distiller. In order to establish the new system, they combined the multi-stage solar still with a sloped plate collector. In order to increase the vaporization rate, the experiments were performed at various depths allowing additional space, and 3% increase was achieved at 2 cm depth in proportion to the classic distiller.

The aim of this study is to obtain drinkable and usable clean water by using this four newly-developed solar stills. For this purpose, a conventional solar still system integrated with solar collector was designed. In this system, in order to enlarge the surface area, the tubular and plate heat exchangers were placed into the distiller integrated with solar water heating collector, and the daily production and the system efficiency values were recorded and then compared.

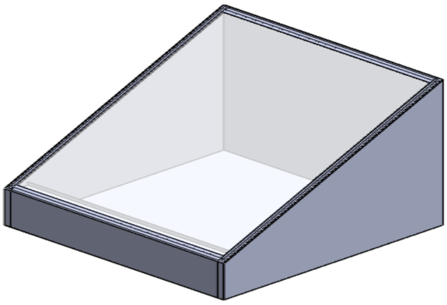
EXPERIMENTAL DESIGN AND METHOD

In this experimental study, the solar still was integrated with solar water heating collector, and the experiments were performed by placing tubular and plate heat exchangers into the distiller. In the experiments, the parameters affecting the performance of solar still integrated with plate solar collector under the conditions of Elazığ city were examined as shown in Figure 1. Within this scope, 5 different experimental settings, equipment and the working principles of these settings are specified below in Figure 2-4.

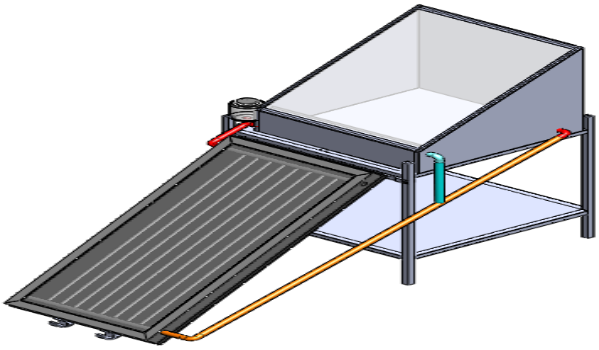
Figure 1. Photograph of the experiment set

Type 1; Conventional solar still was designed. Distilling pool was manufactured from stainless sheet iron in dimensions of 1000x1000x250 mm. The base area was 1m^2, and the slope of cover was 38^o. The basement and internal parts were painted with epoxy filler and mat black paint. In order to prevent leakage from the cover, the solar, heat, and moisture-resistant sealing components were utilized. The sloped top of distiller allowed gathering the condensed waters into a tank, which was placed out of the distiller, through natural convection. Distilled water collection channel, which was placed in the distillation pool, was made of stainless material in 50mm width, 25mm height and 7˚ slope. The transparent cover conveying the solar radiation but preventing the thermal loss protected the surface from external effects such as rain, hail and heat loss from the top. For this purpose, a 4mm-thick glass was used as cover of this system. Moreover, in order minimize the heat loss from sides, bottom and rear parts were isolated with a 4cm-thick polyurethane material.

Type 2; the conventional solar still was integrated with solar water heating collector and then operated via natural convection. The system consisted of planar solar water heating collector, a solar still distiller, table, and connectors. For the experiments, the setting had the dimensions of 930x1930x87.5 mm, and with covering gross surface area of 1.8 m² and net surface area of 1.6 m² and consisting of aluminium oval pipes, flapped and painted in black, planar solar water heating collector. In this system, the heat of water within the solar still was increased via solar energy.



Type 1



Type 2

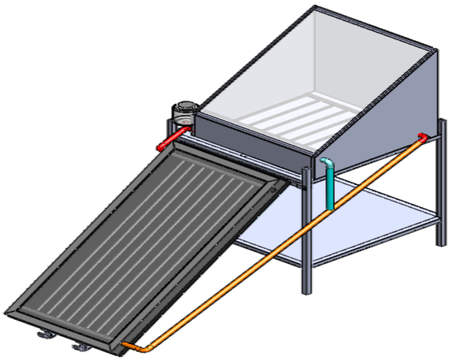
Figure 2. Type 1; Conventional solar still Type 2; Conventional solar still was integrated with solar water heating collector

As a result of increased temperature, the vaporized water reached at the colder top-cover and then condensed. Then, due to the slope of top condensation cover, the distilled water condensed, dropped onto the bottom surface and then flowed into the collection channel place on the front side. The distilled water gathering in collection channel was conveyed out by means of slope, and collected in the distilled water tank.

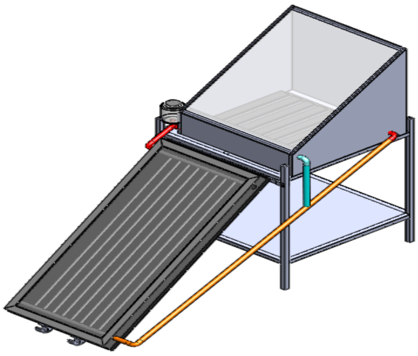
Type 3; By placing tubular heat exchanger into the conventional solar still, it was integrated with the solar water heating collector and then run via natural convection. In this system, there was a planar solar water heating collector, a solar still distiller, a tubular heat exchanger placed into the distiller, table, and connectors. In this experimental setting, different from Type-2, there is a tubular heat exchanger placed within the distiller, and the hot water from planar solar water heating collector passes through the tubular heat exchanger without mixing with the water in hot water distiller, and then returns. In this system, the water increasing its temperature in planar solar water heating collector passes through the tubular heat exchanger within the solar still and then conveys its heat to the water within the solar still distiller. So, the effect of water with increased temperature on the vaporization and condensation is determined, and then compared to other experimental settings.

Type 4; By placing plate heat exchanger into the conventional solar still, it was integrated with the solar water heating collector and then run via natural convection. In this system, a plate heat exchanger was placed into the solar still. By employing the plate heat exchanger, it was aimed to enlarge the areas of both heat transfer surface and absorber surface. In this system, the water having increased temperature in planar solar water heating collector passes through the plate heat exchanger within the solar still distiller, and then conveys its heat to the water within the solar still.

Type 5; By placing a plate heat exchanger into the conventional solar still, it was integrated with the solar water heating collector and then run via forced convection. In this system, different from Type-4, a circulation pump was added into the setting, the system was run at 50 kg/h flowrate as forced convection. Rotameter was utilized in order to measure the flowrate.



Type 3



Type 4

Figure 3. Type 3; Conventional solar still integrated with solar water heating collector and tubular heat exchanger Type 4; Conventional solar still integrated with solar water heating collector and tubular heat exchanger.

In present study, 2 different heat exchangers were designed in order to improve the amount of distilled water production and increase the efficiency of distillers, and then they were placed into the solar still (Figure 5). One of the designed heat exchangers was tubular, while other had the advanced plate design. Hence, the tubulars and advanced plates were placed into the conventional solar still, and the amounts of distilled water obtained from the solar still distillers, and the efficiency values were compared to each other.

Of the heat exchangers used for this purpose; the plate and tubular ones were made of copper and their dimensions were 900x900 mm, the number of tubulars was 8, the manifold material was copper, manifold diameter was 25mm, and the welding method was ultrasonic welding, and the copper tubulars and plates were painted in black.

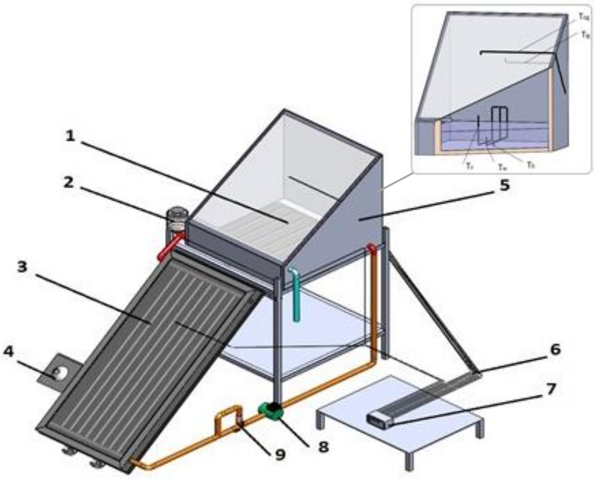
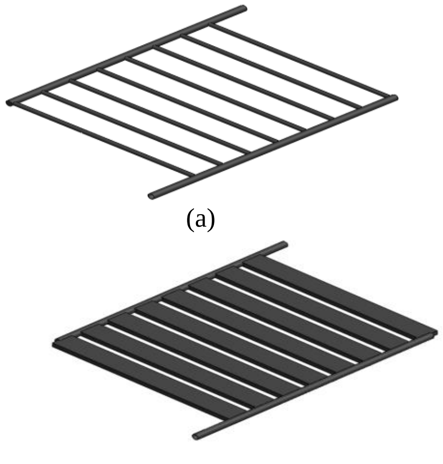


Figure 4. Type 5; Conventional solar still integrated with solar water heating collector and tubular heat exchanger. (1. Heat exchanger, 2.Glass jar, 3.Solar water heating collector, 4. Pyranometer, 5.Solar still , 6. Thermocouple, 7. Digital thermometer, 8. Circulation pump, 9. Rotameter.)



(a)

(b)

Figure 5. (a). Tubular heat exchanger (b). Advanced plate heat exchanger

After the designed experimental settings were established, by adding 100L water into the solar still distiller, the angle of planar solar water heating collectors in systems was set to 38˚. And then, the inlet and outlet temperatures of water into and out of the planar solar water heating collectors, internal temperatures of distillers, and ambient temperature were measured by placing J-type thermocouples at the required points. By using digital thermometer, the temperature of places, where the thermocouples were placed, were hourly measured between 08:00 and 16:00.

Considering the parameters leading to error during the distillation experiments, the total error was determined in accordance with the following formula (Holman, 1971).

$$W_{th} = \left[(x_1)^2 + (x_2)^2 + ...(x_\infty)^2\right]^{1/2} \quad (1)$$

The error parameters arising from different independent variables are different and the parameters resulting from temperature and speed measurement are listed below.

Errors Made in Temperature Measurement
(X_1) Error due to thermo couple pairs = ± 0.25-0.5 ° C,
(X_2) Error due to digital thermometer = ± 0.1 ° C,
(X_3) Error due to connectors and points = ± 0.1 ° C,
(X_4) Mean error that can be done with temperature measurement = ± 0.25 ° C,

Errors Caused by Speed Measurement
(X_5) Error due to sensitivity of anemometry = ± 0.1 m /s
(X_6) Measuring error = ± 0.1 m / s
During the experiments, the total errors were calculated and are presented in Table 1.

Table 1. Total errors occurring during the distillation experiments

Parameters Leading to Error	Total Error
Total error in measuring the temperature at collector inlet	± 0.173 °C
Total error in measuring the temperature at collector outlet	± 0.173 °C
Total error in measuring the water temperature in the solar still	± 0.173 °C
Total error in measuring the glass surface temperature	± 0.173 °C
Total error in measuring the air temperature	± 0.173 °C
Total periodical error in measuring the wind speed	± 0.104 m/s
Total periodical error in reading the temperature values	± 0.1 min
Total periodical error in measuring the air temperature	± 0.1 min
Total periodical error in measuring the radiation	± 0.1 min
Total periodical error in measuring the fresh water produced	± 4.062 ml
Total periodical error in measuring the flow rate	± 0.86 kg/h

As a result of these experiments, the amounts of distilled water obtained from the systems and the efficiencies of these systems were calculated, and then compared to each other. The efficiency of a solar distillation system was the proportion of thermal energy used for obtaining water to solar radiation on the glass cover of the system within a certain time interval (Tiwari et al., 2003). It can be expressed as follows;

$$\eta = q_{ew}/I(t) \quad (2)$$

where, η is the efficiency, q_{ew} is thermal energy used for distilled water, I (t) is solar radiation falling on a glass cover. This expression can also be stated as below (Sodhaet al.,1980), in form of the portion of heat, which is transferred to transparent cover from water surface via vaporization, to the amplitude of radiation on the effective collector surface:

$$\eta = \left[(h_{ew} + h_{sg})/(h_{gw} + h_{sg})\right](T_w - T_a) \quad (3)$$

where, the coefficient of heat transfer via vaporization (h_{ew}) (Malik et al.,1982);

$$h_{ew} = 16.273x10^{-3} h_{cw}(P_w - P_g)/(T_w - T_g) \quad (4)$$

coefficient of heat transfer via convection from water to cover (h_{cw}) (Dunkle et al., 1961);

$$h_{cw} = 0.884[(T_w - T_g) + (P_w - P_g)(T_w + 273)/(268.9x10^3 - P_w)]^{1/3} \quad (5)$$

coefficient of heat transfer from glass cover to the environment (Duffie et al., 1980);

$$h_{sg} = 5.7 + 3.8V \quad (6)$$

coefficient of heat transfer to water surface to transparent cover (Malik et al.,1982);

$$h_{gw} = h_{cw} + h_{rw} + h_{ew} \quad (7)$$

and coefficient of heat transfer via radiation from water surface to cover (h_{rw}) (Sharma et al., 1991);

$$h_{rw} = \varepsilon_{eff}\sigma\left[(T_w + 273)^2 + (T_g + 273)^2\right]\left[T_w + T_g + 546\right] \quad (8)$$

The amount of distilled water obtained hourly from the distiller is calculated according to the formula below.

$$m_{ew} = \frac{h_{ew}(T_w - T_g)3600}{L_w} \quad (9)$$

where L_w is the latent heat of vaporization of water and calculated using the following correlation;

$$L_w = 3044205.5 - 1670.1109\, T_w - 1.14258\, T_w^2 \quad (10)$$

Accordingly, the efficiency of system based on the amount of distilled water is,

$$\eta = \frac{m_{ew} L}{IA3600} \tag{11}$$

The efficiency in the system using the pump is calculated via the following equation;

$$\eta = \frac{m_{ew} L}{IA3600 + Wp.\Delta t} \tag{12}$$

RESULTS AND DISCUSSION

The experiments of solar still integrated with solar water heating collectors were performed on 2 October 2012 under climatic conditions of Elazığ city. The radiation and wind speed values for that day are given in Fig. 6. Conventional solar still (Type 1), conventional solar still integrated with solar water heating collector (Type 2), and the distiller integrated with tubular heat exchanger (Type 3) and with plate heat exchanger (Type 4) were used with natural convection. In addition, the experiment was performed with Type-4 by using forced convection. Throughout the experiments, the temperature measurements were performed on the glass surface of condenser, outer surface of glass, basement, water and vapor, and then expressed via graphics.

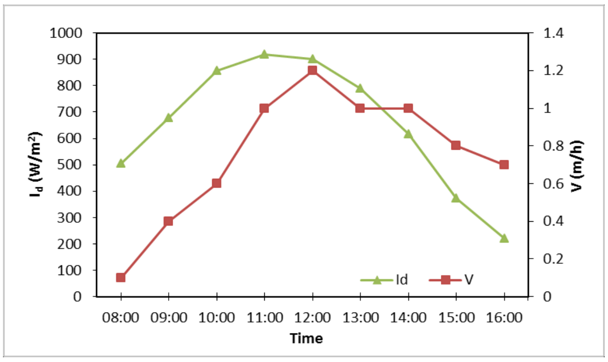


Figure 6. Time-dependent change of the radiation and wind speed values

Type 1 :

For the conventional solar still, as defined in Figure 4, the bottom temperature (T_b), water temperatures (T_w), vapor temperature (T_v), internal surface of glass (T_{ig}), and outer surface of glass (T_{og}) are presented in Figure 7.

As seen in Figure 7, the glass temperatures increased till 12:00 and then declined. The highest temperature of glass surfaces was measured at 12:00, when the internal temperature was 59.3 ˚C and glass surface temperature was 56.6 ˚C. In distillation systems, it has been observed that the amount of distilled water production increased as the glass temperatures decreased. Bottom and water temperatures showed continuous increase during the day, while vapor temperature increased until 12:00 and then decreased. The highest vapor temperature was measured at 12:00 to be 64.1˚. In performance measurements, it has been observed that the temperatures of bottom and water were close to each other.

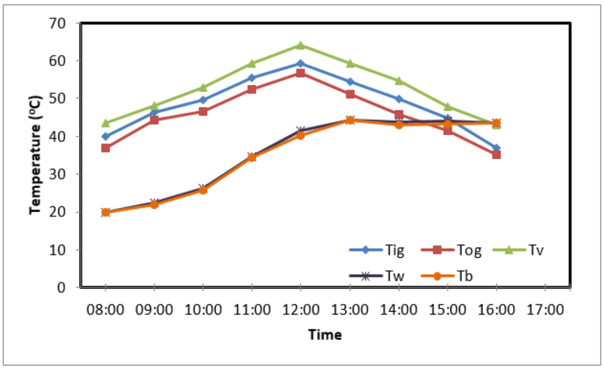


Figure 7. Time-dependent change of temperatures in conventional solar still

In Figure 8, the amount of distilled water obtained by conventional solar still was expressed as m, while the amount of water was expressed as mt. In performed measurements, it was found that the temperature of distilled water continuously increased until 15.00 and then decreased. The highest water production throughout the measurement periods was determined to be 210 ml between 14.00 and 15.00. At the end of the day, a total of 844 mL distilled water was obtained. By means of heat storage within the water inside the tank, the distillation that was slow during daytime continued after the sunset, even during the night-time. One of the most important factors was the exterior temperature decreasing during night-time due to atmospheric conditions. The heat stored in pool during daytime maintained the continuance of distillation until the water temperature decreased to external temperature. The amount of distilled water obtained in the night-time was found to be 1545 ml. The total amount of distilled water obtained in this system in a day was found to be 2389 ml.

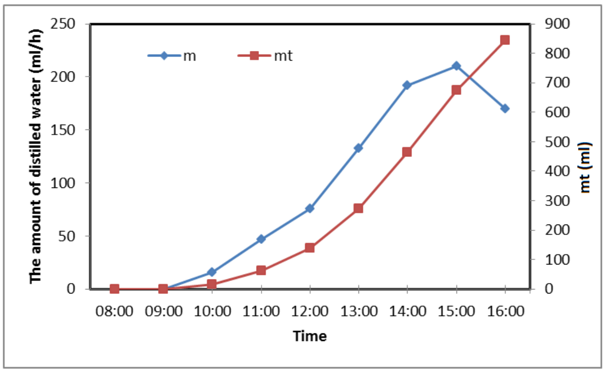


Figure 8. Amount of water distilled in conventional solar still

The distillation of water started with the increase of thermal capacity of distillation pool by the solar radiation intensity. This value was approximately 3-4 MJ/m². It was determined in pools manufactured in different shapes that the distillation continued after the sunset. It was observed that evaporation in the distillation system was minimal in the morning hours and reached maximum between 12: 00-15: 30.

Type 2:

In this system, the solar still was integrated with solar water heating collector. The water within the distiller was transferred via natural convection, and its temperature increased while passing through solar water heating collector. The system temperatures measured in experiments are presented in Figure 9.

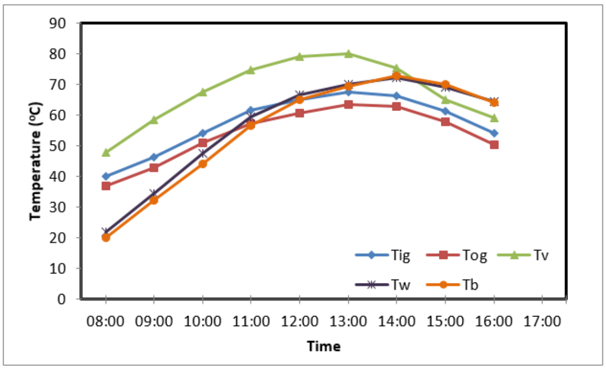


Figure 9. Time-dependent change of temperatures in conventional solar still integrated with solar water heating collector

As seen in Figure 9, the glass temperatures increased till 13:00 and then declined. The highest temperature of glass surfaces was measured at 13:00, when the internal temperature was 67.6 ˚C and glass surface temperature was 63.5 ˚C. Bottom and water temperatures showed continuous increase until 14:00 and 13:00, respectively, and then decreased. The highest vapor temperature was measured at 13:00 to be 80˚C. In performance measurements, an increase was observed in measured temperatures in proportion to the conventional solar still.

The highest water production was achieved between 14:00 and 15:00 as 688 ml. At the end of day, a total of 2582 ml distilled water was obtained. The amount of distilled water obtained during the night-time was measured to be 2630 ml. The total amount of daily production of distilled water in this system was found to be 5212 ml (Figure 10).

Type 3:

In this system, tubular heat exchanger was placed into the conventional solar still integrated with solar water heating collector. Through the natural convection, the water that was heated in solar water heating collector was let to pass through the tubular heat exchanger within the distiller, and the temperature of the water within the distiller increased.

As seen in Figure 11, the glass temperatures increased till 13:00 and then declined. The highest temperature of glass surfaces was measured at 13:00, when the internal temperature was 69.0 ˚C and glass surface temperature was 65.0˚C. Bottom and water temperatures showed continuous increase until 14:00 and 13:00, respectively, and then decreased. The highest vapor temperature was measured at 13:00 to be 81.0˚C. In performance measurements, an increase was observed in measured temperatures in proportion to the conventional solar still.

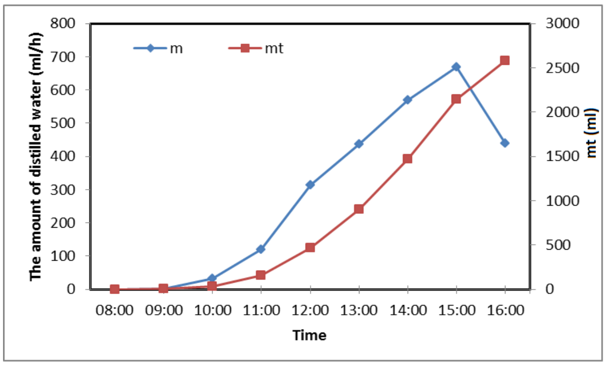


Figure 10. The amount of distilled water distilled in conventional solar still integrated with solar water heating collector

It was observed that the hourly amount of distilled water production in solar still integrated with tubular heat exchanger increased continuously until 15.00 and then decreased.

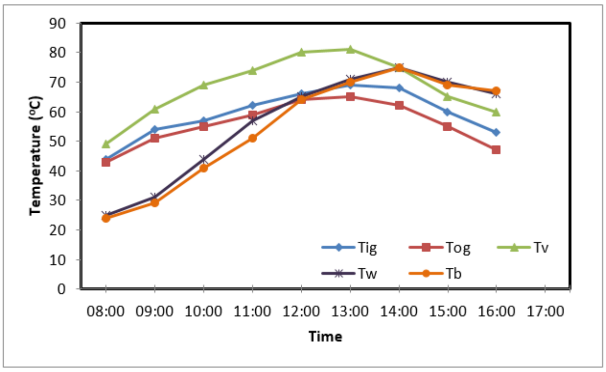


Figure 11. Time-dependent change of temperatures in conventional solar still integrated with tubular heat exchanger

As a result of hourly measurements, the highest amount of water production was obtained between 14:00 and 15:00 (a total of 654 ml). At the end of the day, a total of 2502 ml of distilled water was obtained (Figure 12). The amount of water obtained during the night-time was determined to be 2520 ml. With this system, the total amount of water obtained in a day was found to be 5022 ml.

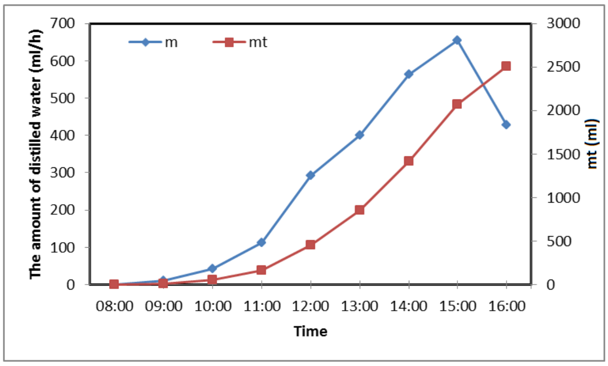


Figure 12. The amount of distilled water distilled in conventional solar still integrated with tubular heat exchanger

Type 4 :

In this system, plate heat exchanger was placed into the conventional solar still integrated with solar water heating collector. Through the natural convection, the water that was heated in solar water heating collector was let to pass through the plate heat exchanger within the distiller, and the temperature of the water within the distiller increased. As seen in Figure 13, the glass temperatures increased till 13:00 and then declined. The highest temperature of glass surfaces was measured at 13:00, when the internal temperature was 73.2 ˚C and glass surface temperature was 70.1 ˚C. Bottom and water temperatures and vapor temperature showed continuous increase until 14:00 and 13:00, respectively, and then decreased. The highest vapor temperature was measured at 13:00 to be 85.8˚. In performance measurements, an increase was observed in measured temperatures in proportion to the conventional solar still integrated with tubular heat exchanger.

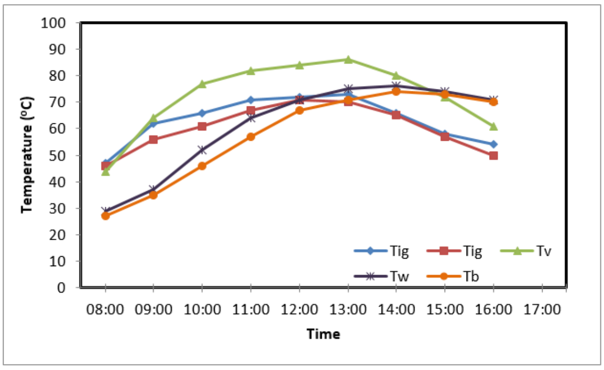


Figure 13. Time-dependent change of temperatures in conventional solar still integrated with plate heat exchanger

It was observed that the hourly amount of distilled water production in solar still integrated with plate heat exchanger increased continuously until 15.00 and then decreased. As a result of hourly measurements, the highest amount of water production was obtained between 14:00 and 15:00 (a total of 692 ml). At the end of the day, a total of 3066 ml of distilled water was obtained (Figure 14). The amount of water obtained during the night-time was determined to be 2722 ml. With this system, the total amount of water obtained in a day was found to be 5788 ml.

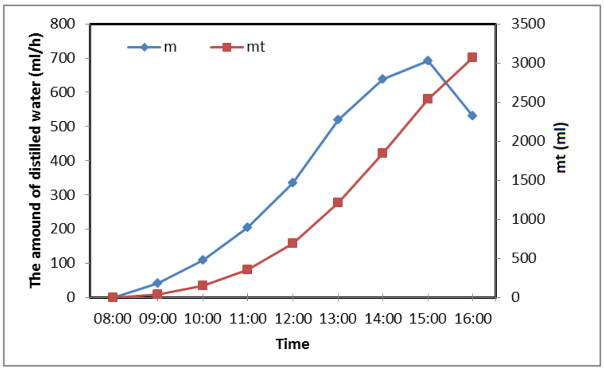


Figure 14. The amount of distilled water distilled in conventional solar still integrated with plate heat exchanger

The efficiency values obtained via natural convection are presented in Figure 15 (η1 for Type 1, η2 for Type 2, η3 for Type 3, and η4 for Type 4.

As seen in Figure 15, it was determined that the solar still integrated with plate heat exchanger was the one having the highest efficiency value. In natural convection systems, it was observed that the efficiency generally increased throughout the day and peaked at the end of daytime. The maximum efficiency values calculated as a result of measurements were 51.47% for conventional solar still, 46.73% for conventional solar still integrated with solar water heating collector, 45.38% for conventional solar still integrated with tubular heat exchanger, and 55.91% for conventional solar still integrated with plate heat exchanger.

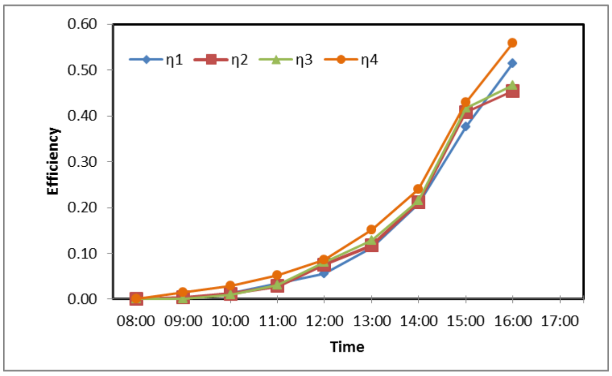


Figure 15. Time-dependent changes of system efficiencies

Type 5 :

In this experiment, the plate heat exchanger was placed into the conventional solar still integrated with solar water heating collector and then run via forced convection.

For the experiment carried out in October, the bottom temperature (Tb), water temperature (T_w), vapor temperature (T_v), internal surface of glass (T_{ig}), outer surface of glass (T_{og}) temperatures are presented in Figure 16.

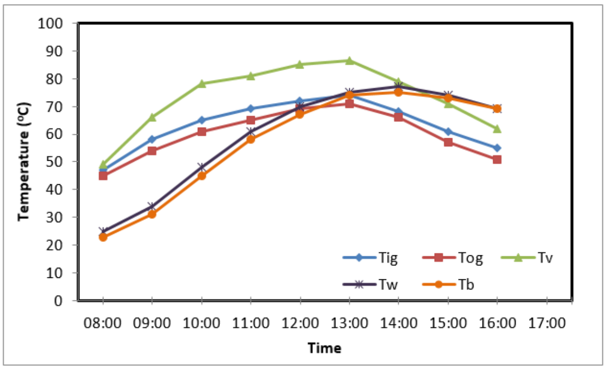


Figure 16. Time-dependent change of temperatures in conventional solar still integrated with plate heat exchanger (forced convection)

As seen in Figure 16, the glass temperatures increased till 13:00 and then declined. The highest temperature of glass surfaces was measured at 13:00, when the internal temperature was 74.2 ˚C and glass surface temperature was 71.0 ˚C. Bottom and water temperatures and vapor temperature showed continuous increase until 14:00 and 13:00, respectively, and then decreased. The highest vapor temperature was measured at 13:00 to be 86.3˚. In performance measurements, an increase was observed in measured temperatures in proportion to the conventional solar still integrated with tubular heat exchanger.

It was observed that the hourly amount of distilled water production in forced convection solar still integrated with plate heat exchanger increased continuously until 15.00 and then decreased. At the end of the day, a total of 3278 ml of distilled water was obtained (Figure 17). The amount of water obtained during the night-time was determined to be 2790 ml. With this system, the total amount of water obtained in a day was found to be 6068 ml.

The results of experiments carried out with solar still integrated with plate heat exchanger via natural and forced convection are presented in Figure 18.

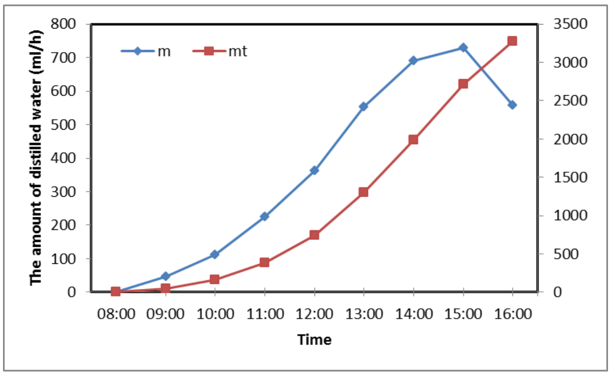


Figure 17. The amount of distilled water distilled in conventional solar still integrated with plate heat exchanger (forced convection)

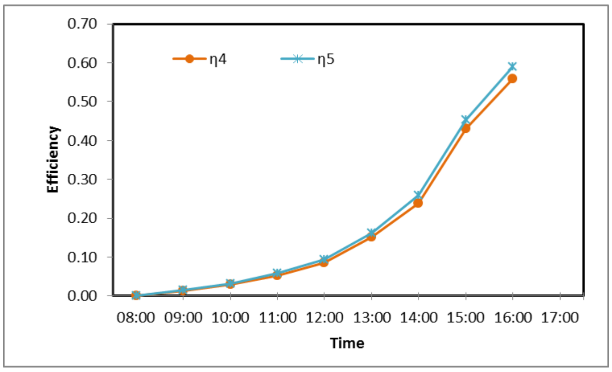


Figure 18. Natural and forced convection system efficiencies

In natural and forced convection systems, it was observed that the efficiency generally increased throughout the day and peaked at the end of the day. The maximum efficiency values calculated as a result of measurements were 55.91% for conventional solar still integrated with plate heat exchanger (natural convection), and 55.91% for conventional solar still integrated with plate heat exchanger (forced convection at 50 kg/h). Accordingly, the productivity of forced convection system was found to be the highest one. There is a harmony between distillers' efficiency and air temperature, received solar energy and water temperature. The air temperature, received solar energy and mean water temperature are the variables depending on each other, and the increase in any of them increases the efficiency of distiller.

CONCLUSIONS

In this study, the experimental research was carried out on the performance of traditional solar still and, by placing different types of heat exchangers within the distiller integrated with solar collector in order to improve performance; the effects of these heat exchangers were also examined.

The results obtained from the analyses of performed experiences are summarized below;

- It was observed that the vaporization peaked between 12:00 and 15:00 in distillation systems. For this reason, the amount of distilled water obtained in morning hours was higher than those obtained in afternoon.
- It was found that the amount of distilled water obtained between 11:00 and 12:00, when the solar radiation peaked, was less than the amount of distilled water obtained between 14:00 and 15:00. This was because most of the energy received between 11.00 and 12.00 was spent on increasing the temperature of the water within distiller. Moreover, since the temperature of transparent cover was high, the level of condensation decreased.
- It was observed that the temperature of transparent cover is of significant importance for the performance of distiller. It was also determined that decreasing the temperature of transparent cover or keeping it constant may improve the efficiency of distiller.
- The maximum amount of distilled water production in conventional solar still integrated with solar water heating collector was measured to be 688 ml between 14.00 and 15.00. At the end of the day, a total of 2582 ml was obtained. The amount of distilled water obtained during the night-time was determined to be 2630 ml, and the total amount of distilled water obtained in a day was calculated to be 5212 ml.
- The maximum amount of distilled water obtained hourly with solar still integrated with tubular heat exchanger was achieved between 14:00 and 15:00 (654 ml). 2502 and 2520 ml of distilled water was obtained during daytime and night-time, respectively, while the total amount of distilled water obtained throughout the day was 5022 ml.
- The maximum amount of distilled water obtained hourly with solar still integrated with plate heat exchanger was achieved between 14:00 and 15:00 (692 ml). 3066 and 2722 ml of distilled water was obtained during daytime and night-time, respectively,

while the total amount of distilled water obtained throughout the day was 5788 ml.

- As a result of the measurements, it was determined that the calculated efficiency value of conventional solar still was 51.47%. In natural convection systems, the efficiency of solar still integrated with solar water heating collector was 46.73%, while that of solar still integrated with tubular heat exchanger was 45.38% and the efficiency of solar still integrated with plate heat exchanger was found to be 55.91%.
- The reason for obtaining lower efficiency from solar still integrated with tubular heat exchanger in proportion to that of solar still integrated with plate heat exchanger was the increase in both heat transfer surface area and absorber surface area by means of plate heat exchanger placed into the solar still distiller. So, the temperature of water within the distiller increased to higher temperatures, and an increase was obtained in vaporization level.
- For solar still systems integrated with solar water heating collector, it was determined that the efficiency of the system integrated with plate heat exchanger was higher than the efficiency values of system integrated with tubular heat exchanger and than that of the conventional system. Moreover, it was observed that the value of 58.99% could be achieved via forced convection system.

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