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Evaluating thermal performance of a basin type modified active solar still

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ABSTRACT

In this paper, an attempt has been made to compare the thermal performance of a modified solar still with that of a conventional single slope basin type active solar still in the summer climatic conditions. Comparison has been made on the basis of theoretical performance indicators like internal heat transfer coefficients and energy fractions. Dunkle's model has been utilized to assess internal heat transfer coefficients at different water depths. Values of various heat transfer coefficients for the modified still are observed superior to the conventional solar still. At 0.01 m water depth, daily average value of evaporative heat transfer coefficient for modified still is observed 13.9% higher than that for the conventional still. Average values of radiative coefficient and convective coefficient for modified still are also higher by 3.5% and 4.5% respectively than those of conventional still. Reliance on different heat transfer coefficients on water depth in the still is likewise analyzed. The modified still has demonstrated on an average 42.85% higher daily evaporative heat transfer coefficient at 0.01 m water depth in comparison to its value at 0.03 m depth. With the increment in water depth (from 0.01 m to 0.03 m), there is a marginal variation in convective coefficient. The energy fractions are also figured and compared. The distillate yield count utilizing thermal model has additionally been done and compared with the experimental results. Theoretical and experimental results are observed to be in close proximities.

Keywords: Modified still; Heat transfer coefficients; Energy fraction; Theoretical yield

1. Introduction

Due to persistent populace increment, the demand of good quality water for domestic and industrial purpose is expanding day by day. To meet this demand, desalination of brackish water is necessary. Numerous desalination techniques are accessible in the market but all involve huge consumption of electrical energy. Solar desalination is a cost-effective alternative. It utilizes solar energy which is a renewable, eco-friendly and freely available source of energy. Solar still is a gadget which carries the solar desalination process.

The solar stills with different designs are being utilized for a long time to deliver potable water particularly in remote arid territories. In the field of solar desalination, an interest in solar still systems revives to develop this device into a more proficient technology for sustainable water production. Various experimental and theoretical investigations have been carried out on different designs and parameters of the solar still to enhance the distillate output. Ayoub and Malaeb [1] presented a critical review of the research work conducted on solar stills' development. They grouped together various studies addressing each parameter of concern and compared results. Novelty in design and newly introduced features were also presented. In a single effect still, the latent heat of condensation is exhausted as waste. In the multi effect still, the heat of condensation of the previous effect is utilized in the next effect to heat water. Rajaseenivasan et al. [2] reviewed the different methods tried by different researches to improve the productivity of multi effect solar still. The performance, economy and operational & maintenance aspects of different types of multi effect solar stills were summarized in the paper.

Dependency of distillate output on top cover has been analysed by many researchers. Jones et al. [3] investigated the effects of using three different cover materials (glass, Plexiglas, and plastic wrap) under a series of environmen-

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tal conditions. The heat transfer model was improved upon by the incorporation of a term for the effective emissivity of the cover, τ_{eff}. They verified the cumulative yield and water temperature profile predictions of the improved model by comparing it with experimental results.

Different models governing heat transfer have been proposed. Sivakumar et al. [4] developed a mathematical model to find the effect of heat capacity of the basin and glass cover on the performance and exergy destruction of single slope passive solar still, considering that the heat transfer and thermal losses from the components of a solar still are influenced by the heat capacity. Al-Garni [5] attempted the productivity enhancement of a single-slope solar still using an immersion-type water heater and external cooling fan. The productivity increased by 250% when a water heater of 500 W capacity was used in the base tank. Also an increment in productivity by 5.2 and 10.3% was observed when an external cooling fan was used to cool the outer glass surface with wind speeds of 7 and 9 m/s, respectively.

Many new designs are proposed by the researchers. Ahsan et al. [6] developed a low cost triangular solar still which was fabricated with cheap, lightweight, locally available materials. The effect of water depth on the daily water productivity was evaluated by varying the water depths (1.5, 2.5 and 5 cm) with the climatic condition of Malaysia and an inverse proportional relationship was revealed between them. It was also concluded that water productivity was nearly proportional to the daily solar radiation. Ayoub and Malaeb [7] significantly increased the evaporative surface area of the solar still in the form of a slowly-rotating hollow cylinder introduced within the solar still. The introduced cylinder resulted in a 200–300% increase in distillate output.

Modification in the conventional design of the still also influences its output. Abdullah [8] investigated the experimental performance of a single slope passive solar still and a stepped solar still coupled with a solar air-heater. The hot air from the solar air heater passes under the base of the stepped still used to heat the saline water. Results showed that, the water productivity from the stepped solar still increased by 112% over the conventional still, when the system was coupled with a solar air-heater and glass cover cooling. The productivity of the stepped still is increased by integrating aluminum filling by about 53% over conventional still. A modified basin type solar still equipped with an air-cooled condenser was constructed and tested by Ibrahim and Elshamarka [9]. The system was operated at reduced pressure in batch-wise mode. Better measured performance of the modified still was obtained compared with that of the conventional one. The system was simulated using a mathematical model and solved numerically using a computer program. The developed model was validated against experimental measurements. The parametric study using the validated model is carried out to explore the improvement potentials of the constructed system.

Still performance also depends upon its orientation. Abderachid and Abdenacer [10] developed a computer program to simulate the effect of the orientations (east–west and south–north), on the performance of a symmetric double slope solar still compared to those of an asymmetric solar still with a double effect, in order to obtain the optimum design parameters for both types. The stability of solar radiation seen in a south–north orientation leads to high reception of solar radiation by both stills. As a consequence, the daily productivity of an asymmetric still (south–north orientation), with a double effect process was found 22.57% higher than that corresponding to the symmetric one, and an increase of 16.23% productivity when oriented in east–west direction. It was also shown that south–north orientation enhanced the performance of the asymmetric still by 16.76%, with a double effect. To calculate the distribution of solar radiation in a solar still, a refined algorithm was developed by Madhlopa and Clarke [11]. In the algorithm, the reflectance and optical view factors of surfaces, and multiple reflections were taken into account. It was found that effective irradiance was lower than the irradiance observed on a horizontal surface outside the solar still and that the refined algorithm yielded lower values of effective solar radiation as well as lower values of distillate output than the previous models. An expression for instantaneous exergy efficiency of a passive solar still was developed by Kumar and Tiwari [12]. The effect of effective absorptivity of a basin liner (0.9–0.6), glass cover tilt (15–45º) and wind velocity (0.0–10 m/s) have were taken into account. It was found that with decrease in absorptivity (0.9–0.6) with time, the energetic and exergetic efficiencies decreased by 21.8% and 36.7% respectively. The effect of the glass cover tilt was found to be insignificant and the respective efficiencies decreased by 0.75% and 0.47% per degree increase in tilt. These efficiencies increased rapidly up to a wind velocity of 2 m/s.

Internal heat transfer rate is the key behind the productivity of the still. Heat transfer coefficients predict the behaviour of the solar still. Many researchers depicted several models for evaluation of these coefficients. Gad et al. [13] made an attempt to estimate the heat transfer coefficients of a conical solar still in the climatic conditions of Egypt. The daily productivity for conical and conventional solar stills was 3.38 and 1.93 L/m^2 day, respectively. Heat and mass transfer coefficients were evaluated and the Nusselt and Sherwood numbers were calculated with the aid of both evaporation measurements and Chilton–Colburn analogy. The maximum value of the total heat transfer coefficient was 66 and 32 W/m^{2}C for conical and conventional solar stills, respectively. Dwivedi and Tiwari [14] evaluated the internal heat transfer coefficients of the single and double slope passive solar stills in summer as well as winter climatic conditions for different water depths (0.01, 0.02 and 0.03 m) by various thermal models. Maleb et al. [15] developed a theoretical model based on governing heat and mass balance equations. The governing equations were solved numerically and the model was calibrated and validated using experimental data. The built model was used to study the effects of important variables. Three empirical correlations to determine heat transfer coefficients were employed and an error analysis was conducted for each case.

Research work referred to above is tabulated as under in Table 1.

In this study, a design modification is proposed over a conventional basin type single slope solar still. An additional condensing surface has been incorporated which enhanced the internal and external heat transfer rates and resulted in better yield output. An endeavour has been made to calculate internal heat transfer coefficients, energy fraction and yield for the modified solar still as well as conventional solar still and comparison has been made.

Table 1
Previous work referred in the paper

Refrerence	Author(s)	Year	Scope of work/parameters studied	Conclusions made
[1]	Ayoub and Malaeb	2012	Reviewed the prevoius work	
[2]	Rajaseenivasan et al.		Reviewed multi effect solar stills	
[3]	Jones et al.	2014	Analysed different cover materials, introduced effective emissivity of the cover, τeff	Highest yield with glass cover
[4]	Sivakumar et al.	2016	Studied effect of heat capacity of the basin	Yield increases by 10.38 %
[5]	Al-Garni	2014	Coupled immersion-type water heater and external cooling fan	Heater increases yield by 250 % whereas fan increases 10.3 %
[6]	Ahsan et al.	2014	Developed a low cost triangular solar still	Concluded that water productivity was nearly proportional to the daily solar radiation.
[7]	Ayoub and Malaeb	2014	Introduced a slowly-rotating hollow cylinders within the still	200–300% increase in distillate output was observed.
[8]	Abdullah	2013	Coupled a solar air heater with a single slope passive solar still and a stepped solar still	112% higer prodution in stepped solar still and 53% higher in conventional still
[9]	Ibrahim and Elshamarka	2015	Incorporated an air-cooled condenser	Better performance of the modified still was obtained
[10]	Abderachid and Abdenacer	2013	Developed a computer program to simulate the effect of the orientations on the performance of a symmetric double slope solar still compared to those of an asymmetric solar still with a double effect,	Productivity of an asymmetric still (south–north orientation), with a double effect process was found 22.57% higher than that corresponding to the symmetric one, and an increase of 16.23% productivity when oriented in east–west direction. It was also shown that south–north orientation enhanced the performance of the asymmetric still by 16.76%, with a double effect.
[11]	Madhlopa and Clarke	2013	To calculate the distribution of solar radiation in a solar still, a refined algorithm was developed	Effective irradiance was lower than the irradiance observed on a horizontal surface outside the solar still and that the refined algorithm yielded lower values of effective solar radiation as well as lower values of distillate output than the previous models.
[12]	Kumar and Tiwari	2011	Developed an expression for instantaneous exergy efficiency of a passive solar still	With decrease in absorptivity (0.9-0.6) with time, the energetic and exergetic efficiencies decreased by 21.8% and 36.7% respectively.
[13]	Gad et al.	2015	Estimated the heat transfer coefficients of a conical solar still	The maximum value of the total heat transfer coefficient was 66 and 32 W/m^{2}C for conical and conventional solar stills, respectively
[14]	Dwivedi and Tiwari	2009	Evaluated internal heat transfer coefficients for single and double slope passive solar stills	Analysed effect of water depth on heat transfer coefficients at different water depths (0.01, 0.02 and 0.03 m) by various thermal models
[15]	Maleb et al.	2016	Developed a theoretical model based on governing heat and mass balance equations	The governing equations were solved numerically and the model was calibrated and validated using experimental data

2. Experimental analysis

2.1. Experimental set-up

For experimental analysis, two basin type solar stills were fabricated. One of them was a conventional basin type single slope solar still and another was a basin type solar still with an additional condensing surface [16]. It was a modification over single slope basin type still (Fig. 1). Keeping the basin area containing water as same, the additional condensing surface was incorporated. In this way, this design is novel. An important advantage of the modified still with secondary cover is that the basic features of the conventional solar still have been preserved. Stills were installed at KIET, Ghaziabad (India) (28.67° N, 77.42° E). The body of each solar still was made up of fiber reinforced plastic (FRP) with 4 mm thickness. Base dimensions of the conventional still were 1 × 1 m^2 and that for the modified still were 1 × 11.3 m^2. Water was trapped in a 1 × 1 m^2 area in both the stills. The inclination of the main condensing cover was 30° with horizontal which is approximately equal to the latitude of Ghaziabad (28.67°) and the secondary condensing cover was perpendicular with the main cover. The orientation of the the still was in such a manner that the main condensing cover faced south and the secondary condensing cover faced north direction. All the condensing covers were made of plane glass of 4 mm thickness. To increase the absorption of solar radiation, the bottom and the side inner surfaces of the solar stills were painted black. Solar stills were mounted on the iron frame work of around 0.5 m height each.

Both the stills were coupled with flat plate collectors individually just to supply initially heated water to them. The collector body comprised of Galvanized Iron sheet. For extreme pick up of solar radiation, the flat plate collectors were tilted at 30° with horizontal (equal to the latitude of Ghaziabad) and facing towards south. For minimizing the heat loss through the base of the collector, a glass wool sheet of 10 mm thick was given in the base of both the

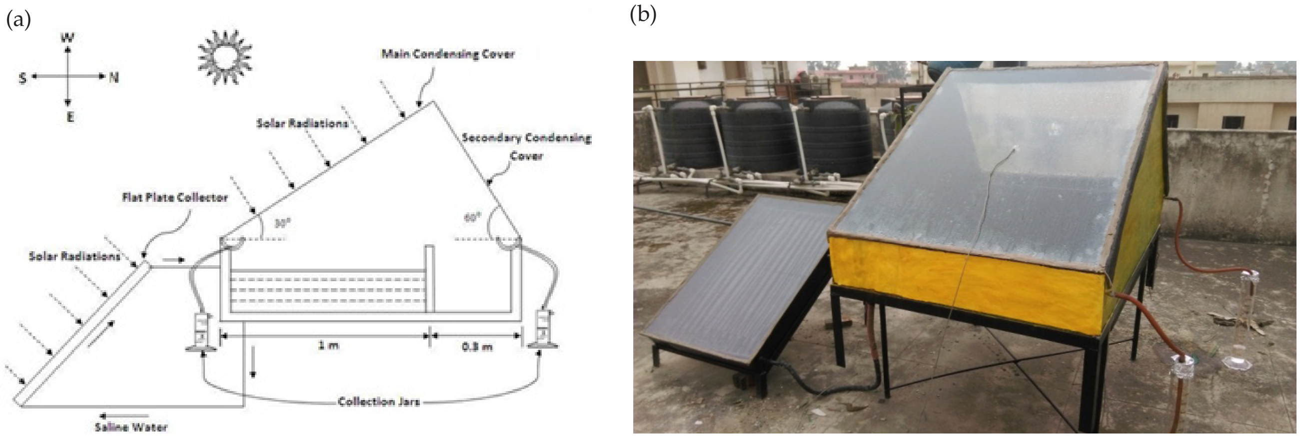

Fig. 1. (a) Schematic diagram of Modified solar still (b) Actual photograph of set-up with Modified solar still.

collectors. Yields from both the covers of the modified still were collected into separate channels provided at lower sides of covers and taken out through insulated flexible pipes into two distinctive collection jars. Thermocouples were settled at various selected points for measuring basin water temperature, vapor temperature, glass covers inner temperatures, glass covers outer temperatures and so on.

Performance of both the stills can be compared in the light of the fact that both are fabricated using indistinguishable materials, having comparable size, running under same climatic conditions &getting equivalent solar radiations through the main condensing cover. Outdoor experiments were conducted in the campus of KIET Group of Institutions, Ghaziabad (India) in the month of April for different water depths (0.01 m, 0.02 m and 0.03 m) at alternate days for both the stills simultaneously. The experiments started at 6:00 in the morning and went on till 10:00 at night.

2.2. Measuring instruments and their error analysis

2.2.1. Instrumentation used

Following measuring instruments were used during the experimental work-

a. Thermocouples: To sense the temperatures at different points, copper-constant and thermocouples were used. Those points were basin water, water coming out from the collector, vapour inside the still, condensing covers' inner and outer surfaces. These thermocouples were calibrated with the Zeal thermometer. Thermocouples were connected with multi channel digital temperature indicator which indicates the temperatures at different points.
b. Digital Anemometer: To measure wind velocity flowing past the condensing cover, a digital Anemometer (LUTRON AM-4201) was used.
c. Solarimeter: To measure the total solar radiation intensity on solar stills and collectors, a Solarimeter (CEL, India make) was used. This instrument was calibrated with the help of a Pyranometer.
e. Mercury thermometer: to measure the ambient temperature, a calibrated mercury-in-glass thermometer was used.
f. Collection Jars: To measure hourly distillate output, calibrated collection jars were used.

2.2.2. Measurement uncertainties

During measurement, various fixed and random errors are the reasons behind uncertainties. Results of measurement can be made accurate and reliable if the effect of these errors is considered. Estimation of internal uncertainties (*U*) was carried out before experimentation [17]. Uncertainty analysis of temperature measurement using thermocouple has been given in the Appendix A. For this purpose, the temperature of boiling water was measured at short intervals and calculations were made as under.

$$U = \sqrt{\frac{\sigma^2}{n-1}} \tag{1}$$

where

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - X_m\right)^2}{n}} \tag{2}$$

Now,

$$\%\ \text{Uncertainity} = \frac{U}{X_m} \times 100 \tag{3}$$

The range, accuracy and uncertainty for the measuring instruments used are summarised in Table 2. The cumulative effect of errors occurred in the measurement of various parameters led to the accuracy of different heat transfer coefficients in the range of ±3%.

3. Theoretical analysis

3.1. Internal heat transfer coefficients

Internal heat transfer is responsible for the transportation of pure water in vapour form leaving behind all the impurities in the basin. It is combination of evaporative,

Table 2
Instruments and their accuracy

Sl. No.	Instrument	Range	Accuracy	% error
1	Thermocouple	0-100 ^{0}C	± 0.1 ^{0}C	± 1%
2	Anemometer	0-15 m/s	± 0.1 m/s	± 2%
3	Solarimeter	0-1000 W/m^2	± 20 W/m^2	± 3%
4	Thermometer	0-100 ^{0}C	± 1 ^{0}C	± 0.5%
5	Collection jar	0-2000 ml	± 5 ml	± 2%

convective and radiative heat transfer. Solar radiations transmitted through the transparent condensing cover (generally glass sheet) are absorbed by the basin liner. The temperature difference between basin liner and impure water in contact with it causes density variation in the water above the surface, resulting in buoyancy. The motion of water above the basin surface is called free convection. Now water leaves the surface in the form of vapor. Here internal heat transfer plays an important role.

Dunkle [18] proposed following relationships for evaluating internal heat transfer in the solar still. These relations are well accepted for the normal operating temperature range and widely used by many researchers [12–15]. Convective heat transfer by humid air in the presence of mass transfer of water is given as

$$\dot{q}_{cw} = h_{cw}.\left(T_w - T_{ci}\right) \tag{4}$$

where, h_{cw} is convective heat transfer coefficient and is expressed as

$$h_{cw} = 0.884\left[\left(T_w - T_{ci}\right) + \frac{\left(P_w - P_{ci}\right)\left(T_w + 273.15\right)}{\left(268.9\times10^3 - P_w\right)}\right]^{1/3} \tag{5}$$

here partial pressures (P_w and P_{ci}) are functions of temperature and are given as

$$P_w = \exp\left[25.317 - \frac{5144}{T_w + 273.15}\right] \tag{6}$$

$$P_{ci} = \exp\left[25.317 - \frac{5144}{T_{ci} + 273.15}\right] \tag{7}$$

Heat transferred per unit area per unit time by evaporation from the water surface to the condensing cover is expressed as

$$\dot{q}_{ew} = h_{ew}.\left(T_w - T_{ci}\right) \tag{8}$$

where h_{ew} is evaporative heat transfer coefficient and is given as

$$h_{ew} = 0.0163 h_{cw}.\left\{\frac{P_w - P_{ci}}{T_w - T_{ci}}\right\} \tag{9}$$

The surface of water and the condensing cover of solar still are treated as the case of infinite parallel planes, because of the small inclination of the glass cover and the larger width of the unit. The rate of radiative heat transfer from the water surface to the condensing cover is expressed as

$$\dot{q}_{rw} = h_{rw}.F_{12}.\left(T_w - T_{ci}\right) \tag{10}$$

here h_{rw} is radiative heat transfer coefficient and is given as

$$h_{rw} = \varepsilon_{eff}.\sigma'\left[\left(T_w + 273.15\right)^2 + \left(T_{ci} + 273.15\right)^2\right].\left[T_w + T_{ci} + 546.3\right] \tag{11}$$

where

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_c} - 1\right]^{-1} \tag{12}$$

Convective and evaporative heat transfer coefficients are calculated for heat transfer between water surface and south facing cover and water surface and north facing cover of the modified still. But the radiative heat transfer between the water surface and the secondary condensing surface is neglected for the modified still. All the three internal heat transfer coefficients are calculated for heat transfer between water surface and south facing cover of the conventional solar still.

3.2. Energy fractions

The heat transfer by each mode can be expressed as a fraction of the total heat transfer which is known as energy fraction. The relative significance of three modes of heat transfer can be better understood by the energy fraction of each mode.

Total rate of internal heat transfer from the water surface to the glass cover is obtained by addition of equations of individual heat transfer

$$\dot{q}_t = \dot{q}_{rw} + \dot{q}_{cw} + \dot{q}_{ew} = h_{1w}.\left(T_w - T_{ci}\right) \tag{13}$$

where total internal heat transfer coefficient is given as,

$$h_{1w} = h_{cw} + h_{ew} + h_{rw} \tag{14}$$

Evaporative, convective and radiative energy fractions are expressed respectively, as

$$F_e = \frac{\dot{q}_{ew}}{\dot{q}_t}; F_c = \frac{\dot{q}_{cw}}{\dot{q}_t}; F_r = \frac{\dot{q}_{rw}}{\dot{q}_t} \tag{15}$$

3.3. Distillate output

The hourly distillate output from the solar still is expressed as

$$\dot{m}_w = \frac{\dot{q}_{ew}.A_c}{L}.3600 = \frac{h_{ew}.\left(T_w - T_{ci}\right).A_c}{L}.3600 \tag{16}$$

This equation has been used by many researchers [9–12] in the past to validate their experimental results. Here latent heat of evaporation of water (L) is a function of temperature and given as;

$$L = 2.4935\times10^6 \times\left[1 - \left(9.479\times10^{-4}T_v + 1.3132\times10^{-7}T_v^2 - 4.7974\times10^{-9}T_v^3\right)\right]; \text{ for } T_v < 70°\text{C} \tag{17}$$

$$\text{and } L = 3.1615\times10^6 \times\left[1 - 7.616\times10^{-4}T_v\right]; \text{for } T_v > 70°\text{C} \tag{18}$$

4. Results and discussion

Experimental observations and various calculated results are detailed in Figs. 2–7. Fig. 2a shows the hourly variation of water temperature of both the stills at different water depths. It is evident that maximum temperature is 70.3°C at 3:00 pm for 0.01 m water depth in the modified still whereas its maximum value is 66.4°C at the same time at the same water depth but for a conventional still. Higher temperature in case of modified design is due to the additional energy entering into the modified still through the north facing secondary cover. At any time, water temperature is lower for higher water depth as almost same amount of energy being utilized to heat higher amount of water. This inverse relation of temperature with water depth has been observed by many researchers in the past.

Fig. 2b exhibits the hourly variation of inner temperature of the main condensing cover. Maximum temperature is found as 64.1°C at 3:00 pm for 0.01 m water depth in the modified still whereas it is max 57.2°C at the same time at the same water depth for a conventional still. These temperatures are lower for higher water depth. From these two figures, it is also evident that at any instant, the temperature difference is always higher at lower water depth.

Internal heat transfer coefficients have been calculated for conventional as well as modified stills. The model proposed by Dunkle has been used. The results for internal heat transfer coefficients are presented in Figs. 2–5. First, the convective heat transfer coefficients for internal heat transfer between water and the condensing cover at different water depths are compared in Fig. 3. Fig. 3a exhibits convective heat transfer coefficient for both the stills at 0.01 m water depth. Its value is least at the start of the day and increases till 3:00 pm. Till this time, its value is greater for the modified still and after that it dominates for the conventional still till 7:00 pm. Marginal difference is observed between its value for the main cover and the secondary cover of the modified still. An almost similar trend is observed at 0.02 m (Fig. 3b) and 0.03 m water depths (Fig. 3c).

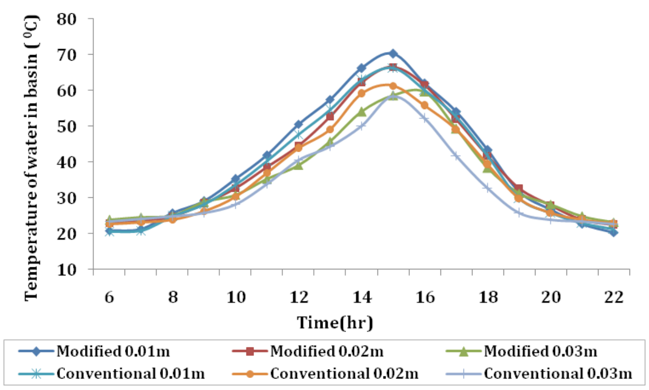

Fig. 2a. Hourly variation of water temperature of both the stills at different depths.

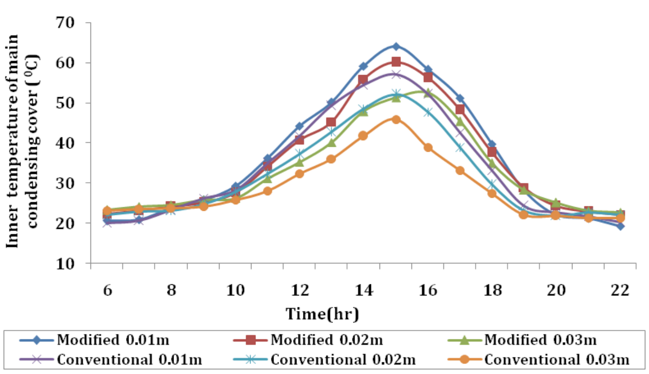

Fig. 2b. Hourly variation of inner temperature of main condensing covers of both the stills at different water depths.

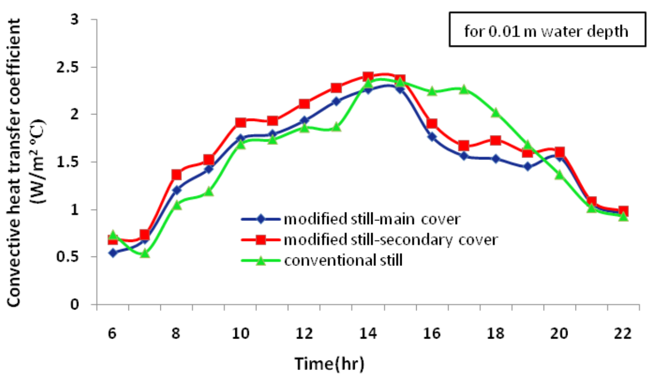

Fig.3a. Hourly variation of internal convective heat transfer coefficient of both the stills at 0.01 m water depth.

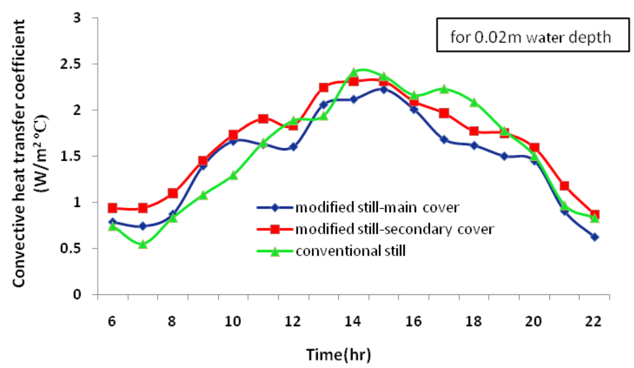

Fig. 3b. Hourly variation of internal convective heat transfer coefficient of both the stills at 0.02 m water depth.

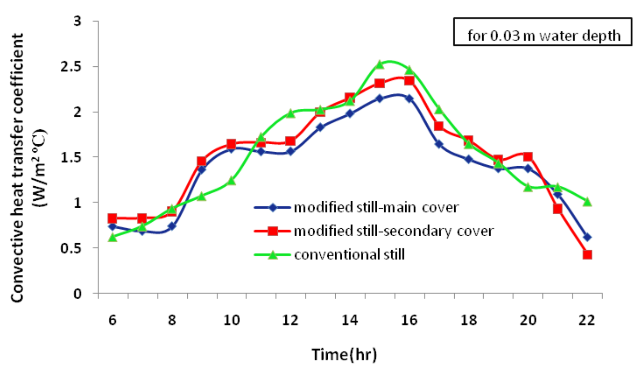

Fig. 3c. Hourly variation of internal convective heat transfer coefficient of both the stills at 0.03 m water depth.

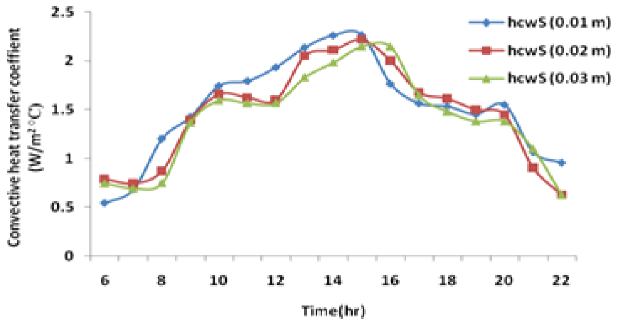

Fig. 3d. Comparison of hourly variation of internal convective heat transfer coefficient for south facing cover of modified still at various water depths in the basin.

On the other hand, no appreciable difference in its value is observed at different water depths for the modified still. Its average value for the south facing cover at 0.01 m water depth is 4% higher than that at 0.02 m depth and 7.3% higher than that at 0.03 m depth (Fig. 3d). So, convective heat transfer coefficient shows hardly any dependency on the water depth.

Hourly variation of evaporative heat transfer coefficient for internal heat transfer between water and the condensing cover at different water depths for both the stills are compared in Fig. 4a, 4b and 4c. For both the stills, at all the depths, evaporative heat transfer increases rapidly till 3:00 pm, and then diminishes. All these figures show its inverse relation with water depth. Its value at any time is highest for minimum water depth (0.01 m) in the still (Fig. 4a). Its average value for 0.01 m water depth is 16.8% higher than 0.02 m depth and 32.3% higher than 0.03 m depth. Their instantaneous values and average values keep on reducing with increasing water depth. This has been reported by many researchers in the past [12,13] also. Reason behind this trend is higher temperature difference at lower water depth.

Maximum value of the evaporative heat transfer coefficient for the conventional still is 37.94 W/m^2°C at 0.01 m water depth which is 13.9% less than that for the modified still (south facing cover : 44.05 W/m^2°C) at the same water depth (Fig. 4a).This depicts that the modified still has better evaporative heat transfer than the conventional model at the same water depth.

At different water depths, hourly variation of evaporative heat transfer coefficients for internal heat transfer between water and south facing main condensing cover for the modified still is shown in Fig. 4d. Its daily average at 0.01 m and 0.03 m water depths are 12.9 W/m^2°C and 9.034 W/m^2°C respectively which is 42.85% higher. So it is evident that the evaporative internal heat transfer reduces with higher water depth.

At different water depths,hourly variation of radiative heat transfer coefficients for internal heat transfer between water and condensing cover for both the stills are compared in Fig. 5a, 5b and 5c. Like other coefficients, its value increases till 3:00 pm due to increment in temperature difference between water and the condensing cover and then start reducing towards the end of the day. It is always higher for the modified still than the conventional still due to a higher temperature difference. On comparing these figures, it can be concluded that this coefficient is also

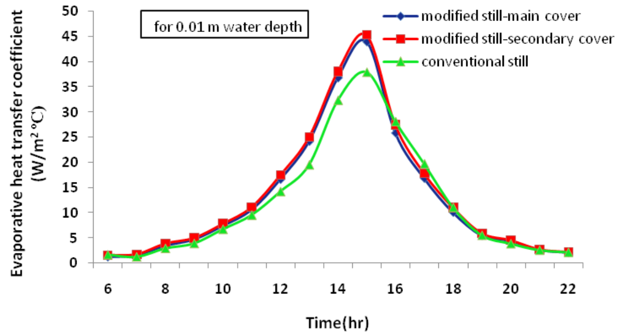

Fig. 4a. Hourly variation of internal evaporative heat transfer coefficient of both the stills at 0.01 m water depth.

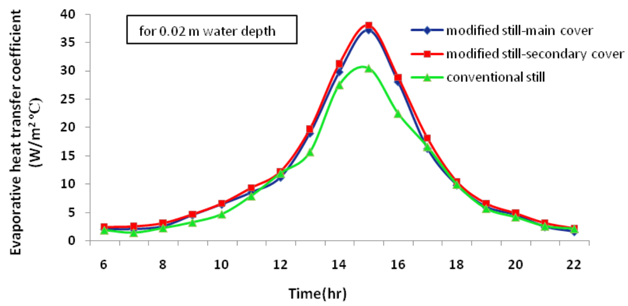

Fig. 4b. Hourly variation of internal evaporative heat transfer coefficient of both the stills at 0.02 m water depth.

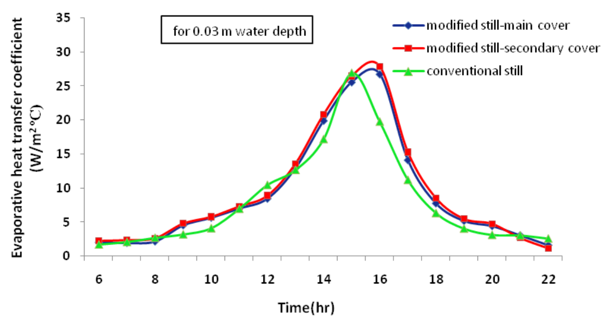

Fig. 4c. Hourly variation of internal evaporative heat transfer coefficient of both the stills at 0.03 m water depth.

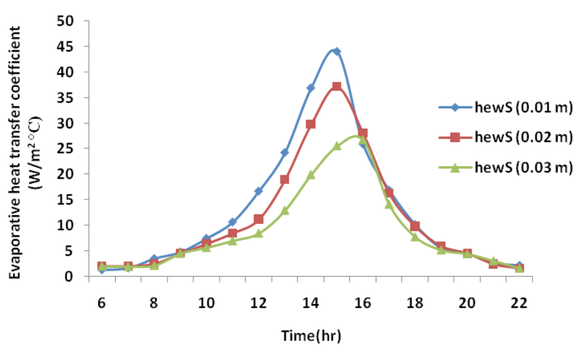

Fig. 4d. Comparison of hourly variation of internal evaporative heat transfer coefficient for south facing cover of modified still at various water depths in the basin.

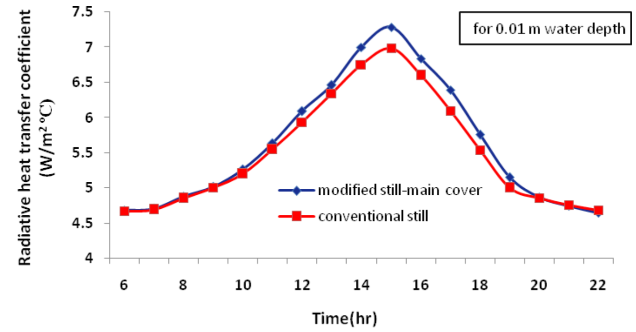

Fig. 5a. Hourly variation of internal radiative heat transfer coefficient of both the stills at 0.01 m water depth.

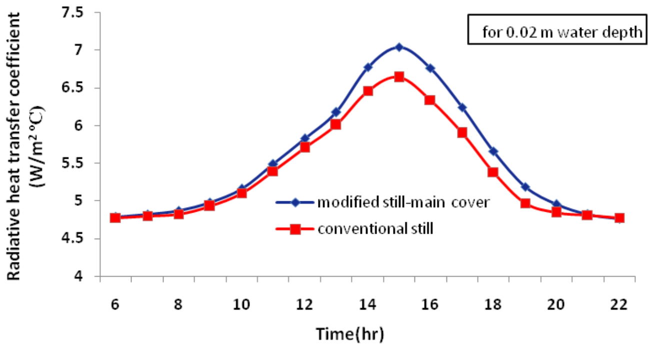

Fig. 5b. Hourly variation of internal radiative heat transfer coefficient of both the stills at 0.02 m water depth.

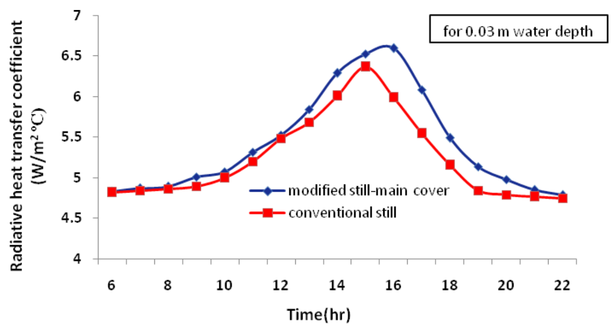

Fig. 5c. Hourly variation of internal radiative heat transfer coefficient of both the stills at 0.03 m water depth.

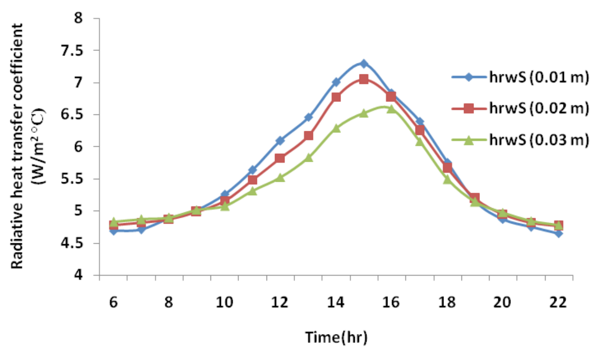

Fig. 5d. Comparison of hourly variation of internal radiative heat transfer coefficient for south facing cover of modified still at various water depths in the basin.

dependant on water depth. This has inverse relation with water depth due to decrement in temperature gradient with increment in water depth (Fig. 5d). It is also to be mentioned that hardly any heat transfer in radiation form takes place between water and the north facing cover due to their relative configuration.

Fig. 6a, 6b and 6c exhibit the variation of energy fraction with the temperature of water in the basin for the modified still at different water depths. Whereas Fig. 6d, 6e and 6f exhibit the variation of energy fraction with the temperature of water in the basin for the conventional still. All these figures conclude that the evaporative energy fraction

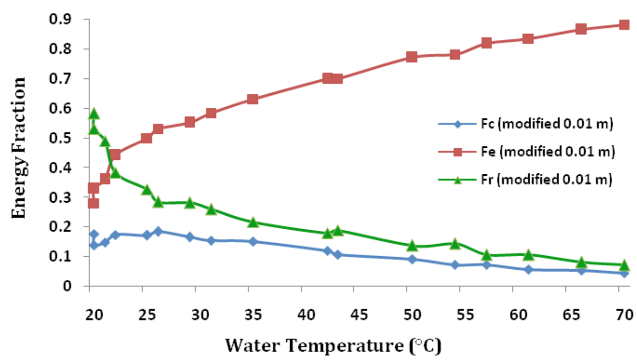

Fig. 6a. Variation of energy fractions of modified still with temperature of water at 0.01 m water depth.

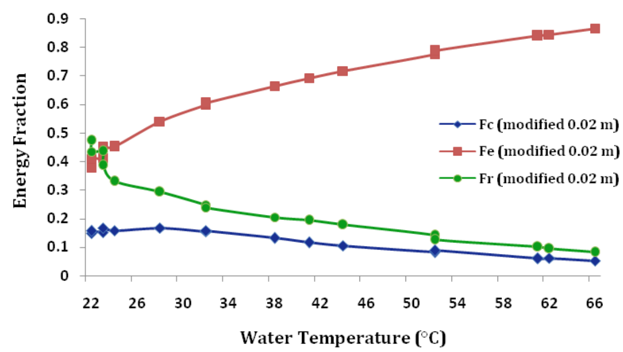

Fig. 6b. Variation of energy fractions of modified still with temperature of water at 0.02 m water depth.

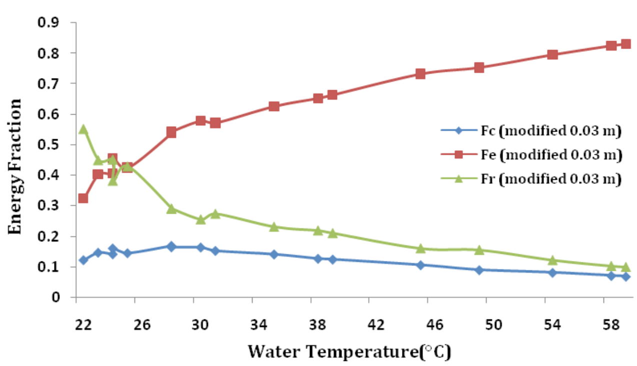

Fig. 6c. Variation of energy fractions of modified still with temperature of water at 0.03 m water depth.

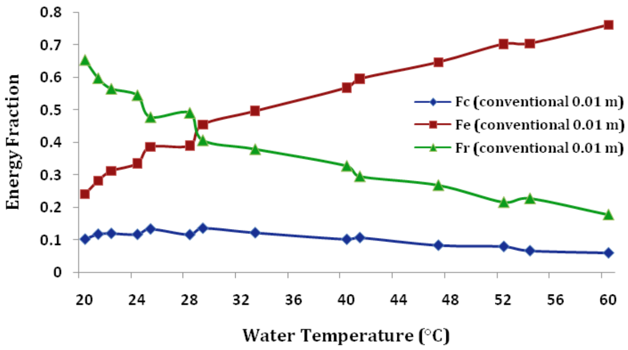

Fig. 6d. Variation of energy fractions of conventional still with temperature of water at 0.01 m water depth.

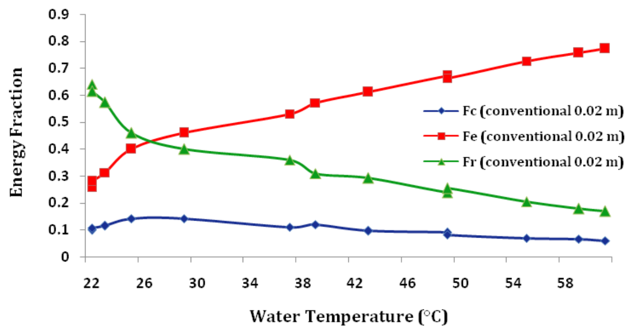

Fig. 6e. Variation of energy fractions of conventional still with temperature of water at 0.02 m water depth.

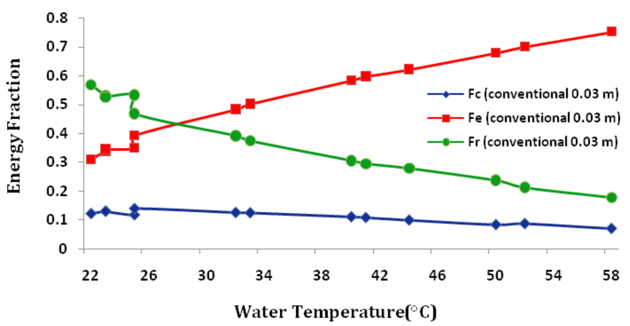

Fig. 6f. Variation of energy fractions of conventional still with temperature of water at 0.03 m water depth.

is very low at the start of the day as well as at the end of the experiment at night. Its value keeps on increasing with increment in the temperature. The value of radiative energy fraction diminishes with increase in water temperature. It dominates over evaporative faction at a lower water temperature (26–28°C), while evaporative fraction dominates over the other two fractions after 26 to 28°C. It is also worth to note that there is hardly any change in the value of convective energy fraction. At any temperature, contribution of heat transfer through the convective mode is least. At high temperature, considering all water depths, evaporative fraction for the modified still is greater than that of the conventional still.

Fig. 7a–7f present the theoretical and experimental results of the hourly yield for the conventional and the

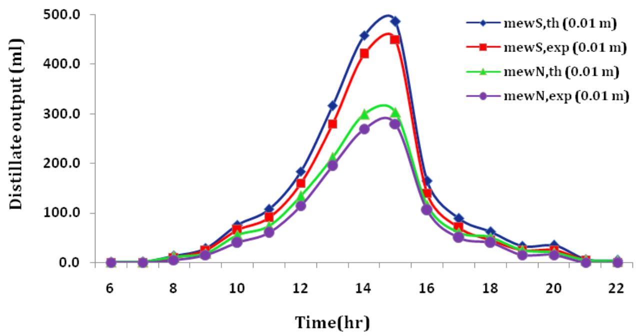

Fig. 7a. Comparison of hourly variation of experimental and theoretical values of distillate output of modified still at 0.01 m water depth.

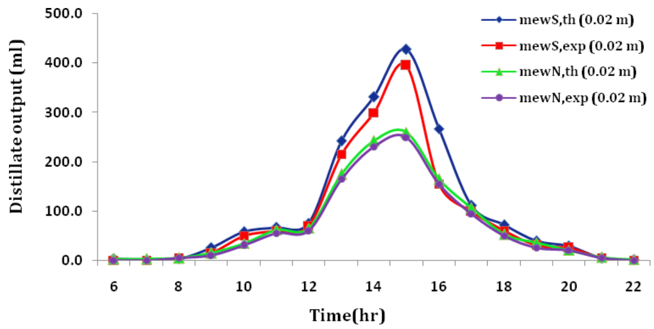

Fig. 7b. Comparison of hourly variation of experimental and theoretical values of distillate output of modified still at 0.02 m water depth.

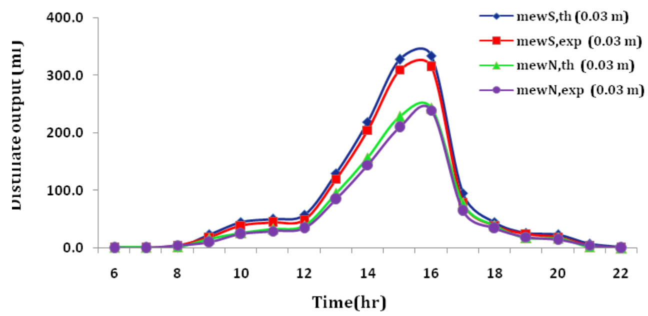

Fig. 7c. Comparison of hourly variation of theoretical and experimental values of distillate output of modified still at 0.03 m water depth.

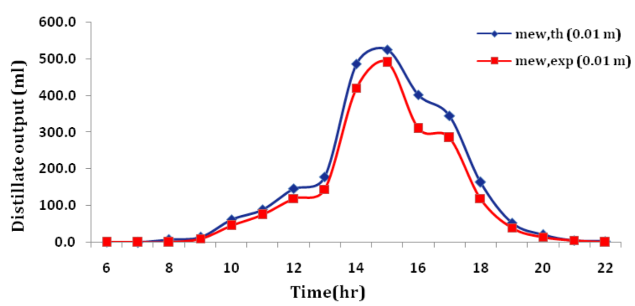

Fig. 7d. Comparison of hourly variation of theoretical and experimental values of distillate output of conventional still at 0.01 m water depth.

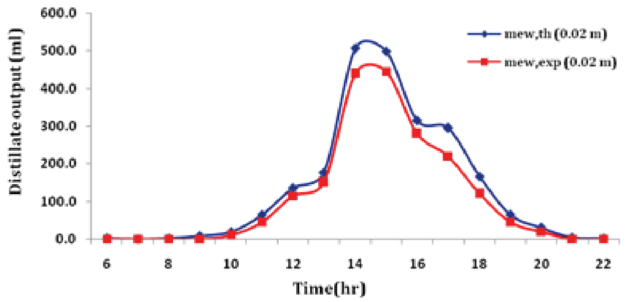

Fig. 7e. Comparison of hourly variation of theoretical and experimental values of distillate output of conventional still at 0.02 m water depth.

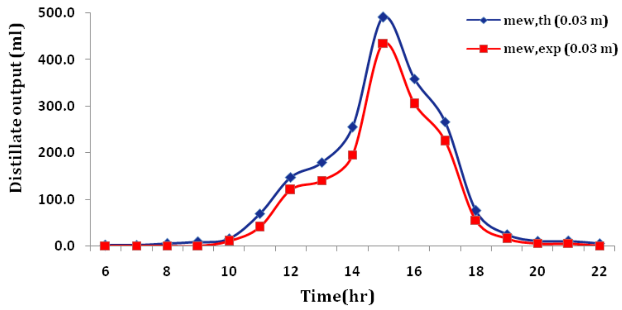

Fig. 7f. Comparison of hourly variation of theoretical and experimental values of distillate output of conventional still at 0.03 m water depth.

modified stills for different depths of water in the basin. Fig. 7a, 7b and 7c explain that for the modified solar still, theoretical daily yield through south facing main condensing cover is calculated as 2062.2 ml, 1752.4 ml and 1398.6 ml at 0.01 m, 0.02 m and 0.03 m water depth respectively which is 12.23%, 15.25% and 8.48% higher than its corresponding measured results. On the other hand, theoretical daily yield through the north facing secondary condensing cover is calculated as 1387.1 ml, 1248.2 ml and 1001.6 ml at 0.01 m, 0.02 m and 0.03 m water depth, respectively, which is 13.12%, 10.35% and 7.65% higher than its corresponding measured results. It is observed that there is a fair agreement between the experimental and theoretical results. Inverse relation of yield with water depth has been reported by many researchers [9].

Fig. 7d, 7e and 7f explain that for the conventional solar still, theoretical daily yield through its single main condensing cover is calculated as 2504.1 ml, 2297.1 ml and 1925.9 ml at 0.01 m, 0.02 m and 0.03 m water depth, respectively, which is 16.93%, 17.72% and 19.48% higher than its corresponding measured results. These values are lesser than their corresponding values for the modified solar still.

5. Conclusions

In this work, a new simple yet efficient modified solar still has been fabricated and experimentally tested along with the conventional design under similar climatic conditions. The combined theoretical and experimental investigations have been carried out towards understanding the interrelated heat and mass transport mechanism in the conventional and modified solar still and a comparison has been made. Performance of a conventional solar still and modified solar still has been compared through internal heat transfer coefficients, energy fractions and distillate output at different water depths. For the modified still, at 0.01 m water depth, daily average value of evaporative heat transfer coefficient has been observed 13.9% higher than that for the conventional still. For the modified still, average values of radiative coefficient and convective coefficient are also higher by 3.5% and 4.5% respectively, than those for the conventional still. Reliance of different heat transfer coefficients on water depth in the still is likewise analyzed. The modified still has demonstrated on an average 42.85% higher daily evaporative heat transfer coefficient at 0.01 m water depth in comparison with its value at 0.03 m depth. With the increment in water depth (from 0.01 m to 0.03 m), there is marginal variation in convective coefficient. So the modified still shows improved heat transfer coefficients and yield output which proves its better performance over the conventional design. The energy fractions are also figured and compared. Experimental results of yield output are also compared with theoretical values. At lower water depth, the modified still produces better yield. It can be concluded that a basin type solar still with additional condensing surface produces better fresh water at lower water depth.

Symbols

A	—	Area (m^2)
h	—	Internal heat transfer coefficient (W/m^2 °C)
I	—	Solar intensity per unit area (W/m^2)
$\dot{m}$	—	Hourly distillate output (kg)
$\dot{q}$	—	Heat transfer rate per unit area (W/m^2)
T	—	Temperature (°C)
n	—	No. of observations

Greek

ε	—	Emissivity
σ'	—	Stephan-Boltzman constant ($W/m^{20}K$)
σ	—	Standard deviation

Subscripts

a	—	Ambient
b	—	Basin surface
c	—	Collector suface
ci	—	Inner surface of condensing cover
co	—	Outer surface of condensing cover
cw	—	Convective from water surface
eff	—	Effective
ew	—	Evaporative from water surface
rw	—	Radiative from water surface
v	—	Vapour
w	—	Water
N	—	North direction
S	—	South direction

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Appendix A

Uncertainty analysis of temperature measurement through thermocouples

n	X_i	$(X_i-X_m)^2$
1	101.8	4.9729
2	102.7	9.7969
3	97.5	4.2849
4	98.8	0.5929
5	98.1	2.1609
6	97.1	6.1009
7	101.3	2.9929
8	98.2	1.8769
9	97.4	4.7089
10	102.8	10.4329
	$\Sigma(X_i-X_m)^2 = 47.921$	

σ^2	4.79
U	0.73
U %	0.74 ≃ 1