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Modeling and Verification of Double Slope Single Basin Solar Still Using Laboratory and Actual Solar Conditions

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Abstract

A double slope single basin, passive type, still with basin area of 1.75 m^2 is fabricated and tested under laboratory conditions. The solar radiation heat is simulated by using 2 kW electrical resistance heater placed below the inner basin. The heat supply is varied using control circuit. The still is tested for varying input condition to simulate the actual solar radiation condition with different minimum depths of water in the basin ranging from 2 cm to 0.2 cm. The experiment is also carried out at different constant input conditions with a constant depth of water. The variation of different parameters with production rate has been studied. It is found that the production rate increases with the increases of water and glass temperature. But at higher operating temperature, the production rate increases with the decrease in temperature difference between water and glass. A new model is recommended for the still with shallow basin. The experiment is also conducted with the same still at actual sunshine conditions and compared with the model. The experimental values are in close agreement with model values.

Keywords: Solar Still; Laboratory Simulation; Minimum Depth; Modeling; Productivity Enhancement.

Symbols

A	Area (m^2)
C	Specific heat (J/kg K)
Gr	Groshof number
h_c	Heat transfer coefficient (W/m^2 K)
h_e	Evaporative heat transfer coefficient based on temperature difference (W/m^2 K)
h_{ew}	Evaporative heat transfer coefficient based on pressure difference (W/m^2 K)
h_{fg}	Latent heat of evaporation of the water (J/kg)
h_{ga}	Heat transfer coefficient of the glass upper surface to air (W/m^2 K)
k	Thermal conductivity (W/m K)
L_c	Length (m)
M	Molecular weight
m	Mass production rate (gr/min or kg/m^2/h)
Nu_L	Nusselt number
P	Perimeter (m)
p	Pressure (N/m^2)
Pr	Prandtl number
Q	Heat transfer rate (W)
Q_c	Convection heat transfer rate from water surface to glass (W)
Q_e	Evaporation heat transfer rate from water surface to glass (W)
Ra_L	Rayleigh number
T	Temperature, ^{o}C

Greek symbols

ω	Specific humidity of air, kg of vapour/kg of dry air.
$\in$	Emissivity of the glass,

Subscripts

a	Atmosphere, air
b	Basin
g	Glass
ga	Glass to atmosphere
s	Saturation condition
w	Water
ws	Water vapour at saturation condition

1. Introduction

A lot of works have been done on improving the effectiveness of the simple solar still, which converts the brackish water into fresh water, using solar energy. Recently, the authors reviewed the progress in improving the effectiveness of simple single basin solar still [1]. Studies show that basin water temperature is the significant parameter that affects the effectiveness of the still. The basin water temperature is at maximum when the heat capacity of the basin is less. The heat capacity of the basin depends on the depth of the water in the basin. For

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given solar intensity variation, the still production rate is higher, when depth is at minimum [2-6].

A Number of studies in the literature is available to examine heat transfer process of the still. The most widely acceptable study was made by Dunkle [7]. Since then, most of researchers used the prosed Dunkle's [7] model for their analysis. But, the above model is suitable for mean basin water temperature of 50°C. Clark [8] conducted steady state experiment on solar still; and examined the validity of the various correlations, proposed earlier for evaluating the heat transfer coefficients. Shawaqfeh and Farid [9] investigated heat and mass transfer processes and recommended new correlations for internal convective heat transfer coefficient. Kumar and Tiwari [10] recommended to test and model the fabricated still for various atmospheric conditions for predicting the performance at a particular place. An experimental still has been tested, and analysis have been made to study the water to cover heat transfers by Porta et al. [11] and a correlation to calculate the production rate of the still is also recommended [12]. Recently Tripathi and Tiwari [3, 13] studied the effect of basin water depth on the internal heat transfer coefficients.

The authors already conducted experiment with a laboratory solar still, for layer of water with different basin materials; and studied the performance and noted the peculiar behavior of the still at higher basin water and glass temperatures [14]. At lower depths, the basin water temperature is high, and the production rate of the still is not in proportion with basin water temperature and the difference between the basin and glass temperatures. The objective of this work is to conduct three experimental works to analyze the performance of the double slope single basin solar still. Two works are carried out in laboratory conditions; one with varying heat input condition. Here, the experiments are carried out with varying depths ranging from 2 cm to 0.2 cm. This will help in studying the effect of solar insulation on productivity. The second experiment is conducted with constant heat input condition to study the variation of production rate with various temperatures. Hence, constant depth of 1 cm is also maintained. A new model for the still is proposed from the above analysis. The model is verified by testing the still at actual solar radiation condition for minimum depths of water in the basin. For the still at actual sunshine condition, the heater is taken out, and the bottom is leveled with cement concrete. This concrete layer stores excess heat during noon and releases heat during evening and night. This increases the nocturnal production.

2. Internal and External Heat Transfer Processes

The modes of heat transfer inside the still between the water surface and the glass cover are convection accompanied with evaporative mass transfer in the form of water vapour and radiation. The radiation heat transfer is very small if compared with other two heat transfers, and the production of the still is not affected significantly by this heat transfer. The evaporative heat transfer is responsible for the transportation of water mass from water surface to cover. This evaporative heat transfer increases with the vapour pressure difference between the water and glass; and is responsible for bulk motion of air inside the still. This bulk motion increases the convection heat transfer. Hence the convection and evaporation heat transfer inside the still are interrelated.

Dunkle [6] used the following correlation developed by Jakob [15] to estimate the convection heat transfer coefficient inside the still, (Relation.1)

$$h_c = 0.884\left[\left(T_w - T_g\right) + \frac{\left(p_w - p_g\right)\left(T_w + 273.15\right)}{268900 - p_w}\right]^{\frac{2}{3}}$$

The convective heat transfer is given by [7],

$$Q_c = A_b h_c (T_w - T_g) \qquad (2)$$

The evaporative heat transfer coefficient as per the detailed derivation given by Malik et al. [16] is given by,

$$h_{ew} = \frac{M_w h_{fg}\, p}{M_a C_p (p - p_w)(p - p_g)} h_c \qquad (3)$$

Dunkle [6] assumed that the p_w and p_g are considerably smaller than the total pressure p, and the mean operating temperature is 50°C and estimated the value of h_e as,

$$h_{ew} / h_c = 0.016273 \qquad (4)$$

In equation (3), the values p_w and p_g are considerably smaller than p for lower range of basin water and glass temperatures. When the still is with shallow basin, the mean water and glass temperatures are higher than 50°C; and the equation (4) can not be used. At higher temperatures, the partial pressure values are considerably higher, and the equation (4) will not yield a constant value. The evaporative heat transfer is given by [16],

$$Q_e = A_b h_{ew} (p_w - p_g) \qquad (5)$$

The mass transfer rate of water vapour is given by [16],

$$m_w = \frac{Q_e}{h_{fg}} \qquad (6)$$

At higher basin water temperature, the water is more susceptible to evaporation and the water mass proportion in the still air is high. The percentage of mass of water vapour present in the air inside the still is given as by assuming the air as saturated,

$$\text{percentage of vapour} = \frac{\omega_s}{1+\omega_s} \times 100 \qquad (7)$$

where ω_s is the kg of vapor present in the one kg of dry air at saturated condition and it is given as [17],

$$\omega_s = 0.662 \frac{p_{ws}}{p - p_{ws}} \qquad (8)$$

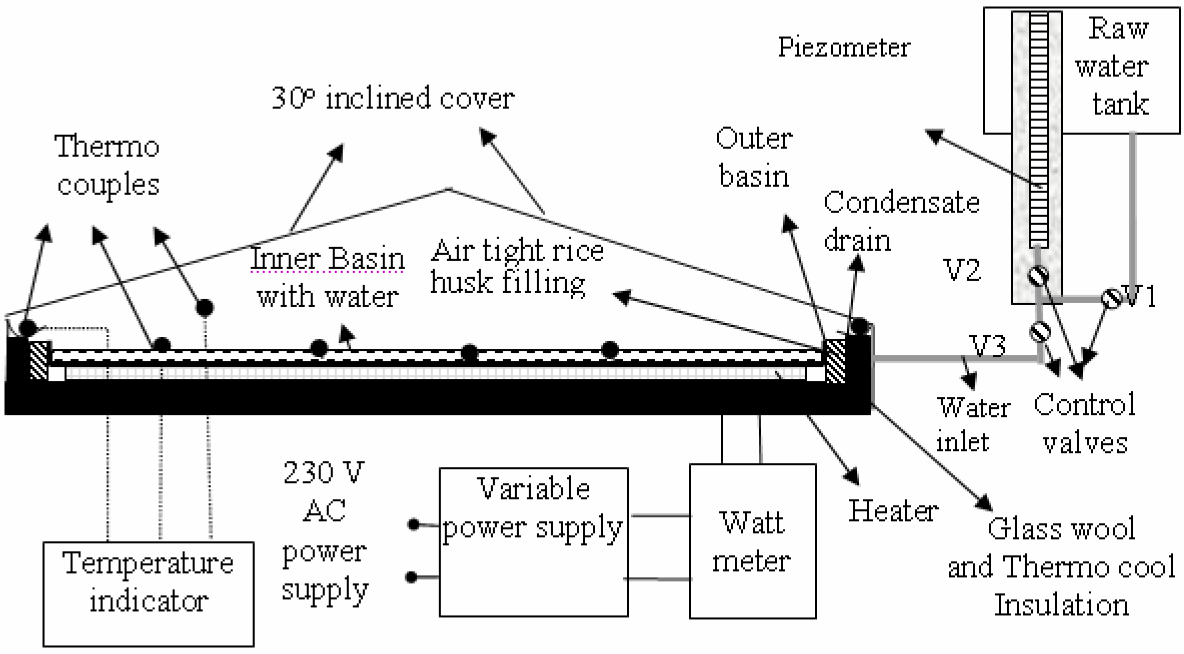

Figure 1. Single basin double slope laboratory still.

The increase in p_{ws} with temperature is exponential. Hence, at higher basin and water temperature, the productivity depends on rate of heat transfer from the glass cover to the atmosphere. The effect of the temperature difference between the water and glass, which is the driving force for the bulk motion of air inside the still on condensation and transportation of water mass from basin to glass, is less significant.

The evaporative heat transfer coefficient, h_e based on the temperature difference between the water and glass can be calculated using following relation,

$$Q_e = m_w h_{fg} = A_b h_e (T_w - T_g) \tag{9}$$

The amount of heat transfer from the glass upper surface to the atmosphere is given by:

$$Q_{ga} = A_g\{h_{ga}(T_g - T_a) + \in_g [(T_g + 273)^4 - (T_a + 273)^4]\} \tag{10}$$

In most of the studies this values is taken as constant of 4.5 W/m^2 K as recommended by Duffie [18] including the radiation effect for no freeze condition. In this work, the actual convection heat transfer coefficient of the inclined surface was calculated using the procedure given by Incropera and Devwitt. [19].

The relation for average Nusselt number for the glass cover for entire range of Rayleigh number has been recommended by Churchill and Chu [20] and is of the form: (Relation.11)

$$Nu_L = \left\{ 0.825 + \frac{0.387 Ra_L^{\frac{1}{6}}}{\left[1 + (0.492/\mathrm{Pr})^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\} = \frac{h_g L_c}{k} \tag{11}$$

where $L_c = \dfrac{A_g}{P}$ = 1.18 m.

The overall heat transfer coefficient of the glass surface, including the radiation heat transfer to atmosphere and without considering sky radiation, can be calculated as:

$$Q_{ga} = A_g h_{ga}(T_g - T_a) \tag{12}$$

3. Laboratory and Solar Still

A single basin double slope solar still has been fabricated with mild steel plate, as shown in Figure 1. The overall size of the inner basin is 2.08 m × 0.84 m × 0.075 m, and that of the outer basin is 2.3 m × 1m × 0.25 m. The gap between the inner and outer basin is packed with rice husk as insulation material. The top is covered with two glasses of thickness 4mm, inclined at 30^o on both sides, using wooden frame. The outer surfaces of the still are covered with glass wool and thermo cool insulation. The condensed water is collected in the V-shaped drainage provided below the glass lower edge of the still. The condensate collected is continuously drained through flexible hose and stored in a jar placed on the electronic weighing machine on both side of the still. A hole in the basin side wall allows inserting the thermocouples for the measurement of the basin water, still, and condensate temperature. To measure the basin temperature, four thermocouples were placed at the basin at different locations. Two thermocouples were dipped into the water in the collecting drainage on either side. The hole is closed with insulating material to avoid the heat and vapour loss. One thermocouple is exposed to atmosphere to measure the atmospheric temperature. This thermocouple is placed in a shadow area to prevent the variation in temperature due to incidence of sun radiation on the thermocouple.

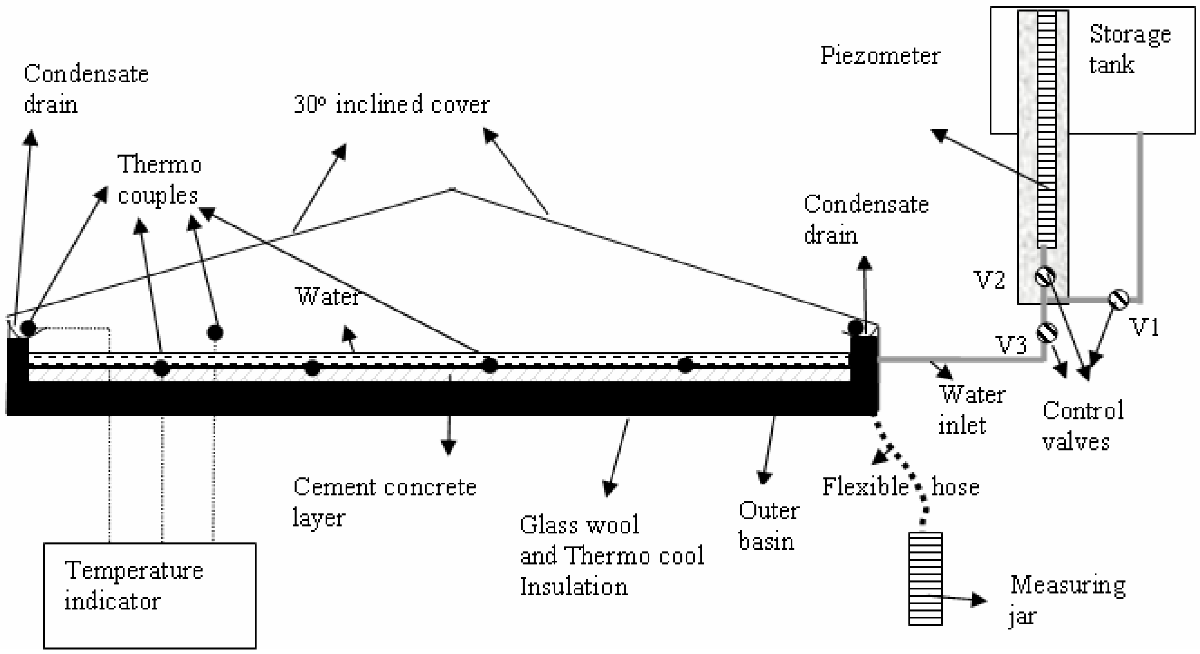

Figure 2. Single basin double slope solar still.

Another hole is provided for water inlet. Through this hole, a small tube is inserted to supply raw water continuously to the basin from storage tank through a flow regulator to keep the mass of water in the basin always constant. The heating coil of 2000 W is placed below the inner basin to supply necessary heat energy to the basin. The input to the heater is given through a control circuit, which controls the input electrical energy. An energy meter is fitted with the circuit to measure the input energy.

To convert the laboratory still into an actual solar still, the heater and power supply and measurement systems were removed. The inner basin is also removed. The bottom of the still is leveled with 5 cm thick cement concrete to minimize heat loss through the basin and to spread the minimum depth of water uniformly, shown in Figure 2. The concrete surface is black painted to improve the radiation absorption capacity. The distillate output was recorded with the help of a measuring jar. The solar intensity was measured with the calibrated PV type sun meter.

4. Experimental Procedure

The experiment was carried out in the fabricated laboratory still at Steam Laboratory, National Engineering College, Kovilpatti (9°11'N, 77°52'E), a city in southern India during December 2005 to February 2006. In the laboratory still, the heat input is given to the solar still using heating coil through control circuit. For a given constant depth of basin water condition, the input to the heater is varied for every 15 minutes from 0 - 775 W/m^2 between 6 AM an 12 noon and from 775 - 0 W/m^2 between 12 noon and 6 PM to match with the local average solar radiation condition [8]. During night, the heater supplies no heat. For given depth, all the observations are taken for 24 hours duration, starting from 6 AM. The temperature of the atmosphere, basin water, and the condensate are noted for every 15 minutes. The energy meter readings and condensate collected on both side of the still are also noted. The experiments were conducted for 2 cm, 1.5 cm, 1 cm, 0.5 cm and 0.2 cm depth of water in the still basin for same solar condition without freeze. For experimentation with depth of water 0.5 cm and 0.2 cm, a light black cotton cloth is used to spread the water through the entire area of the basin. The condensate temperature is taken as the temperature of the glass cover. Figure 3 shows energy input given to the laboratory still at various times and corresponding variation in atmospheric temperature.

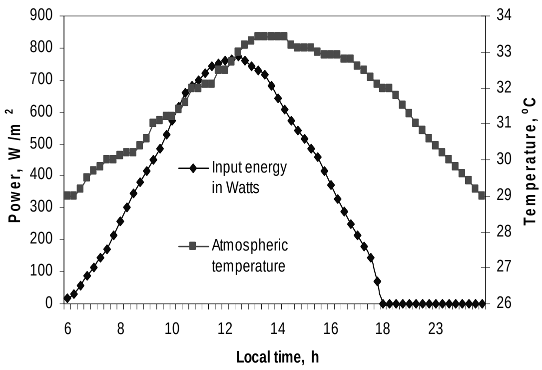

Figure 3. Input energy and atmosphere temperature variation in the simulated solar still.

The still is also tested under various constant input conditions with different depths of water in the basin. Heat is supplied by the heater until the still reaches steady state condition. Then power is cut off and the still is allowed to cool down naturally to reach equilibrium state with atmosphere. The readings are taken for every 15 minutes from the time the still starts to deliver water production until it delivers significant amount of output. The experiments are carried out for the constant input powers from 300 W to 1500 W.

The experiments with solar still at actual sunshine conditions were conducted during February to April 2007 for various depths ranging from 10 cm to 0.5 cm. The observations are taken for 24 hours duration, starting from 6 AM. The total radiation on horizontal plane, the temperatures of the atmosphere, basin water and condensate and the mass of condensate collected are noted for every 30 minutes.

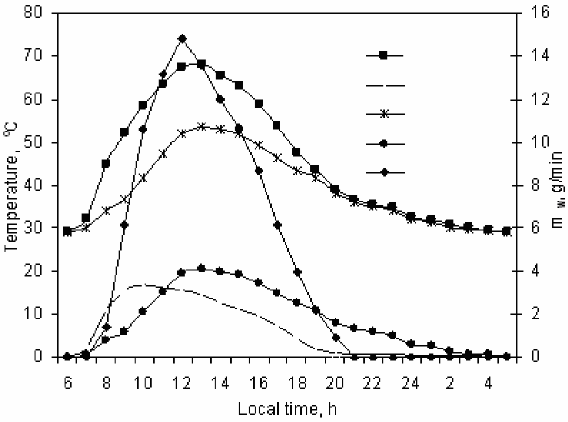

Figure 4. Variation in temperatures and production rate for laboratory still with varying input – set I.

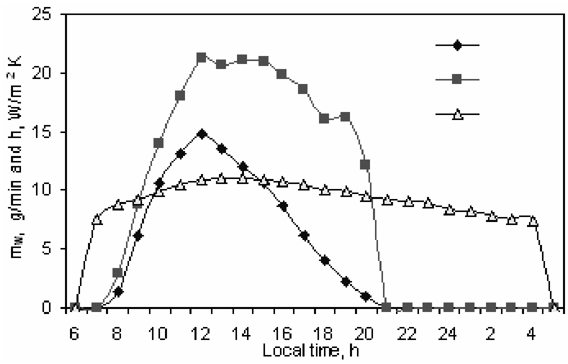

Figure 5. Variation in heat transfer coefficients and production rate for laboratory still with varying input

5. Results and Discussion

5.1. Analysis of Laboratory Still at Variable Input Condition

The evaporative heat transfer coefficients are calculated using equation (9), and the overall heat transfer coefficient of the glass surface to the atmosphere is calculated using equations (10) to (14). Figure 4 shows the variation of water and basin temperatures, water-glass temperatures difference, and glass-atmospheric temperatures difference, and water production rate with time for laboratory still with a depth of 0.5 cm and under varying input condition. The variation of all parameters with production rate is normal and as expected. The variation of difference in temperature between water and glass is also different here. Initially, during morning hours when the input power is less, the production rate increases with this temperature difference.

When water temperature exceeds 50^{o}C, this temperature difference reaches a maximum value and starts to decrease there after. The still production rate continues to increase until the difference in temperature between glass and atmosphere increases. The difference between the glass and atmospheric temperatures is at maximum when the production rate is at maximum. Then all water and glass temperatures and difference in temperatures start to decrease with production rate.

The variation of the internal evaporative heat transfer coefficient and overall heat transfer coefficient for glass with local hours are in relation with production rate, shown in Figure 5. This variation is similar for different depths of water in the basin.

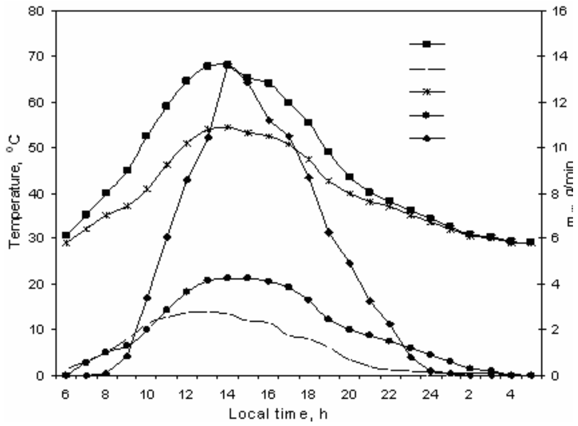

Figure 6. Variation in temperatures and production rate for laboratory still with varying input – set II.

The variation of the water and glass temperature and difference in water-glass and glass-atmospheric temperatures, are similar for the still with different lower depths ranging from 2 cm to 0. 2 cm. The starting time and the duration in which the production rate increase with the decrease of the temperature difference between water-glass. Figure 6 shows the variation of these parameters for a still with 1 cm depth. For this still the peculiar behavior starts around 12 Noon and lasts up to around 2 PM. For the still with 0.5 cm depth, the peculiar behavior occurs during 10 PM and 1 PM [Figure 4].

For a given solar intensity variation in lower depth still, this peculiar behavior starts early and lasts longer duration and for higher depth, and starts early and lasts for shorter duration. For deep basin still, during lower solar intensity variations in a day, the still may not experience this peculiar operation. If a still experience this peculiar behavior for longer duration, the production per day will be high.

5.2. Analysis of Laboratory Still at Constant Input Condition

The variation of the different parameters of the laboratory still at constant input of 1500 W is shown in the Figure 7. The production rate of the still increases with the increase of water and glass temperatures during heat supply period. Also the production rate increases with the increase in water-glass temperature difference during this period. The production rate decreases with these parameters during cooling. This is the normal operation of the still.

During heating period, the production rate increases with the decrease in water-glass temperatures difference. It is the peculiar behavior of the still. During heating, the rate of decrease of water-glass temperature difference is minimal, and the corresponding rate of increase in production rate is higher. This peculiar behavior is

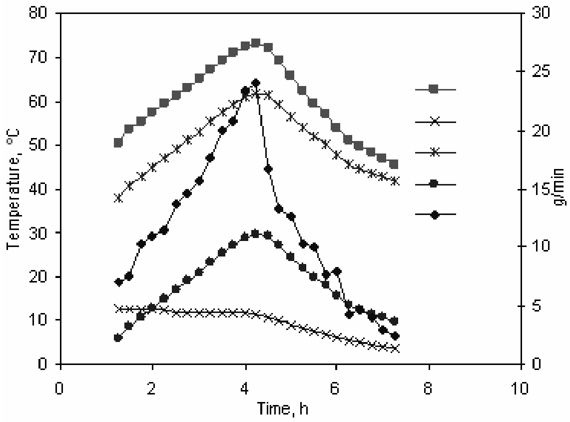

Figure 7. Variation in temperatures and production rate for laboratory still with 1500 W constant input.

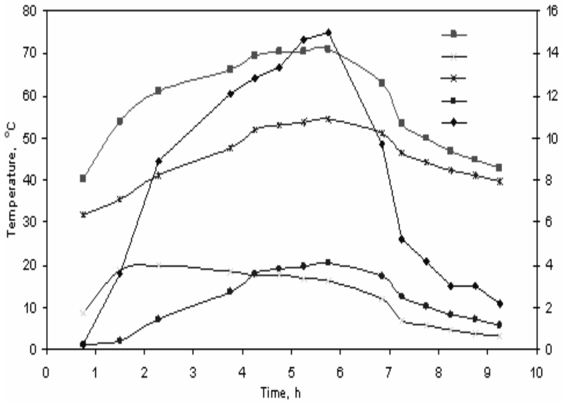

Figure 9. Variation in temperatures and production rate for laboratory still with 1200 W constant input.

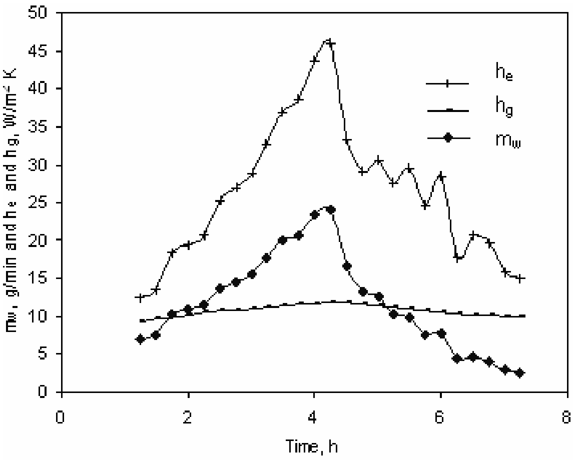

Figure 8. The variation in heat transfer coefficient and production rate for laboratory still with 1500 W constant input.

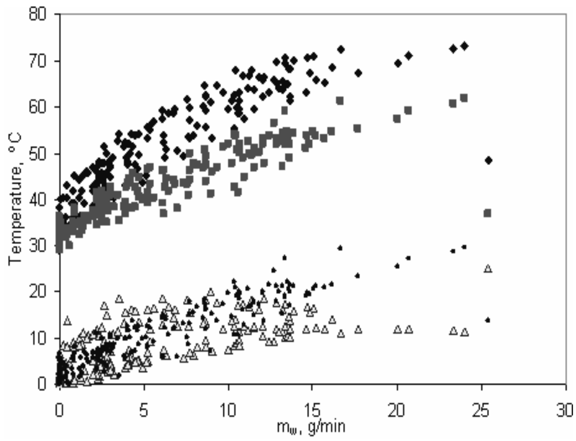

Figure 10. Variation of production rate with different temperatures for laboratory still.

observed only during heating. During cooling, normal behavior is observed.

Figure 8 shows the variation production rate, internal evaporative heat transfer, and the external overall heat transfer coefficient of the glass cover with for the still. The variations of these parameters are in relation with the variation of production rate.

For the laboratory still with constant input, the variations of different parameters are similar for different constant input powers. For higher input power, rate of temperature rise for water and basin is higher, and production starts early. The water-glass temperatures initially increase with production rate for lower water and glass temperatures as shown in Figure 7. When the water temperature is around 55°C, this difference temperature attains a maximum value then starts to decrease. Similar variations are observed for the still with 1200 W input also as shown in Figure 9.

5.3. Modeling of Still

To study the production rate variation with water and glass temperatures, water-glass and glass-atmosphere temperature differences, a correlation plot is drawn by using the observations of the still under varying operating conditions as shown in the Figure 10. Both water and glass temperatures and difference between glass and atmospheric temperature are increasing with production rate. The overall variation of the difference between water glass temperatures is different. Initially this value increases with production rate, attains a maximum value and starts to decrease. The maximum value of this different corresponds to a water temperature around 55°C. The production rate is 5 g/min when the temperature difference between water and glass is in the range 5°C to 20°C. Similarly other parameters also have a range of values for a particular production rate.

At lower temperatures of water and glass, the water vapour present in the air inside still is in minimum proportion. The water mass proportion increases exponentially with the still air temperature, (equations (7) and (8)). Hence, production rate of the still depends on basin water and glass temperatures. At higher water temperature, water is more susceptible for evaporation, and the water vapour proportion in the still air is high. When the glass temperature is high, both heat transfer from glass to atmosphere and the production rate are also high. When the water and glass temperatures are higher, their difference is less, and the production rate is high. This is the reason for the peculiar operation of the still.

The amount of condensation at the glass lower surface mainly depends on the mass of air circulated, and in contact with the glass lower surface. This circulation depends on the temperature difference between water and glass. If the glass temperature is higher or water temperature is lower, this difference will be low and the production rate is also low. Hence the production rate is a complex function of water and glass temperatures and the

(11)

$$
\begin{aligned}
m_w = & -1.48\times10^{-3}T_w(T_g - T_a) - 3.901\times10^{-3}T_g(T_g - T_a) + 1.124\times10^{-3}(T_g - T_a)(T_w - T_g) \\
& + 4.809\times10^{-3}(T_g - T_a)^2 + 0.146\times(T_g - T_a) + 7.185\times10^{-4}T_w(T_w - T_g) - 1.196\times10^{-3}(T_w - T_g) \\
& - 1.732\times10^{-3}(T_w - T_g)^2 + 0.039\times(T_w - T_g) + 9.918\times10^{-5}T_wT_g + 7.349\times10^{-5}T_g{}^2 + 0.035T_g \\
& + 0.42 - 0.081T_w + 8.932\times10^{-4}T_w{}^2
\end{aligned}
\qquad (15)
$$

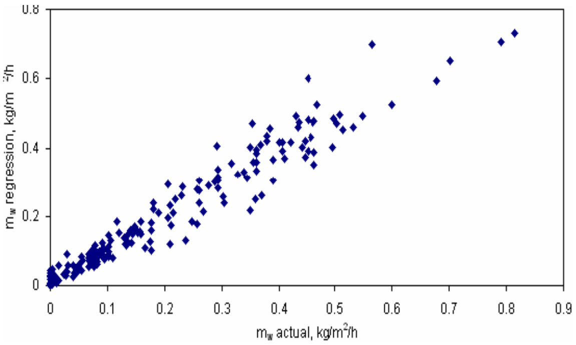

Figure 11. Comparison between actual and calculated values of production rate for laboratory still

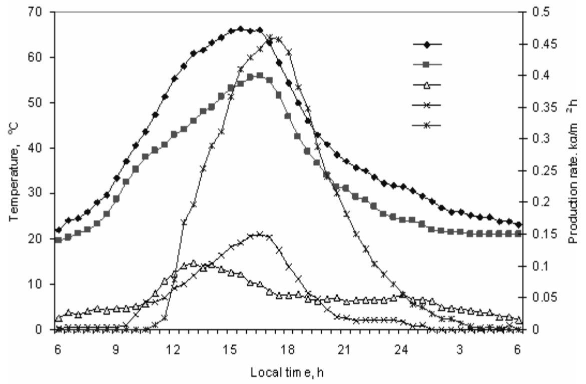

Figure 12. Performance of the solar still with medium depth

difference between the water-glass and glass-atmospheric temperatures.

The observation from laboratory still experiments at constant depth with varying constant input and with varying depth with constant varying input are used to establish a regression equation using Mathcad-12 software. Two-degree fitting function is used. The following equation is obtained for the production rate of the still in kg/m^2/h.

The above equation (equation 15) is taken as a new model. Using this model, the production rate is calculated using the observations of laboratory still experiments, and the calculated values are compared with actual values. The Figure 11 shows the comparison between the actual and calculated production rate values by using the model. It is found that most calculated values are closer to actual values with a correlation coefficient of 0.974.

5.4. Analysis of the Still Under Solar Radiation Condition

The same laboratory still is tested under actual solar radiation condition for different depths of water in the basin. Both Figures No. 12 and and No. 13 show the performance of the stills when the depths of water are 3 cm and 1cm. The production rate of the still varies proportionally with different water, glass temperatures,

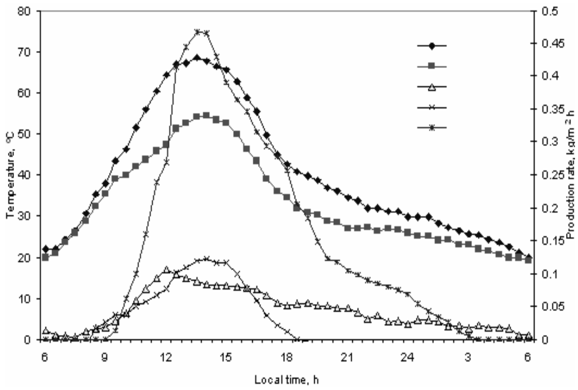

Figure 13. Performance of the solar still with lower depth .

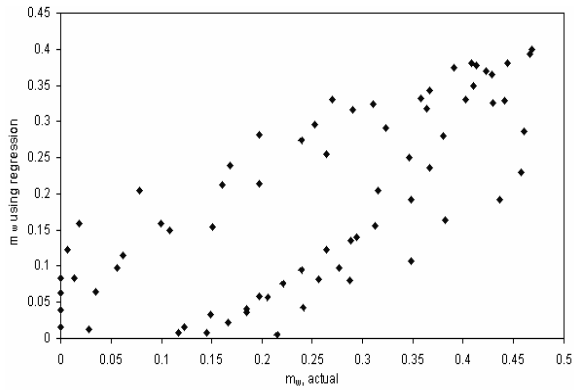

Figure 14. Comparison between actual and calculated values of production rate for actual solar still

and difference between glass and atmospheric temperatures. Similar with laboratory still, for actual still also, the production rate increases initially with the increase of the temperature difference between water and glass, but at higher temperature when the basin water reaches around 55^{o}C, this difference is at maximum. But the production rate increases until the difference between the glass and atmospheric temperatures starts to decrease.

Hence the still, and under actual sunshine conditions, behaves similarly to laboratory still with varying input. Using the observed values of different temperatures, the new model is used to calculate the production rate for the actual solar still with different depths of 4 cm, 3 cm and 1 cm. The actual values and calculated values are compared by using the new model. The Figure 14 shows the comparison between the actual and values calculated, using the new model. The most of the calculated values are close to actual values with a correlation coefficient of 0.8646. The deviation in values due to sky radiation effect and wind velocity effect even though, during experiment time, no appreciable wind is observed.

6. Conclusion

A double slope single basin, passive type, still with basin fabricated; and tested under laboratory conditions. The heat is supplied to the basin using electrical resistance heater placed below the inner basin. The heat supply is varied using control circuit. The still is tested for varying input condition to simulate the actual solar radiation condition with different minimum depths of water in the basin ranging from 2 cm to 0.2 cm. The experiment is also carried out at different constant input conditions with a constant depth of 1 cm water. The variation of different parameters with production rate variation has been studied.

It is found that the production rate increases with the increases of water and glass temperature. At lower water and glass temperatures, the production rate is proportional with the temperature difference with water and glass. At higher operating temperatures, the production rate increases with the decrease in temperature difference between water and glass until the difference between the glass and atmospheric temperature increases. This is the peculiar behavior of the still. The reason for this behavior is the higher proportion of water vapour at higher still temperature. The still overall production rate per day will be high when the still operation in this peculiar behavior for longer duration.

A new model is proposed for the still with shallow basin. The experiment is also conducted with the same still at actual sunshine conditions. The still under solar radiation condition with lower depth behaves similarly to laboratory still. The experimental production rate values are in close agreement with model values. The proposed model can be used to predict the production rate of the still with minimum depth of water in basin in the range of 2 cm to 2 mm and for the basin water temperature up to 80^{o}C.

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