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Single Basin Solar Still Coupled with Evacuated Tubes - Thermal Modeling and Experimental Validation

K. Sampathkumar*[1], T.V. Arjunan+ and P. Senthilkumar#

Abstract – *An attempt made to couple the water-in-glass evacuated tubes with single basin solar still is reported in this paper. Even though many active methods have been developed to increase the productivity of the solar still, the proposed experimental technique has increased the daily average production to 72%. For high temperature distillation, evacuated tubes have better performance when compared to flat plate collector and other solar collectors. Outdoor experiments were conducted to predict the performance of a single basin solar still coupled with evacuated tubes for the climatic condition of Coimbatore (latitude: 11°N; longitude: 77°E and an altitude of 409 m above sea level), Tamilnadu, India. A thermal model was developed using energy balance equations and the results obtained were in good agreement with the experimental results. The payback period of this system was found to be 235 days based on the economic analysis.*

Keywords – Desalination, evacuated tube, productivity, solar energy, solar still.

1. INTRODUCTION

Water is the best doctor in the world. Most of the human diseases are due to polluted or non purified water resources. Even today, under developed countries and developing countries face a huge water scarcity because of unplanned mechanism and pollution by manmade activities. The pollution of water resources have increased slowly due to the industrialization and urbanization. Most of the water pollution is caused by the industries like paper mills, dying industries and leather industries which were started near the rivers and ponds. These activities adversely affected the rural areas and agriculture in the countries like India. The basic medical facilities never spotted numerous villages in India. The rural people still are not aware of the consequences of drinking untreated water.

Desalination has become need of the hour in water polluted areas to avoid the water borne diseases. More conventional and non-conventional desalination techniques were invented to correct the manmade errors. The desalination techniques using the conventional energy sources again caused other type of pollution to the nature. Any technique, which is friendly to nature and eco system, should be developed in the present scenario to stop environmental degradation. One of such system is solar desalination for purification of water using freely available solar energy. Variety of models were developed and widely used in various countries. New designs and methods were developed in the past decades for solar desalination.

Solar stills are broadly classified into passive and active solar stills. One of the main drawbacks of the passive solar still is lesser productivity. To overcome the above, various active solar stills were developed. Malik *et al.* [1] discussed the historical review of solar desalination system in 1982. Recently Arjunan *et al.* [2] reviewed the status of solar desalination in India. Qudais *et al.* [3] experimentally investigated the solar still using external condenser and concluded that the productivity and efficiency were considerably greater for the external condenser-type still than for the conventional still. Garcia and Gomez [4] studied the design parameters for the distillation system coupled with a solar parabolic trough collector. Tanaka *et al.* [5] have predicted the production rate of compact multiple effect diffusion type solar still consisting of a heat pipe solar collector as 21.8 kg/m^2 distilled water on sunny days based on the mathematical analysis. Singh *et al.* [6] found that the efficiency of the system with a solar concentrator was higher than solar collector. Zeinab *et al.* [7] designed the modified solar still coupled in a solar parabolic focal pipe and simple heat exchanger, which has resulted in 18% of increase in productivity. Velmurugan *et al.* [8, 9] obtained 27.6% increase in productivity by coupling mini solar pond with solar still and also studied the performance of stepped solar still with mini solar pond. A high temperature solar distillation with shallow solar pond was studied in [10] and concluded that the annual average productivity was increased by 52.36%. Integration of solar still in a multi source, multi use environment was studied in [11].

The active solar still with different condensing cover materials were studied by Dimri *et al.* [12] and found that yield was directly related to the thermal conductivity of the condensing materials; copper yielded greater when compared to glass and plastic. Kumar *et al.* [13], [14] found that the hybrid (PV/T) active solar still gives higher yield (more than 3.5 times) than the passive

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solar still. Voropoulos *et al.* [15], [16] experimentally and theoretically studied solar stills coupled with solar collectors and storage tank and they found that, the productivity has doubled. Also they designed a hybrid solar desalination and water heating system [17]. Sodha *et al.* [18] studied the average daily yield of solar still and found that the increase in inlet water temperature by utilization of waste hot water increases the productivity proportionally. Tiwari *et al.* [19] analysed the active regenerative solar still and concluded that the overall efficiency varies from 15 to 19% in high temperature distillation system [20]. Sanjay Kumar *et al.* [21] found that an active solar still with water flow over the glass cover yields maximum output. Singh *et al.* [22] found that the annual yield was at its maximum when the condensing glass cover inclination was equal to the latitude of the place. Yadav *et al.* [23] studied the transient solution for solar still integrated with a tubular solar collector, flat plate solar collector in thermosiphon mode [24] and high temperature distillation system [25]. Tiris *et al.* [26] found that the maximum yield of 2.575l/m^2 day for a simple solar still and 5.18 l/m^2 day when integrated with flat plate collector. Badran *et al.* [27] found that its production was increased by 231% while to be efficiency decreased by about 2.5%. The solar still productivity increased 36% by coupling flat plate collector. Badran *et al.* [28] found that the productivity was proportional to the solar radiation. Rai *et al.* [29] studied the single basin solar still coupled with flat plate collector and found that the daily production rate increased by 24% higher than the simple single basin solar still. Dwivedi and Tiwari [30] experimentally studied the double slope active solar still under natural circulation mode. From the study, they observed that, the double slope active solar still under natural circulation modes gives 51% higher yield in comparison to the double slope passive solar still. Tiwari *et al.* [31] inferred that, the internal heat transfer coefficients should be determined by using inner glass cover temperature for thermal modeling of passive and active solar stills. The heat transfer coefficients mainly depends on the shape of the condensing cover, material of the condensing cover and temperature difference between water and inner glass cover. The above works were mostly using flat plate collector, solar pond, solar parabolic concentrator, heat pipe and utilization of hot water to increase the daily average production of the solar still.

The evacuated tube solar collector has more advantages than the flat plate collectors for water heating purposes. Evacuated tube solar collectors are well known for their higher efficiencies when compared to flat plate solar collectors. In flat plate collectors, sun rays are perpendicular to the collector only at noon and thus a proportion of the sunlight striking the surface of the collector is likely always to be reflected. But in evacuated tube collector, due to its cylindrical shape, the sun rays are perpendicular to the surface of the glass for most of the day. The evacuated tubes greatly reduce the heat losses by means of vacuum present in the tubes. Morrison *et al.* [32] found that circumferential heat distribution is an important parameter influencing the flow structure. The performance of water-in-glass evacuated tube solar water heaters was studied by in [33]. Morrison *et al.* [34] concluded from the studies on water in glass evacuated tube water heater that, it was most successful due to its simplicity and low manufacturing cost and also evacuated tube solar collectors had better performance than flat plate solar collectors, in particular for high temperature operations. Budihardjo *et al.* [35] experimentally and numerically investigated the natural circulation flow rate through single ended water in glass evacuated tubes mounted over a diffuse reflector. Han *et al.* [36] reported that, currently the market price of flat plate and heat pump solar water heaters (SWH) are 30–50% higher than similarly sized evacuated tube SWHs. Tiwari *et al.* [37] developed thermal models for flat plate collector (FPC), concentrating collector, evacuated tube collector (ETC) and ETC with heat pipe. The results showed that, the productivity of the active solar stills were much higher when compared to the passive solar still. Within the active solar stills, the higher output was produced by ETC with heat pipe followed by the concentrating collector, ETC and FPC. A thermal model with flat plate collector was developed and experimentally validated. Many active solar still designs and their performances have been reviewed in detail by [38]; however none has experimentally studied the performance of solar still coupled with evacuated tubes.

In this present experimental work, evacuated tubes were directly coupled with solar still and the following performance tests were conducted and theoretically analysed.

- the productivity of simple single basin solar still
- the productivity of single basin solar still with evacuated tubes
- the effect of water depth on still productivity
- the effect of various heat transfer coefficients on still productivity
- the effect of various temperatures and solar radiation on still productivity

2. THERMAL MODELING

The theoretical analysis is done by using energy balance equations on various components of the solar still [37] and evacuated tubes. The following assumptions are made for the analysis,

a. The solar still is vapour-leakage proof.
b. The level of water in the basin is maintained at a constant level.
c. Inclination of the glass cover is small.
d. The system is under quasi-steady state condition.
e. The heat capacity of the glass cover, absorbing material and insulation is negligible.
f. No stratification in water mass.

The energy balance equations of three main components of the active solar still are as follows:

- Glass cover:

The rate of energy absorbed and rate of energy received from the water surface by radiation, convection and evaporation is equal to the rate of energy lost to air.

$$\alpha'_g I_{effs} + q_{rw} + q_{cw} + q_{ew} = q_{rg} + q_{cg} \tag{1}$$

where, fractional solar flux absorbed by the glass cover (α'_g) is taken [12] as 0.05

- Water mass:

The rate of energy absorbed and the rate of energy convected from the basin liner is equal to the rate of energy stored and rate of energy transferred to the glass cover.

$$Q_u + \alpha'_w\left(1-\alpha'_g\right)I_{effs} + q_w = M_w C_w \frac{dT_w}{dt} + [q_{rw} + q_{cw} + q_{ew}] \tag{2}$$

where, fractional solar flux absorbed the water surface (α'_w) is taken [12] as 0.05.

The mass of the water in the still is maintained as 70 kg.

The specific heat of water in the solar still is taken [37] as 4190 J/kg°C.

- Basin liner:

The rate of energy absorbed is equal to the rate of energy transferred to water and rate of energy lost by conduction through bottom and sides.

$$\alpha'_b\left(1-\alpha'_g\right)\left(1-\alpha'_w\right)I_{effs} = q_w + q_b \tag{3}$$

where, fractional solar flux absorbed by the basin liner (α'_b) is taken [12] as 0.8.

The radiative heat transfer between water and glass is given by [8],

$$q_{rw} = h_{rw}\left(T_w - T_g\right) \tag{4}$$

The radiative heat transfer coefficient between water and glass is given by [37],

$$h_{rw} = \varepsilon_{eff}\sigma\left[\left((T_w + 273)^2 + (T_g + 273)^2\right)\left(T_w + T_g + 546\right)\right] \tag{5}$$

where, Stefan Boltzmann constant (σ) is taken as 5.67×10^{-8} W/m^{2}K^4.

The effective emissivity (ε_{eff}) is taken [37] as 0.82.

The convective heat transfer between water and glass is given by [8],

$$q_{cw} = h_{cw}(T_w - T_g) \tag{6}$$

The convective heat transfer coefficient between water and glass is given by [39]

$$h_{cw} = \frac{K_v}{L_v} C\left(Gr\,\mathrm{Pr}\right)^n \tag{7}$$

'C' and 'n' values were calculated using experimental results by regression analysis method given by Tiwari *et al.* [31] and it is calculated as 0.04954 and 0.3921 respectively.

Where,

$$Gr = \frac{L_v^3 \rho^2 g \beta \Delta T'}{\mu^2} \tag{8}$$

Average spacing between the water and glass cover (L_v) is taken as 0.150m.

The temperature dependent physical properties of vapor were calculated using expressions given by [39].

$$\Delta T' = \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w}\right] \tag{9}$$

$$P_w = \exp\left[25.317 - \frac{5144}{(T_w + 273)}\right] \tag{10}$$

$$P_g = \exp\left[25.317 - \frac{5144}{(T_g + 273)}\right] \tag{11}$$

$$\mathrm{Pr} = \frac{\mu\, C_v}{K_v} \tag{12}$$

The vapor temperature of evaporation and condensation surface is calculated by [40],

$$T_v = \frac{\left(T_w - T_g\right)}{2} \tag{13}$$

The rate of evaporative heat transfer between water and glass is given by [8],

$$q_{ew} = h_{ew}(T_w - T_g) \tag{14}$$

The evaporative heat transfer coefficient between water and glass is given by [8],

$$h_{ew} = (16.273 \times 10^{-3})\, h_{cw} \frac{(P_w - P_g)}{(T_w - T_g)} \tag{15}$$

The total heat transfer coefficient is given by [37],

$$h_{tw} = h_{rw} + h_{cw} + h_{ew} \tag{16}$$

The temperature of the glass is assumed to be uniform since it is very thin.

The external radiation and convection losses from the glass cover to atmosphere is given by [39],

$$q_{tg} = q_{rg} + q_{cg} \tag{17}$$

The total heat transfer coefficient between glass and atmosphere is given by [41]

$$h_{tg} = 5.7 + 3.8(v) \tag{18}$$

The wind velocity during the test period is taken as 1 m/s.

The convective heat transfer between basin and water is given by [8]

$$q_w = h_w \ (T_b - T_w) \tag{19}$$

The convective heat transfer coefficient between basin and water is taken as 135 W/m^{2}K [8].

The conductive heat transfer between basin and atmosphere is [37]

$$q_b = h_b \ (T_b - T_a) \tag{20}$$

The conductive heat transfer coefficient between basin and atmosphere is given by [37],

$$h_b = \left[\frac{L_i}{K_i} + \frac{1}{h_{tg}} \right]^{-1} \tag{21}$$

The thickness of insulation material is 0.004 m and the thermal conductivity of insulation material (PUF) is 0.024 W/m°C.

Substituting Equations 4, 6, 14 and 17 in Equation 1, the energy balance equation of glass cover becomes

$$\alpha_g^{'} I_{effs} + h_{tw}(T_w - T_g) = h_{tg}(T_g - T_a) \tag{22}$$

After simplifying Equation 22

$$T_g = \frac{\alpha_g^{'} I_{effs} + h_{tw} \ T_w + h_{tg} \ T_a}{h_{tw} + h_{tg}} \tag{23}$$

Substitute Equations 19 and 20 in Equation 3, the energy balance equation of basin liner becomes,

$$\begin{aligned} &\alpha_b^{'} \ (1 - \alpha_g^{'}) \ (1 - \alpha_w^{'}) I_{effs} \\ &= h_w (T_b - T_w) + h_b (T_b - T_a) \end{aligned} \tag{24}$$

$$T_b = \frac{\alpha_{-b}^{'} I_{effs} + h_w \ T_w + h_b \ T_a}{h_w + h_b} \tag{25}$$

where,

$$\alpha_{-b}^{'} = \alpha_b^{'} \ (1 - \alpha_g^{'}) \ (1 - \alpha_w^{'}) \tag{26}$$

Useful thermal energy supplied to the still through evacuated tubes are given by [37],

$$Q_u = A_{ET} F_R \left[(\alpha\tau)_e I_{effe} - U_{LE} \left[\frac{A_L}{A_{ET}} \right] (T_w - T_a) \right] \tag{27}$$

A_{ET} is a diameter of absorber glass tube × total length of the tubes and it calculated as 0.564 m^2.

$A_L = \pi A_{ET}$ and it is calculated as 1.77 m^2.

The heat removal factor (F_R) is taken [37] as 0.831.

The inner and outer diameter of the evacuated tube is taken as 0.047 m and 0.058 m, respectively.

The effective absorptance – transmittance product $(\alpha\tau)_e$ of evacuated tube is taken [37] as 0.8.

The overall heat transfer coefficient (U_{LE}) of evacuated tubes is taken [37] as 2.44 W/m^2°C.

Substituting Equations 23 and 25 in Equation 2 and obtained the following differential equation,

$$\frac{dT_w}{dt} + aT_w = f(t) \tag{28}$$

where a and $f(t)$ are different expressions as follows

$$a = \frac{UA_{eff}}{(M_w \times C_w)} \tag{29}$$

where,

$$UA_{eff} = U_{LS} + A_L F_R U_{LE} \tag{30}$$

$$U_{LS} = U_b + U_t \tag{31}$$

$$U_b = \frac{h_w \ h_b}{h_w + h_b} \tag{32}$$

$$U_t = \frac{h_{tw} \ h_{tg}}{h_{tw} + h_{tg}} \tag{33}$$

$$f(t) = \frac{IA_{eff} + UA_{eff} \ T_a}{M_w C_w} \tag{34}$$

$$IA_{eff} = A_{ET} \ F_R (\alpha\tau)_e I_{effe} + (\alpha\tau)_{effs} I_{effs} \tag{35}$$

$$(\alpha\tau)_{effs} = \alpha_b^{'} \ \frac{h_w}{h_w + h_b} + \alpha_w^{'} + \alpha_g^{'} \ \frac{h_{tw}}{h_{tw} + h_{tg}} \tag{36}$$

To obtain the approximate analytical solutions following assumptions are made.

a is constant during time interval 0 – t , $f(t)$ is constant, $\overline{f(t)}$ over the time interval 0 – t

In the initial condition in Equation 28, t = 0, $T_w = T_{w0}$ is

$$T_w = \frac{\overline{f(t)}}{a}[1 - \exp(-at)] + T_{w(0)} \exp(-at) \tag{37}$$

The calculated values of Tg and Tw using Equations 23 and 37 at the end of the specified time interval become initial condition for next iteration of mathematical simulation and so on.

The hourly yield is given by:

$$m_{ew} = \frac{h_{ew}(T_w - T_g)}{L} \times A_s \times 3600 \tag{38}$$

where, the basin liner still area (A_s) is taken as 1m^2.

L is latent heat of vaporization and it is calculated using the following expression:

For Tv<70°C

$$2.2935 \times 10^6 \times \left[1 - 9.4779 \times 10^{-4} T_v + 1.3132 \times 10^{-7} T_v^2 - 4.7974 \times 10^{-9} T_v^3 \right]$$

For Tv>70°C

$$3.1615 \times 10^6 \times \left[1 - \left(7.616 \times 10^{-4} \times T_v \right) \right]$$

A thermal model has been developed using MATLAB 7.0 to calculate various heat transfer coefficients, glass temperature, water temperature and hourly yield of solar still, by providing the initial values of water and glass temperature, ambient temperature and intensity of solar radiation.

3. EXPERIMENTAL STUDY

Experimentation

The experimental setup was designed, fabricated and installed at Tamilnadu College of Engineering, Coimbatore (11˚N, 77˚E), Tamilnadu, India. The major elements of the experimental setup are single basin solar still and evacuated tubes. The schematic diagram of the experimental setup used for the study is shown in the Figure 1. The still is made up of aluminum plate of 1m × 1m area, which acts as a basin also. The inner side of the aluminum plate serves as absorber plate and it is painted black for a maximum of 0.1m height from the bottom to absorb higher incident solar radiation. Remaining area in the aluminum plate acts as reflector to increase the radiation effect in the solar still. Another box type outer structure with an area of 1.05m × 1.05m was designed to hold the still along with the insulation. The side and bottom heat losses are reduced by providing 0.04m thickness insulation of PUF (Polyurethane foam) with the thermal conductivity of 0.024 W/m^2°C.

The ordinary window glass with the thickness of 0.004m and angle of 11˚ with respect to horizontal axis (latitude of Coimbatore) was used for condensation of water in the basin. The distillate water condensed from the glass is collected in a U shaped aluminum plate fitted at the lower side of the still. Further a rubber pipe is connected to the collection tray to collect the desalinated water in a measuring jar. The inlet and outlet pipes are connected by making holes in upper and lower side of the still respectively. The thermocouples are fixed inside the still by providing small holes. The glass plate is held intact with the still using silicon rubber sealant and prevents the vapor leakages from the still.

On the lower side of the still, eight holes with diameter of 0.06m were made to fix the evacuated tubes. Water in glass type evacuated tubes are used for this study with a length of 1.5m, outer diameter 0.058m, inner glass diameter 0.047m and glass thickness of 0.0016m. The rubber gasket was used to fix the evacuated tubes in inner side of the basin. The evacuated tubes angle was maintained as 45˚ with respect to horizontal surface to receive the maximum solar radiation.

The other ends of the evacuated tubes were placed safely on a separate metal structure using a sponge material in between. The leakage of the water from the gasket was prevented by using rubber silicon sealant. A metal frame was used to hold the evacuated tubes and it was connected with still stand at an angle of 45˚. A corrugated structure with two reflector plates made of aluminum was fixed to the metal frame in a similar angle in order to increase the reflective radiation to evacuated tubes. The pictorial view of the solar still augmented with evacuated tubes is shown in the Figure 2.

Instrumentation and Observations

The wind speed was measured by digital wind anemometer with the range of 0-15 m/s and accuracy of ±0.2 m/s. The J type thermocouples were fixed in various locations of solar still and evacuated tubes to measure the temperature. The thermocouple with a range of 0°C - 700°C and accuracy of ±1°C were used. The intensity of solar radiation was measured by using a solarimeter (manufactured by Central Electronics Limited (CEL), New Delhi, India) with a range of 0-1200 W/m^2 and accuracy of ±5 W/m^2.

A plastic measuring jar with the capacity of 1000 ml and accuracy of ±5 ml was used for collection of desalinated water from the still. For each experiment, the glass cover was cleaned in the morning to avoid the dust deposition over outer layer of the glass. Extensive experiments were conducted in clear sunny days from July 2008 to May 2009. The readings were recorded at hourly intervals from 9 AM to 6 PM.

4. RESULT AND DISCUSSIONS

Experiments were conducted to predict the performance and to analyze the effect of various parameters on the still performance. The various values calculated from the theoretical model were validated by the experimental results. The closeness between the theoretical and experimental values can be explained in terms of the coefficient of correlation (r) and root mean square percentage deviation (e). The expressions given by [42] are given below:

$$r = \frac{N\sum X_iY_i - \sum(X_i)\sum(Y_i)}{\sqrt{N\sum X_i^2 - \left(\sum X_i\right)^2} \times \sqrt{N\sum Y_i^2 - \left(\sum Y_i\right)^2}}$$

$$e = \sqrt{\frac{\sum (e_i)^2}{N}}$$

where $e_i = \dfrac{X_i - Y_i}{X_i}$

The hourly variations of solar intensity and ambient temperature during the test day of April 21, 2009 have been shown in the Figure 3. It is observed that, the intensity of solar radiation on the evacuated tube surfaces was higher than the radiation on the solar still glass cover. This may be due to the difference in inclination of evacuated tubes (45°) and glass cover (11°).

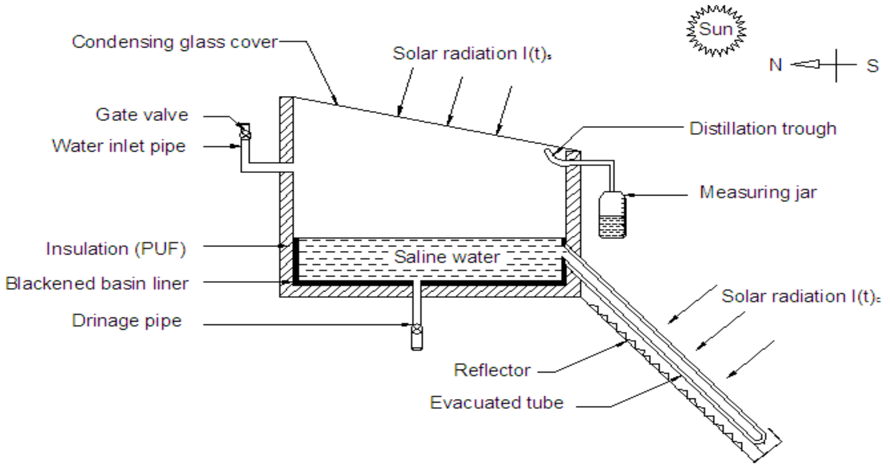

Fig. 1. Schematic diagram of experimental setup.

Fig. 2. Photographic view of solar still coupled with evacuated tubes.

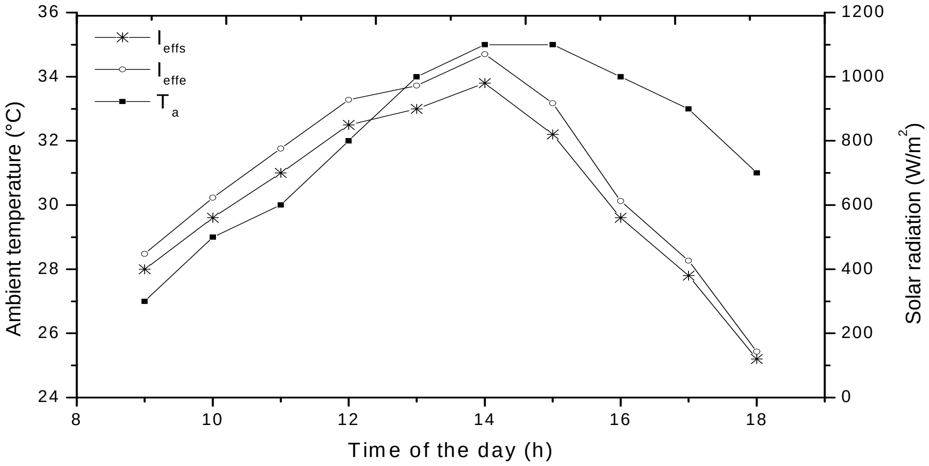

Fig. 3. Hourly variation of solar intensity and ambient temperature.

Effect of Solar Intensity and Ambient Temperature

The solar intensity is a important parameter, which directly influences the productivity of the solar still. The performance of the solar still is studied by conducting experiments during various months with different intensity of daily average solar radiation. The effect of intensity of solar radiation on productivity is plotted in the Figure 4. The study revealed that the productivity increased with the intensity of solar radiation.

The effect of the ambient temperature is shown in the Figure 5. The gradual rise in ambient temperature increases the productivity and vice versa. It is due to the reason that, when the ambient temperature increases, heat loss from the glass cover to atmosphere decreases, as there would be reduction in the temperature difference between the glass cover and ambient temperature. The maximum ambient temperature (35°C) was recorded at 14 and 15 hours on the day of the experiment.

Effect of Water Depth on Still Productivity

The depth of water in the basin had a major impact on the still productivity. The effect of various water depths in simple solar still and with evacuated tubes are shown in Figure 6.

The water depth increases the mass of water in the basin and hence takes more time for evaporation. The lower water depth results in high temperature in the basin water and increases the evaporation rate. It can be inferred that, the solar still productivity would increase with the decrease in water depths in the basin for both simple and evacuated tube solar stills.

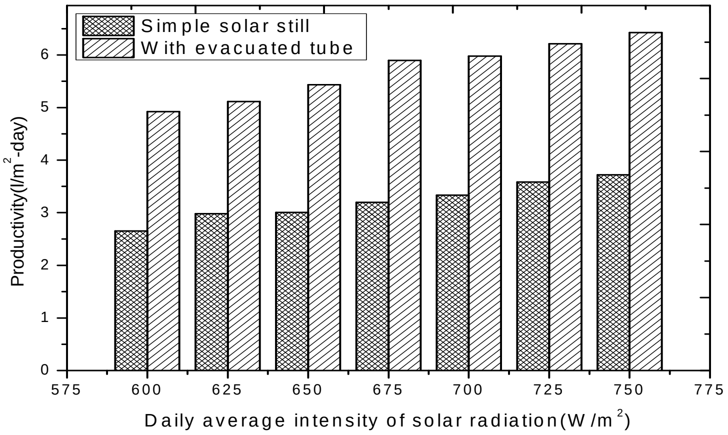

Fig. 4. Effect of solar intensity on productivity.

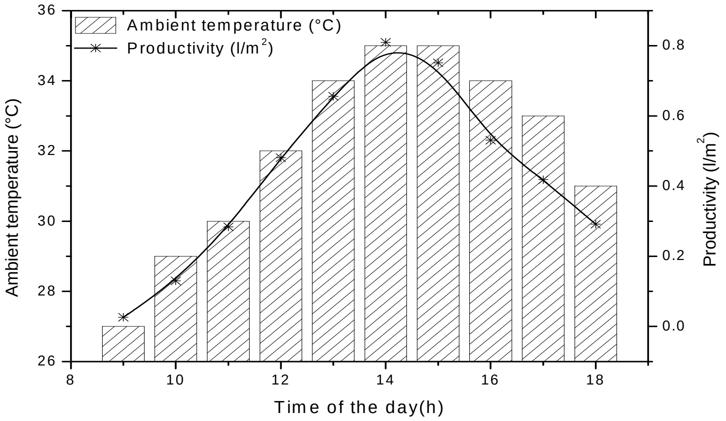

Fig. 5. Effect of ambient temperature.

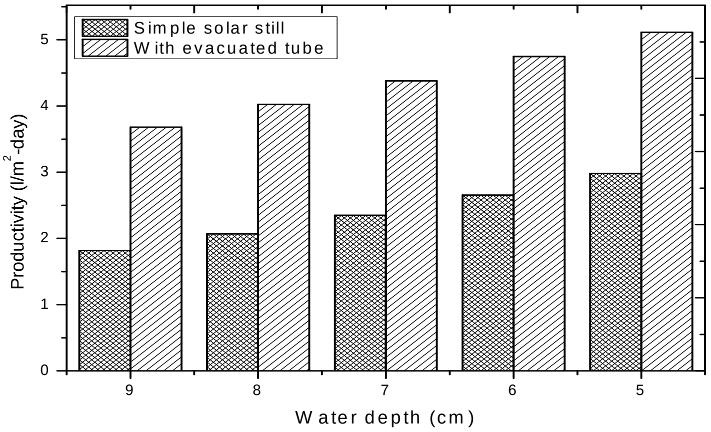

Fig. 6. Effect of water depth on still productivity.

Effect of Coupling Evacuated Tubes on Still Productivity

The effect of evacuated tubes coupled with solar still is compared with simple solar still and the results are shown in Figure 7. It shows that, the productivity of the evacuated tube solar still is much higher than the simple solar still throughout the day. The additional heat energy supplied from evacuated tubes increases the basin water temperature in the still and in turn the temperature difference between the water and glass increases. This leads to higher productivity in the evacuated tube solar still. It is found that, the productivity of the evacuated tube solar still is 72% higher than the simple solar still. It is also observed from the Figure 7 that, there is a fair agreement between theoretical and experimental hourly yield with the coefficient of correlation of 0.99.

Hourly Variation of Heat Transfer Coefficients

The hourly variation of internal heat transfer coefficients namely convective, evaporative and radiative are shown in Figures 8, 9 and10, respectively.

It can be observed from Figures 8 and 9 that, the convective and evaporative heat transfer coefficient values are high in the evacuated tube solar still than the simple solar still. This may be due to higher temperature difference between the water and glass in the evacuated tube solar still.

By comparing the Figures 7 to 10, it is clearly understood that the convective and evaporative heat transfer coefficients have more influence on the still productivity than the radiative heat transfer coefficient.

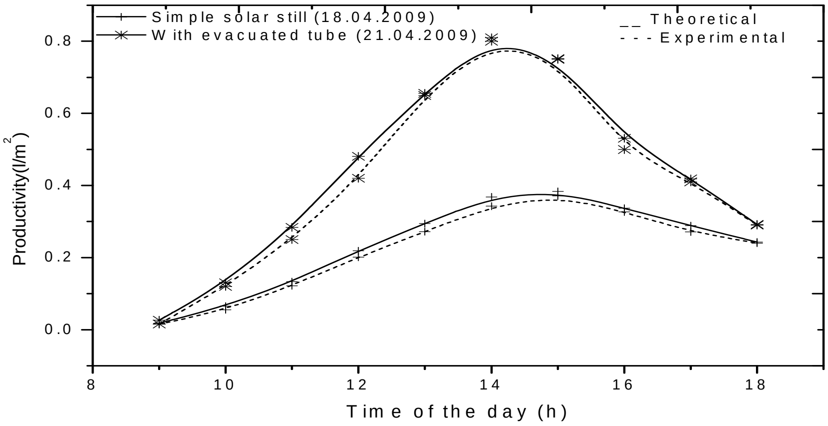

Fig. 7. Effect of coupling evacuated tubes on still productivity.

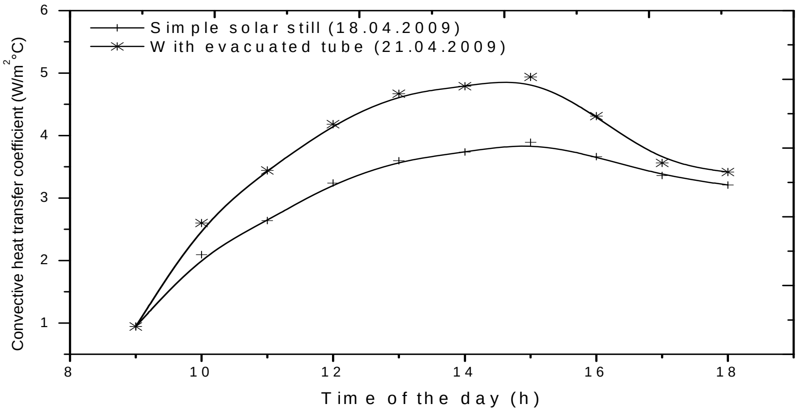

Fig. 8. Hourly variation of convective heat transfer coefficient.

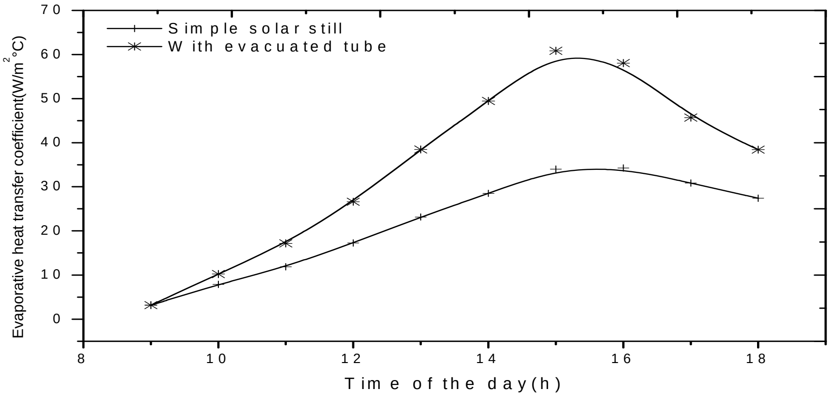

Fig. 9. Hourly variation of evaporative heat transfer coefficient.

Hourly variation of theoretical and experimental water and glass Temperatures

The hourly variation of water and glass cover temperatures of simple solar still and evacuated tubes solar still are shown in Figures 11 and 12. It is seen that, the maximum temperature of water (62°C) and glass (55°C) are obtained in the evacuated tube solar still at 16 hours, which are higher than the simple solar still's water (54°C) and glass (44°C) temperatures. It is due to additional thermal energy from the evacuated tubes to the basin water. It could be noticed from the Figure 11 and Figure 12 that the theoretical prediction of water and glass temperatures is in good agreement with the experimental results.

The values of coefficient of correlation and root mean square percentage deviation between theoretical and experimental values of productivity, water temperature and glass temperature for simple solar still and with evacuated tube solar still have been given in Table 1.

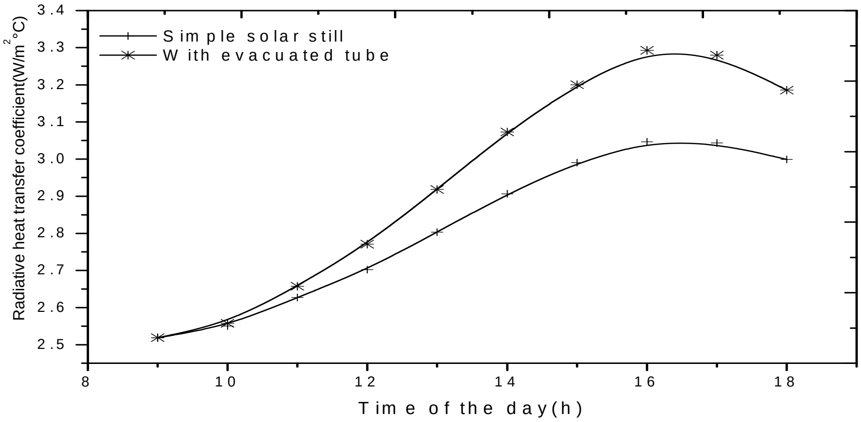

Fig. 10. Hourly variation of radiative heat transfer coefficient.

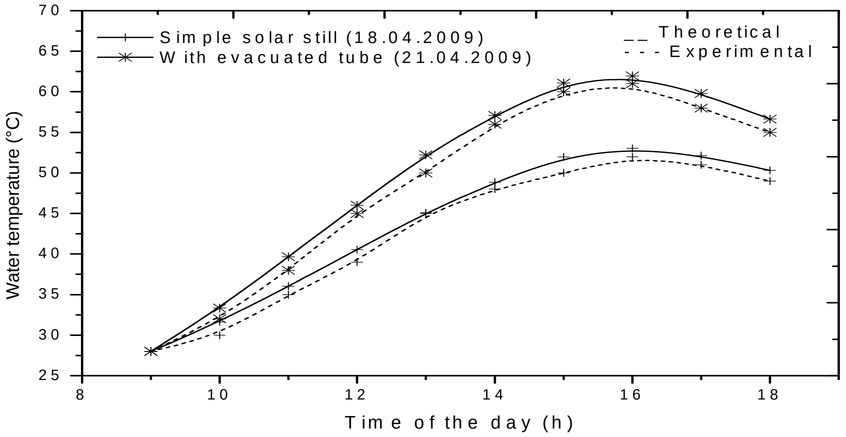

Fig. 11. Hourly variation of theoretical and experimental water temperature.

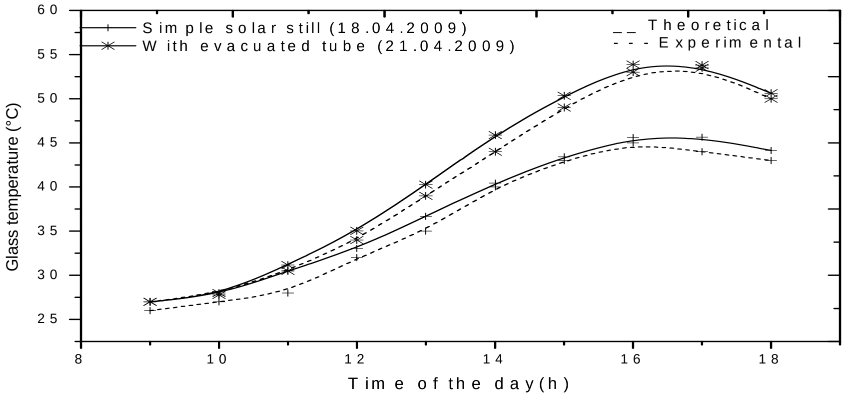

Fig. 12. Hourly variation of theoretical and experimental solar still glass cover temperature.

Table 1. Coefficient of correlation and root mean square percentage deviation.

Method/Parameter	r	e
Simple solar still		
Productivity	0.99	24.6
Water temperature	0.99	7.66
Glass temperature	0.99	10
With evacuated tube		
Productivity	0.99	26.5
Water temperature	0.99	8.16
Glass temperature	0.99	5.4

Various active solar distillation methods (flat plate collector, parabolic collector, solar pond, hybrid PV/T system) used for productivity enhancement by other researchers and the present method (evacuated tubes) are illustrated in Table 2

5. ECONOMIC STUDY

The simple economic study has been carried out based on the method developed by Velmurugan *et al.* [9]. The payback period of the solar still coupled with evacuated tubes depends on the fabrication cost, operating cost, maintenance cost, cost of feed water and subsidized cost offered by government sectors. The fabrication cost includes the cost of aluminum plate, GI sheet, PUF, metal frame, evacuated tubes, glass and rubber hose. The present active solar still with proper maintenance can serve up to 12 years. The salvage of the still is neglected. The various costs involved are given below in Indian Rupees (INR).

1 USD = 49 INR as on September, 2009
Fabrication cost = Rs. 12000
Operating cost = Rs. 5/day
Maintenance cost = Rs. 5/day
Cost of feed water = Rs. 1/day
Cost of distilled water/liter = Rs. 12
Productivity of solar still/ day = 5 l
Cost of water produced/day = Rs. 60
Subsidized cost (4%) = Rs. 480
Net profit = Cost of water produced – Operating cost – Maintenance cost – Cost of feed water
= 60-5-5-1
= Rs. 49
Payback period = (Investment – Subsidized cost) / Net profit
Payback period = 11520/49 = 235 days

Based on the above economic analysis, the present active solar still is more economical.

Table 2. Increase in production by various active methods by other authors.

Author	Active method	Increase in production
Badran *et al.* [26]	Flat plate collector (Experimental study)	36%
Rai *et al.* [27]	Flat plate collector (Experimental study)	24%
Zeinab S., *et al.* [7]	Parabolic collector (Experimental study)	18%
Velmurgan, V., *et al.* [8]	Solar pond (Experimental study)	27.6%
Shiv Kumar *et al.* [12]	Hybrid PV/T (Experimental study)	250%
Tiwari *et al.* [37]	ETC with heat pipe (Theoretical study)	112%
	ETC (Theoretical study)	100%
	Concentrating collector (Theoretical study)	102%
	Flat plate collector (Experimental study)	59%
Present work	Evacuated tubes (Experimental study)	72%

6. CONCLUSIONS

On the basis of the experimental and theoretical results, the following conclusions have been drawn for the single basin solar still coupled with evacuated tubes.

- The present study indicates another method to increase the productivity of solar still in an effective way.
- The water temperature is increased by means of additional heat energy input from evacuated tubes, which in turn increased the productivity of the solar still.
- The average daily output increased by 72%, when the evacuated tubes were coupled with solar still.
- The thermal model developed for this analysis gives very good agreement with experimental results.
- The convective and evaporative heat transfer coefficients have more influence on the still productivity than the radiative heat transfer coefficient

The conjecture of the economic analysis showed that the payback period of this system is 235 days.

NOMENCLATURE

Symbols

A_s	Basin liner still area (m^2)
A_{ET}	Diameter of outer glass tube × total length of the tubes (m^2)
C	Constant for Nusselt number expression
C_v	Specific heat of working fluid (J / kg°C)
C_w	Specific heat of water in solar still (J / kg°C)
e	Root mean square of percentage deviation
F_R	Heat removal factor
g	Acceleration due to gravity (m/s^2)
Gr	Grashof number
h_b	Basin liner overall heat transfer coefficient (W /m^2°C)
h_{cw}	Heat loss coefficient by convection from water surface (W /m^2°C)
h_{ew}	Heat loss coefficient by evaporation from water surface (W /m^2°C)
h_{rb}	Basin liner radiative heat transfer coefficient (W /m^2°C)
h_{rg}	Glass cover radiative heat transfer coefficient (W /m^2°C)
h_{rw}	Basin water radiative heat transfer coefficient (W /m^2°C)
h_{tg}	Total glass heat transfer loss coefficient(W /m^2°C)
h_w	Convection heat transfer coefficient from basin to water (W /m^2°C)
h_{tw}	Total water heat transfer loss coefficient(W /m^2°C)
I	Intensity of solar radiation (W /m^2)
K_v	Thermal conductivity of humid air (W /m°C)
K_i	Thermal conductivity of insulation material (W /m°C)
L	Latent heat of vaporization (J/kg)
L_i	Thickness of insulation material (m)
L_v	Average spacing between water and glass cover (m)
m_{ew}	Hourly output of still (kg / m^2h)
M_w	Mass of water in basin (kg)
n	Constant in Nusselt number expression
N	Number of observations
Pr	Prandtl number
P_g	Glass saturated partial pressure (N /m^2)
P_w	Water saturated partial pressure (N /m^2)
Q_u	Useful thermal energy gain from the evacuated tubes (W/m^2)
q_b	Rate of total energy from the basin liner (W /m^2)
q_g	Rate of total energy from the glass cover (W /m^2)
q_w	Rate of total energy from the water surface (W /m^2)
q_{cg}	Rate of energy lost from glass cover by convection W /m^2
q_{cw}	Rate of energy lost from water surface by convection (W /m^2)
q_{ew}	Rate of energy lost from water surface by evaporation W /m^2
q_{rg}	Rate of energy lost from glass cover by radiation (W /m^2)
q_{rw}	Rate of energy lost from water surface by radiation (W /m^2)
q_{rg}	Rate of energy lost from glass cover by radiation (W /m^2)
q_{tg}	Total rate of energy lost from glass cover (W /m^2)
r	Coefficient of correlation
t	Time (s)
T_a	Ambient temperature (°C)
T_b	Temperature of basin water (°C)
T_g	Glass cover temperature (°C)
T_v	Vapor temperature (°C)
T_w	Water temperature (°C)
U_b	Overall bottom heat loss coefficient (W /m^2°C)
U_t	Overall top heat loss coefficient (W /m^2°C)
U_{LE}	Evacuated tube heat loss coefficient (W /m^2°C)
U_{LS}	Solar still l heat loss coefficient (W /m^2°C)
v	Wind velocity (m/s)
X_i	Theoretical or predicted value
Y_i	Experimental value

Greek

μ	Viscosity of fluid (N.s/m^2)
β	Coefficient of volumetric thermal expansion (1/K)
α'	Fraction of solar flux
$\alpha\tau$	Absorptance – transmittance product
ρ	Density of humid air (kg/m^3)
σ	Stefan Boltzmann constant
ε_{eff}	Effective emissivity

Subscripts

b	Basin liner
e	Evacuated tube
eff	Effective
g	Glass cover
s	Solar still
w	Water
0	Initial

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