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# STUDY AND THERMAL MODELING OF COST EFFECTIVE SINGLE SLOPE BASIN TYPE SOLAR STILL

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**ABSTRACT**

*Performance analysis of a single slope basin type solar still has been carried out based on the experimental data recorded at Aligarh for some typical days(Feb 2015 to Mar 2015). Heat transfer rates due to convection, radiation and evaporation have been estimated by making heat balance at various sections in the solar still, constructed for the purpose. The radiative, convective and evaporative heat transfer coefficients between the water surface and the glass cover through the humid air are evaluated using standard correlations and those used by other authors. The experimental data include the temperatures of basin liner (absorber plate), water mass, humid air, glass cover surface and the ambient air. Solar heat absorbed by the glass cover, water mass, and the basin liner are estimated for different depths of the water mass considering the solar flux measured on a horizontal surface near the solar still. The distillate output has been calculated using the heat of evaporation of water in the still and compared with the measured values for similar conditions.*

*The experimentally measured temperatures at various sections in the still have been exhibited graphically. The estimated values of the heat transfer coefficients and the heat transfer rates at different points have also been presented. Heat balance at various sections has been verified. The radiative, convective and evaporative heat transfer rates increase with time of heating from 20 to100 W/m$^2$, 5 to 30 W/m$^2$ and 10 to 300 W/m$^2$, respectively; the respective heat transfer coefficients increasing from 8 to 10 W/m$^2$K, 1.5 to 2.5 W/m$^2$K and 6 to 30 W/m$^2$K. Increase in the combined heat transfer coefficient in the upward (top) direction is 5 to 45 W/m$^2$K the overall top loss coefficient is 12 to 16 W/m$^2$K and the bottom loss coefficient is 0.56 W/m$^2$K. For 0.03 m, 0.04 m and 0.05 m water depths, the internal heat transfer rate increases from 125 to 450 W/m$^2$, 100 to 350 W/m$^2$ and 60 to 200 W/m$^2$, while the top loss remain as 150 to 350 W/m$^2$, 140 to 380 W/m$^2$ and 140 to 350 W/m$^2$, respectively. The results obtained are quite comparable with those presented by researchers in the literature.*

***Keywords: Heat Transfer Coefficient, Heat Transfer Rate, Distillate Output***

## I. INTRODUCTION

Fresh water is a necessity for the maintenance of life and also the key to man's prosperity. Though there is huge amount of water over the earth surface yet it is very difficult to fulfill the need of the people with pure and potable water.

A report published by the World Bank in the year of 1982, shows that out of 2400 million people living in the developing countries, less than 500 million (around 20%) have access to potable water and peoples who do not have access to potable water raise by 70 million each year. Most of the villages in

many areas in country are isolated and are thinly populated. The only source of potable and drinkable water to these villages is the rain water stored in wells, ponds etc. It is generally observed in these villages that one or more members of the family, in addition to bringing firewood needed for cooking, are always kept engaged in bringing water from long distances, spending much human energy and time which otherwise could be used for some productive purpose. Though availability of a lot of water is underground in most of these cases, especially in desert areas, it is saline (impurities is of the order of 5000-10,000 ppm) as seawater (which contains salt of the order of 35,000 ppm) and is not fit for consumption purposes. For human consumption, 500 ppm is generally considered

as the maximum value for drinking; and for agricultural purposes; salt content of the order of 1000 ppm on average is taken as a maximum level. In addition to quantity of water, there are many places even in urban areas, where water is polluted and is not always completely safe for consumption.

Most diseases in these areas are caused by polluted water.

According to the study made by the World Health Organization, polluted water and sanitation deficiency are the cause of 80% of all the diseases which make a person unfit, temporarily or even permanent. It has been also estimated that near 500 million people in the developing countries are suffering from diseases produced by water.

[5]To solve these problems, new drinking water sources should be discovered. Some of the readily accessible sources of water are the deep ground water, shallow ground water, uplands lakes and reservoirs, rivers, canals and low land reservoirs. The deep ground water is generally of very high bacteriological quality, but may be rich in dissolved solids, especially carbonates and sulfates of calcium and magnesium along with chlorides and bicarbonates. The water immerging from shallow ground water is usually abstracted from wells or bore holes. A variety of soluble materials may be present including potentially, toxic metals such as zinc and lead. In the upland lakes and reservoirs, the bacteria and pathogen are usually low, but bacteria algae and protozoa may be present along with low ph value of water. The low land surface water have significant bacterial load and may also contain algae, suspended solids and a variety of dissolved constituents. Due to contamination of these resources by human being itself, water from these resources need to be purified before drinking purpose.

Desalination is the outlet for further unlimited sources of freshwater from the sea. Today, many countries rely heavily on desalination technologies to meet their requirements of fresh water. In recent years, desalination of water has been one of the most important technological works undertaken in many countries. Many areas in Middle East and elsewhere, have little or no natural water supplies which can be used for human consumption and, hence, depend heavily on water produced by desalination. Some of the common methods of water treatment are,

**(i)Boiling** Water is heated hot and long enough to inactivate or kill micro-organism that normally live in water at room temperature. This method is very common and removes most of the micro-organism, but not the solutes.

**(ii)Carbon Filtering** Charcoal, a form of carbon with a high surface area, absorbs many toxic compounds.

**(iii)Distilling** Distillation involves boiling of water to produce the vapor which on condensation, liquefies. Though the solutes are not properly vaporized, but 99.9 % pure water can be obtained by distillation.

**(iv).Reverse Osmosis:** Pure water is forced under pressure into the impure solution through a semi-permeable membrane. Reverse osmosis is theoretically the most through method of purification.

**(v)Ion exchange:** Most common ion exchange system use a zeolite resin bed to replace unwanted $Ca^{++}$ and $Mg^{++}$ ions with benign (soap friendly) $Na^{+}$ or $K^{+}$ ions. This is the common water softener.

**(vi)Electro deionization:** Water is passed between a positive electrode and a negative electrode. Ion selective membranes allow only selective ion to pass through them.

**(vii)Solar distillation:** The solar distillation method is an easy small scale cost effective technique for providing safer water at homes or in small communities yet effective and inspirited by the way nature makes rain. In the solar distillation, the sun energy is used to heat water to the point of evaporation. As the water evaporates, water vapor condenses on the glass and trickles down the surface for collection. This process removes impurities such as salt and heavy metals as well as dominates microbiological organism. The end result is water cleaner than the purest rainwater.

## II. SOLAR DISTILLATION

A solar still operates on the same principal as rain water i.e. evaporation and condensation**[3]**. The root for production of rain water is based on a hydrological cycle in which large scale process of solar distillation produces fresh water naturally. The essential features of the hydrological cycle can be as the production of vapors above the surface of the liquid, followed by transport of vapors by winds, then cooling of air-vapor mixture, condensation, and precipitation. This natural process is copied on a small scale in basin type solar stills. In solar distillation, the solar radiation falls on the glass cover from which some portion of the solar radiation is reflected to the atmosphere, some of it is transmitted through the glass and the remaining part gets absorbed by the water mass. The solar radiation absorbed by the water mass is also divided in three portions. Some of the radiation is reflected by the water mass, some is transmitted by the water and remaining is absorbed by the base of the solar still. The water in the still start heating, receiving heat from the base of the still and after absorbing its latent heat it forms moisture of water and air. This mixture of water and water vapor get condensed on the inner surface of the condensing surface (glass cover).

A solar distillation plant of a single basin has a top cover made of glass, with an interior surface made of a water proof membrane. The interior surface uses a blackened material to improve absorption of the sun's rays. Water to be cleaned is poured into the still to partially fill the basin. The glass cover allows the solar radiation to pass into the still, which is mostly absorbed by the blackened base. The water begins to heat up and the moisture content of the air trapped between the water surface and the glass cover temperature increases. The base also radiates energy in the infra red region which is reflected back into the still by the glass cover, trapping the solar energy inside the solar still. The heated water vapor evaporates from the basin and condenses on the inside of the glass cover. In this process, the salt and the microbes that were in the original water are left behind. Condensed water trickles down the inclined glass cover to an interior collection throughout to a storage bottle.

### 2.1 The Conditions that Favor the Use of Solar Stills are as Follows

(a) Salty water is available while other sources are fully exploited

(b) Total water need is less than a few $m^3$/day.

(c) Hot climate (plentiful sunlight)

(d) Expensive and/ or unreliable fuel supply

(e) Rainfall below 0.5 t/yr (rainwater catchments-impractical)

(f) High water transportation cost (generally, more than Rs 500/$m^3$ or US$ 10 / $m^3$).

### 2.2 The Main Users of Distilled Water Are

(a)Industries for industrial purpose,

(b)Hospitals and dispensaries for sterilization,

(c)Automobile garages and workshops for radiator and battery maintenance,

(d)Telephone exchange for battery maintenance

(e)Laborites for analytical work,

(f) Marshy and coastal areas to get fresh potable water.

### 2.3 Factors that Influence the Solar Distillation

(a)Temperature of the feed saline water to the still is high.

(b)Average temperature difference between feed water and condensing surface

## III. MATHEMATICAL FORMULATION

### 3.1 Solar Radiation

Figure 1 illustrates division of the incident solar radiation (I) fall over surface.

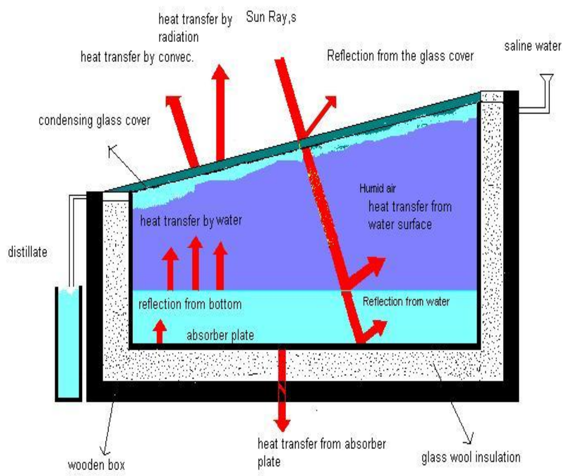


**Fig. 1 Solar Energy Distribution and Heat Transfer Rates in a Solar Still**

A part of this incident radiation is absorbed by glass cover; a part is reflected and remaining is transmitted ($\tau_g$I) inside the enclosed solar still which strikes over the water surface, partially gets reflected (R'$_w$I) and absorbed by the water mass ($\alpha_w$'I). The solar radiation at last; reaches on to the absorber plate where it is mostly absorbed Following equation has been accounted for decreasing the signal strength of the solar flux in the water mass

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which is based on absorptivity and depth of water mass. The values of $\mu_j$ and $n_j$ are taken from Tiwari**[1]**

$$\alpha'_w I = (1-R_g)(1-\alpha_g)(1-R_w)I\left[1-\sum \mu_j \exp(= njd_p)\right]$$

### 3.2 Water mass

Energy balance on the water mass in the solar still gives,

$$\alpha'_w I + h_{bw}(T_b - T_{w)} = \left[\frac{(MC)_w}{A}\frac{dT_w}{dt} - \frac{\dot{m}_e h_{fg}}{A}\right] + Q_{\text{int}}$$

Where $Q_{int}$ is the rate of heat transfer between the water surface and glass cover inner surface due to evaporation, radiation and convection as:

$Q_{int} = Q_{ew} + Q_{rw} + Q_{cw}$

Where the evaporative rate of heat transfer is given by,

$$Q_{ew} = \dot{m}_e h_{fg} / A \qquad (2.14)$$

In terms of mass transfer coefficient the mass evaporated will be,

$$\frac{\ddot{me}}{A} = h_D \ (\rho_w - \rho_{gi})$$

Assuming, the evaporated water vapor to behave as a perfect gas,above equation in terms of partial pressure becomes,

$$\frac{\dot{m}_e}{A} = \frac{h_D M_w (p_w - p_{gi})}{R_0 T}$$

Since the heat of evaporation comes from the surrounding air due to convection,following heat and mass relation**[2]** will be used.

$$\frac{h_{cw}}{h_D} = \left[\rho c_p Le^{2/3}\right]$$

The radiative heat transfer coefficient between the water surface and the inner surface of glass cover assuming both as infinite parallel planes are evaluated as:

$$Q_{rw} = \sigma\varepsilon_{eff}\,(T_w^4 - T_{gi}^4)$$

The convective heat transfer between the water and the inner surface of the glass cover through the humid air is given by,

$$Q_{cw} = h_{cw}(T_w^4 - T_{gi}^4)$$

The heat transfer coefficient $h_{cw}$ was also obtained from the following relation proposed by Dunkle **[4]**

$$h_{cw} = 0.884\left[(T_w - T_{gi}) + \frac{(p_w - p_{gi})(T_w + 273)}{268.9x10^3 - p_w}\right]$$

The radiative and evaporative heat transfer coefficients were respectively evaluated as;

$h_{rw} = Q_{rw} / (T_w - T_{gi})$

$h_{ew} = Q_{ew}/ ( T_w - T_{gi})$

### 3.3 Glass Cover

The distillate output were calculated by

$$\dot{m}_e = \frac{Q_{ew} A}{h_{fg}}$$

## IV. EXPERIMENTAL SET-UP

### 4.1 Solar Still

The solar still experimental set-up that is a basin type single slope solar still made of 0.002 m galvanized iron sheet having base internal area of 1.2mx0.72m with its longer dimension placed in the east-west direction as shown in Fig. 3.1.South facing end of the still basin is 0.1m while the north facing end is 0.3m high, hence making a angle of 11 degree with the horizontal surface. The basin is kept in a wooden box made from a 0.023 m thick board having outer base dimensions of 1.3mx0.82m and sides 0.15 m and 0.35 m to fit in and fill the gaps of around 0.025 m by loosely packed glass wool for providing thermal insulation. The solar still's basin is blackened for increasing the solar energy absorption capacity. The sloppy opening of the basin has a proper seat for placing glass cover with a rubber gasket of 0.005 m thickness and 0.10 m width in between for sealing. The still is placed in such a way that facing southern side to capture maximum solar flux. The sloppy glass cover having thickness of 0.005 m act as a solar energy transmitter and also as a condensation surface for the water steam generated in the solar basin

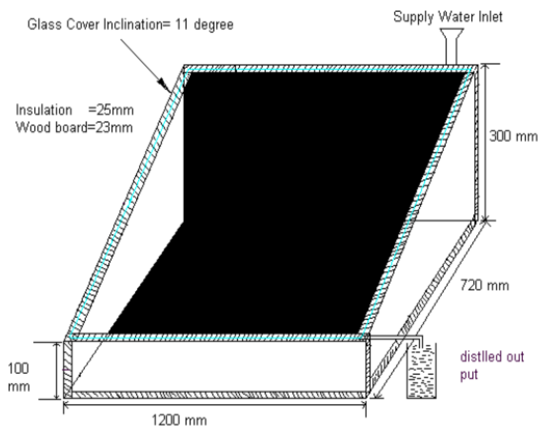


**Fig. 2 Schematic View of the Solar Still**

The condensate trickles down past the sloppy glass cover and collects in a suitably fabricated trough at the bottom end which is then subsequently drained out into a measuring jar. The whole assembly is mounted on an iron frame of suitable dimensions (35mmx35mmx5mm) and strength at a height of around 0.3m.

## V. RESULTS AND DISCUSSION

The experimental such as- temperature at various sections in the solar still set up and the distilled output for different water depths in the basin are observed. Thus, heat transfer coefficient of the fluid at different points, heat transfer rates and distilled output are estimated by using appropriate co-relations.The observations taken out of the data analysis are discussed here.

### 5.1 Heat Transfer Coefficients

The radiative, convective and evaporative heat transfer coefficients evaluated for the data obtained on the solar still, come out to be 8-10 W/m$^2$ K$^4$, 1.5 to 2.5 W/m$^2$K and 6 to 30 W/ m$^2$K. This shows that the evaporation process plays a vital role in the distillation although it also depends upon the convection process

In Fig. 3 is shown the combined heat transfer coefficient due to radiation, convection and evaporation in the distiller. It also increases with the time of heating and is high for low water depths. It varies between 5 to 45 W/m$^2$ K. Fluctuations in the values of the heat transfer coefficient are due to disturbance in the atmospheric conditions at the time of the experiment.

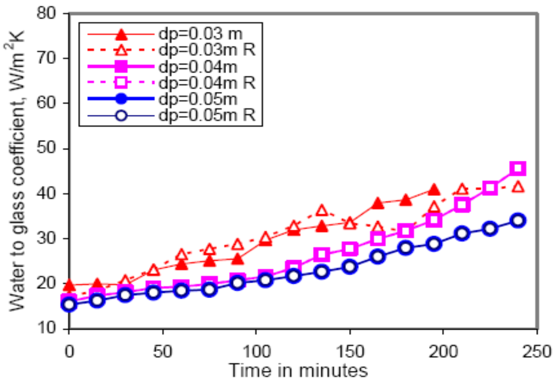


**Fig. 3 Combined Heat Transfer Coefficient ($h_{lw}$) from Water to Glass Cover**

### 5.2 Heat Transfer Rates

Figures 4 to 9 show rate at which solar energy is absorbed by the absorber plate and the water ($Q_{absorbed}$), heat transfer to the water mass ($Q_{water}$), heat from the water to the glass cover ($Q_{internal}$), heat contained in the glass cover and the heat transfer to the ambient from the glass cover.

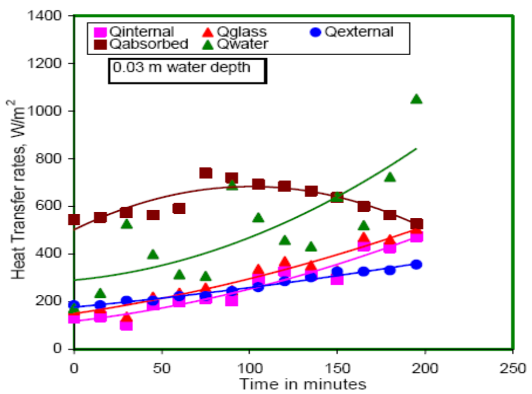


**Fig. 4 Heat Transfer Rates at Various Sections of the Solar Still with Time**

All these plots have been also represented by mean average lines of second order. Most of them show increasing trend with time of heating except in few cases, where the solar flux gets disturbed due to change in the weather conditions or cloudy atmosphere. In an ideal, steady state condition, the solar energy absorbed ($Q_{absorbed}$) should balance the heat taken by the water mass ($Q_{water}$). But, the heat of the water mass appear as scattered and do not show any set pattern because its evaluation considers several assumptions for the sensible heat in the water, heat transfer to the glass cover in the form of evaporation, conduction and radiation, which themselves are evaluated using empirical equations and property co-relations for the fluids and heat lost from the bottom and side surfaces of the solar still.

However, the heat dissipated out from the glass cover ($Q_{external}$) suitably balances the heat in the glass cover, being slightly higher than the internal ($Q_{internal}$).

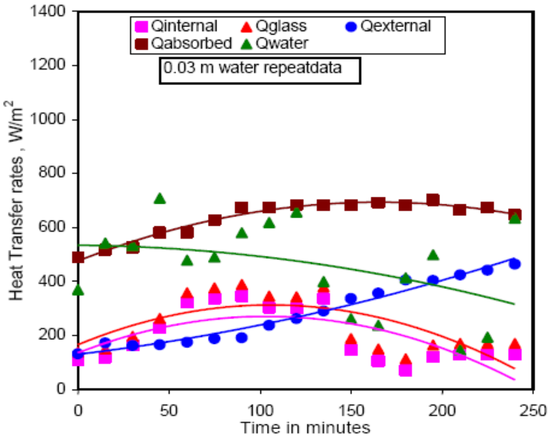


**Fig. 5 Heat Transfer Rates at Various Sections of the Solar Still with Time**

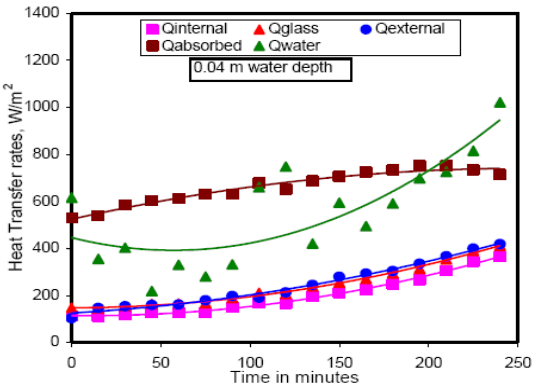


**Fig.6 Heat Transfer Rates at Various Sections of the Solar Still with Time.**

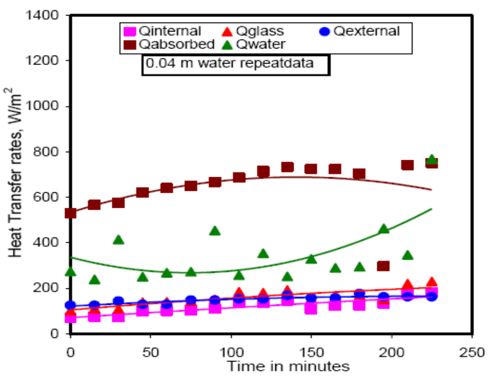


**Fig. 7 Heat Transfer Rates at Various Sections of the Solar Still with Time**

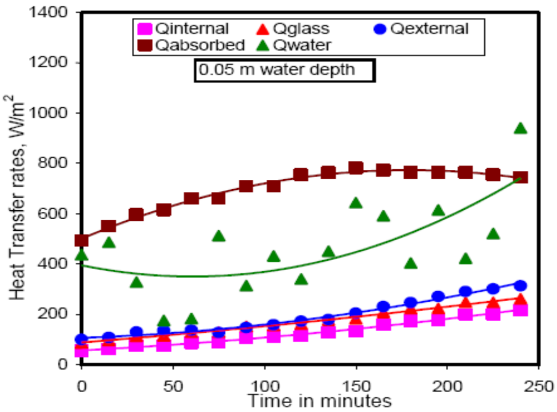


**Fig. 8. Heat Transfer Rates at Various Sections of the Solar Still with Time**

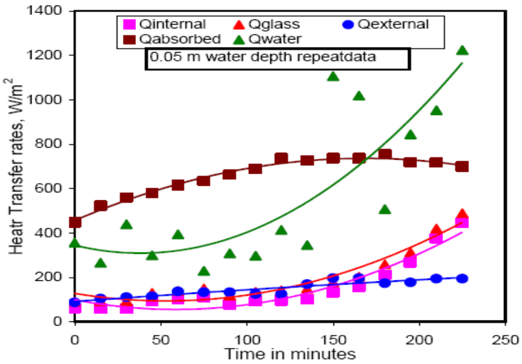


**Fig. 9 Heat Transfer Rates at Various Sections of the Solar Still**

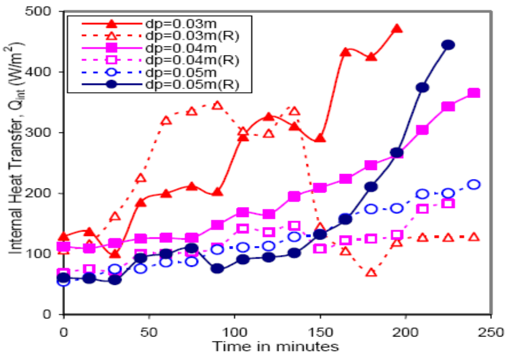


**Fig. 10 Internal Heat Transfer Rate from Water Surface with Time for Different Depths of Water**

The total internal heat transfer due to radiation, convection and evaporation are shown in Fig. 10. It also increases with time and is high for low water depths. For data on typical days, the internal heat transfer rate increases from 125 to 450 W/m$^2$ with 0.03 m 100-350 W/m$^2$ with 0.04 m and 60- 200 W/m$^2$ with 0.05 m of water depths during three hour of heating.

The overall top loss for different water depths is plotted in Fig. 11. which increase with time and are high for low water depth. For four hours of heating, the top loss from the solar still lies between 150 to 350 W/m $^2$, 140 to 380 W/m$^2$ and 140 to 350 W/m$^2$ for 0.03 m, 0.04 m and 0.05 m depths of water, respectively.

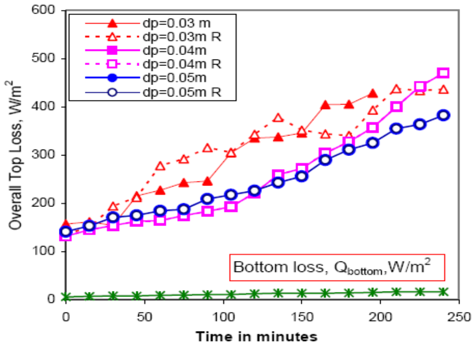


**Fig. 11 Overall Top Loss ($Q_{top}$) and Bottom Loss**

## 5.3 Distillate Output

The measured and calculated distillate out put rate with the time of heating is shown in Fig. 12 to 14 respectively for the water depths of 0.03 m, 0.04 m, and 0.05 m.

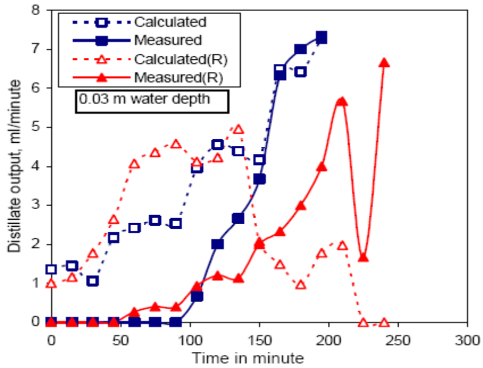


**Fig. 12 Calculated and Measured Distillate Output with Time for 0.03m Water Depth**

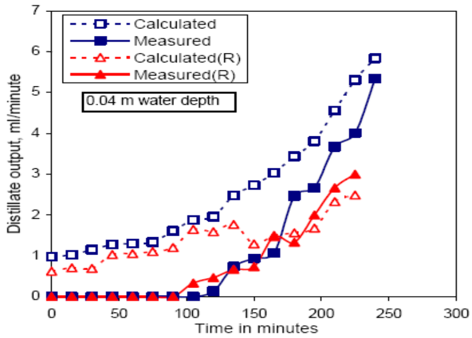


**Fig. 13 Calculated and Measured Distillate Output with Time for 0.04m Water Depth**

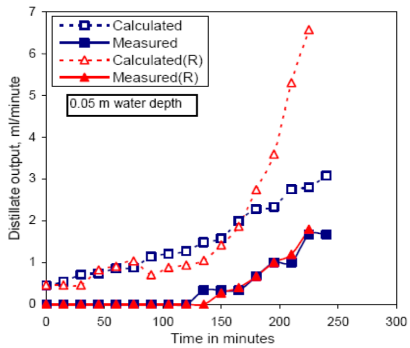


**Fig. 14 Calculated and Measured Distillate Output with Time for 0.05m Water Depth**

The repeated data for the same depth but on different day are also shown in the figures. There seems to be a great difference in the measured and calculated values at the start-up time, although they become quite close after around two hours of heating. The difference in their values at the start-up time is obvious, because the real evaporation starts immediately when there is rise in temperature of the water even up to a few degrees. The evaporated vapors rise up and condense on the glass cover. They slowly then trickle down up to the lowest edge of the glass cover and accumulate in the drain passage until they become enough to drain down into the measuring jar. This takes an hour or two to indicate the measured values of the distillate output. The calculated distillate out -put the glass cover while the measured values are those collected in the measured jar getting indicated after a long time from the start-up. represent the real evaporated vapor, due to the internal heat transfer between the water and

One of the interesting result arising out of the distillate out-put plots in the Fig. 12 to 14 is that for the data of some typical days, after around three hours of the heating periods measured value is quite equal to the calculated value for the water depth of 0.03 m is slightly less for the water depth of 0.04 m and very less for the 0.05 m depth.

Figure 15 show measured distillate out-put at different water depths along with the repeated data for same depths. It is quite distinct that the distillate output is more at low water depths. The calculated distillate output shown in Fig. 16. however does not show prominent distinction.

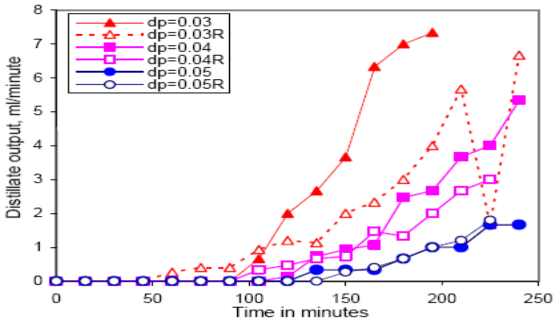


**Fig15 Measured Distillate Output with Time for Different Depths of Water**

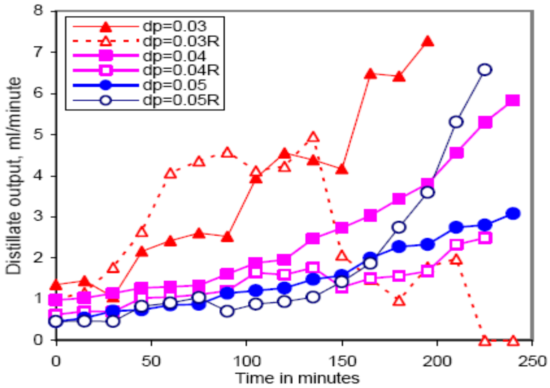


**Fig16 Calculated Distillate Output with Time for Different Depths of Water**

Figure.17 shows comparison of the distillate out-put data for some typical days. After four hours, the measured values of the distillate out-put rate become around 6.5 ml /minute, 4 ml/ minute and 1.5 ml/minute at water depths of 0.03 m, 0.04 m and 0.05 m, respectively. The total distillate outputs during the four hours of solar heating come out to be around 450, 315 and 110, respectively for the 0.03 m, 0.04 m and 0.05 m.

Similarly the calculated distillate rate after four hours come out to be around 7 ml/minute, 5.5 ml / minute and 2.5 ml/ /minute, respectively at the water depths of 0.03 m, 0.04 m, and 0.05 m.

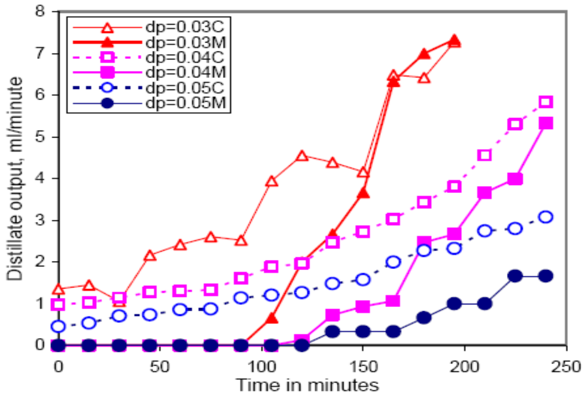


**Fig 17 Calculated and Measured Distillate Output with Time for Different Depths of Water**

## VI. CONCLUSIONS

1. The radiative, convective and evaporative heat transfer coeff. Between the water mass and glass cover increase with time of heating and are generally high for low water depths. They come out to be 0.008 to 0.010 KW/m2 –k4, 0.0015 to 0.0025 KW/m2 –k4, 0.006 to 0.030 KW/m2 –k4 respectively; the evaporation process play a vital role in the distillation process.
3. The combined heat transfer coefficient due to radiation, convection and evaporation in the distiller also increases with the time of heating and is high for low water depths. it varies between 0.005 to 0.045 KW/m2 –k.

4. The combined heat transfer coefficient due to convection, radiation from the glass cover to the ambient, however, show decrease in their values with the time and are high for high water depths.
5. The overall top loss coeff. is estimated at 0.012 to 0.016 KW/m2 –k.
8. The bottom loss coeff. remains nearly constant which is equal to 0.00056 KW/m2 –k.
6. The rates at which solar energy is absorbed by the absorber plate and the water, heat transfer to the water mass, heat from the water to the glass cover , heat contained in the glass cover and the heat transfer to the ambient from the glass cover, represented by mean average lines of second order, generally show increasing trend with time of heating.
7. Heat of the water mass do not show any set pattern because its evaluation involves assumption and errors in the empirical and property co-relation used.
8. The solar energy reaching the absorber, after transmission and absorption through the glass cover and the water mass, get reduced by about 75%.
9. The radiative heat transfer rates for the water depth of 0.03 m to 0.05 m come out to be nearly 20 to 100 W/m2,whereas,the convective and evaporative rates are around 5 to 30 W/m2 and10 to 300 W/m2,respectively.
10. The internal heat transfer rates increases from 125 to 450 W/m2 with 0.03 m, 100-350 W/m2 with 0.04 m and 60-200 W/m2 with 0.05 m of water depths during three hours of heating.

11. The overall top loss lie between 150 to 350 W/m2 , 140 to 380 W/m2, 140 to 350 W/m2 for 0.03m ,0.04m ,and 0.05 m depths of water, respectively.
12. After four hours,the measured values of the distillate output rate is 6.5ml/min,4 ml/min and 1.5 ml/min at water depth of 0.03m,0.04m,0.05m,respectively.
13. The calculated distillate rate after four hours come out to be around 7 ml/min,5.5 ml/min and 2.5 ml/min,respectively at the water depth of 0.03m,0.04m,0.05m.

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