Chapter 3

EXPERIMENTAL SET UP AND MATHEMATICAL MODELING OF PASSIVE SOLAR STILLS

This chapter deals with an experimental set up of three cases and thermal modeling of three different cases of passive solar still. Experiments of first three cases, including varying glass cover thicknesses, passive solar still with vacuum tubes and double basin passive solar still with vacuum tubes during clear sky days of January-2011 to June 2013. Experiment on double basin passive solar still with vacuum tubes for increment in distillate output of the upper basin of energy absorbing materials is conducted during July – 2013 to June – 2014 described at the end.

3.1 Experimental Setup of Solar Stills with Varying Glass Cover Thicknesses

Glass cover is a very important component of passive solar still. Good selection of glass cover gained higher distillate output. Figs. 3.1 and 3.2 show the schematic and real view of the experimental setup installed at Gujarat Power Engineering & Research Institute, Mehsana, India. Fig. 3.3 shows data logger attachment with computer for continuous logging parameters during six months of the experiment. The experimental setup consists of three passive solar stills with condensing glass cover inclination of 23° (Latitude of Mehsana City), fabricated to accommodate 0.040 m water depth maximum. All stills possess glass thicknesses of 0.004, 0.005 and 0.006 m respectively. The bottom surface of each still was painted black for higher absorptivity. It is concluded (Tiwari et al., 2003) that the output of still is maximum for the least water depth in the basin. Hence, in this present experiment all stills used with 0.01 m water depth. Vertical side of the still was at a depth of 0.250 m, whereas the height of the vertical side was kept 0.450 m. The effective basin area of each still is kept 1 m × 1m and it is made of Fiber reinforced plastic (FRP) of 0.050 m insulation thickness. Here, total seven thermocouples are located inside stills. Among, seven thermocouples, six measured water and glass cover temperatures and seventh exposed to atmosphere to measure ambient temperature. The output from the still is collected through a channel fixed at the end of the smaller vertical side of the basin. A water tank (50 kg capacity) is installed in the system as a constant head tank which is
used to control the level of water inside the still (maintain the water level in the basin constant along time) by using a solenoid control valve as shown in Fig. 3.4. Table 3.1 shows accuracy and error of various instruments used in experiments and illustration is shown in Appendix –IV. Table 3.2 represents the dimensions of passive solar still used in the present experiment.

Fig. 3.1 Schematic diagram of experimental setup of passive solar stills with varying glass cover thickness

Fig. 3.2 Experimental set up of passive solar stills with varying glass cover thicknesses
Fig. 3.3 Data logger with laptop attachment for solar stills with varying glass cover thickness

Table 3.1 Accuracies and Errors for various Measuring Instruments (A K Tiwari and G N Tiwari (2006))

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Instrument</th>
<th>Accuracy</th>
<th>Range</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Copper Constantan Thermocouple</td>
<td>±0.1°C</td>
<td>0-100°C</td>
<td>5%</td>
</tr>
<tr>
<td>2</td>
<td>Solarimeter</td>
<td>±1W/m²</td>
<td>0-1400W/m²</td>
<td>2.5%</td>
</tr>
<tr>
<td>3</td>
<td>Measuring Jar</td>
<td>±10 ml</td>
<td>0-1000 ml</td>
<td>10%</td>
</tr>
<tr>
<td>4</td>
<td>Anemometer</td>
<td>±1 m/s</td>
<td>0-15 m/s</td>
<td>10%</td>
</tr>
</tbody>
</table>
### Table 3.2 Dimension of Passive Solar Still

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of basin in solar still</td>
<td>1 m²</td>
</tr>
<tr>
<td>Outer area of solar still</td>
<td>1.05 m × 1.05 m</td>
</tr>
<tr>
<td>Inclination of glass cover</td>
<td>23°</td>
</tr>
<tr>
<td>Lower end height of solar still</td>
<td>0.30 m</td>
</tr>
<tr>
<td>Higher end height of solar still</td>
<td>0.45 m</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Transmissivity of 0.004, 0.005 and 0.006 m glass cover</td>
<td>0.9, 0.81, 0.72</td>
</tr>
</tbody>
</table>

### 3.2 Components used in Solar Stills having Varying Glass Cover Thicknesses

Components used in this present experiment are given below:

#### 3.2.1 Solar still

It is a simple device to convert available brackish water into drinkable water. A dimension of passive solar still is shown in Table 3.2. Here, all stills consist of the same area, but only glass cover thicknesses are varying.

#### 3.2.2 Solenoid Control Valve

In this present experiment, water depth should remain constant, otherwise the distillate output of a solar still would be varied (A A Badran et al., 2005), hence solenoid control valve is provided to all passive solar stills for maintaining constant water depth. Fig. 3.4 shows the solenoid control valve.

#### 3.2.3 Suryampai
It is a device used to measure solar intensity falling on passive solar still. It is put directly on Solar still glass cover to measure solar intensity in terms of W/m². It has a probe, which is directly connected to a data logger for logging of solar intensity to the laptop to measure solar radiation at every one hour. Fig. 3.5 shows Suryampai used in the experiment. It will also remain same for all experiments on passive solar stills. Specifications of Suryamapi and Data Logger are given in Annexure – IV.

![Solenoid control valves](image1)

Fig. 3.4 Solenoid control valves for maintaining a constant water level

![Suryampai](image2)

Fig. 3.5 Suryampai (1333 solar power meter Korea)
3.2.4 Thermocouples

The main purpose of thermocouple is to measure temperature at various locations of passive solar still. Here, three thermocouples are used to measure temperature of water, inner glass cover and ambient temperature. Due to good corrosion resistance and wide temperature range, K type thermocouples are used for measurement of temperature in passive solar still (Yadav and Kumar, 1991). They are directly coupled to the data logger for logging temperatures at varying interval throughout the day. Fig. 3.6 shows K type thermocouples used in the measurement of temperature.

Fig. 3.6 Thermocouples (K-Type)

3.2.5 Data Logger

Fig. 3.7 Data logger, 315 model, made by Sigma Controls, Ahmedabad
The data logger is a device, which takes the data of thermocouples, solar radiation and wind speed inside the laptop/computer attached to it in a time interval. The data logger is shown in Fig. 3.7. Here, data logger logged the temperature data at every one hour of time interval.

3.2.6 Anemometer

Wind velocity of a particular location is measured by an anemometer. It measures wind velocity in m/s. Wind velocity has not much impact on performance of a passive solar still, hence wind velocity is not used in the analysis (Tiwari et al. 2003). Fig. 3.8 shows anemometer.

3.2.7 Measuring Jar

Fig. 3.8 Anemometer

Fig. 3.9 Measuring jar
To collect the distillate of passive solar still, measuring jar is used in the present experiment. For measurement of distillate output of three stills, three separate measuring jars are provided. Collecting capacity of measuring jar is 0-1000 kg. Fig. 3.9 shows measuring jar used in the Present experiment.

3.3 Procedure of Experiment

Procedure of calculating experimental values is given below

3.3.1 Procedure of Calculating Experimental Values

The experiments were performed for six months from January 2011 to June 2011 on the terrace of Gujarat Power Engineering & Research Institute, Mehsana for all sunny days. Solarimeter is put on solar still for receiving solar radiation. All experiments were started at 7 A.M. local time and lasted till the 6 AM of the next morning. The three stills for varying thickness of glass cover were experimented for a constant water depth of 0.01 m. The following parameters were measured every hour.

- Water temperature
- Inner glass cover temperature
- Ambient Temperature
- Distillate output
- Solar Intensity

Water, glass cover, and ambient temperatures were recorded with the help of calibrated K type thermocouples in combination with the data logger arrangement. The distillate output is recorded by measuring jar. The solar intensity was measured with the help of a calibrated solarimeter. Uncertainty analysis of instruments shown in Appendix –I.

The entire analysis included here is primarily split into two sections called seasonal performance analysis and establishment of thermal model. The total daily distillate output and radiation for any day of experimentation have been calculated by summing up all the 24 hours average values of that day. The number of clear sky days in each month has been followed and recorded.
Thus, the total monthly distillate output and insolation have been worked out by multiplying their corresponding daily distillate values to the number of clear sky days in that month. In the end, the total six months values of the distillate output for a certain thickness have been computed by the sum of monthly corresponding values for every month. Nevertheless, the seasonal total value of distillate output has been computed by the sum of total monthly values for those three months comprise a special time of year.

3.3.2 Procedure of Calculating Theoretical Values for Passive Solar Stills with Varying Glass Cover Thicknesses

The following procedures have been followed for computation of various theoretical values on an hourly basis of passive solar still. This procedure will remains same for all types of passive solar still.

**Step I**

1. Initially at t=0, the morning observed values of water temperature ($T_w$) and inner glass cover surface ($T_{ci}$), have been used to determine the hourly value of evaporative, convective, radiative and total heat transfer coefficient

2. For the known value of $h_1$, other design parameters and climate parameters (Appendix - II), the new values of water temperature at t have been determined using equation given in Appendix II.

3. For the known value of $T_w$ at t, other value like $T_{ci}$ has been determined. From the known values of $T_w$ and $T_{ci}$, the theoretical distillate output has been determined using equation given in Appendix II.

**Step II**

1. For the new values of $T_w$ and $T_{ci}$ from Step I, the new values of the evaporative, convective,
radiative heat transfer coefficients have been determined.

2. From the known values of above heat transfer coefficients, the new value of the total heat transfer coefficient has been determined. For known value of $h_1$, other design parameters and climate parameters, the new values of $T_w$ at $t$ have been determined.

3. From the calculated new value of $T_w$ and $T_{ci}$ from step II, the new value of $T_{ci}$ has been determined and for the known values of $T_w$ and $T_{ci}$, the theoretical distillate output has been determined.

**Step III**

1. The above said procedure has been repeated on an hourly basis.
2. The known values of $T_w$, $T_{ci}$ and distillate output has been compared with experimental results.

The above procedure will be used for evaluating $T_w$, $T_{ci}$ and $m$ for all three solar stills having varying glass cover thicknesses.

A computer program in MICROSOFT EXCEL PACKAGE 2007 was used to determine the various heat transfer coefficients of passive solar still. The values of which were then used to determine the theoretical values of water temperature, inner glass cover temperatures and distillate output by providing initial values of water and glass cover temperatures. The solar intensity and ambient temperature values have been taken from daily observation. Fig. 3.10 shows a flow chart for calculation of theoretical values.
Start

Read system design parameters

Initialize \( i = 0 \)

Read \( I(s), T_i \) Initial Value of \( T_w, T_{ci} \)

Initialize \( m = 0 \)

Display \( m, T_w, T_{ci}, r, e \)

Is \( t > 3600 \)  

\( t = t + 1 \)

Calculation of Theoretical values of \( m, T_w \) and \( T_{ci} \) using excel programme

Read Experimental value of \( m, T_w \) and \( T_{ci} \)

Calculate \( r \) and \( e \)

Where, \( N = \) Number of Observation

Is \( I = N \)  

\( I = I + 1 \)  

YES

STOP

Fig. 3.10 Flow chart of computer model of solar still with varying glass cover thicknesses
3.4 Thermal Modeling of Passive Solar Still

The transmitted radiation through the glass cover surface is absorbed by the water inside the passive solar still basin. The water temperature increases and heat are transferred from water to glass cover by three modes. Evaporative, convective and radiative heat transfers occur due to the temperature difference between the water surface and lower surface of the glass cover. The evaporative heat transfer is accompanied by the mass transfer due to the partial vapour pressure difference between the water surface and glass cover. The evaporated water vapour condenses at the lower surface of the glass cover and releases its latent heat of vaporization to the glass cover. A small fraction of heat is lost to the surroundings, i.e. Ambient through the bottom and side walls by conduction and convection. The saline water is allowed in the basin through a dripping arrangement such as drop by drop flow of water compensates the water mass to take the sensible heat to attain equilibrium with basin water. Fig. 3.11 shows the overall energy balance equation of single basin passive solar still for 0.004 m glass cover thickness.
In order to write energy balance equations for solar still, following assumptions have been made:

- Inclination of glass cover is very small.
- The heat capacity of the glass cover, the absorbing material and the insulation (bottom and sides) is negligible.
- The solar still is vapor-leakage proof.
- Condensation of the glass cover is film type.
- There is one dimensional heat flow through back insulation.
- Every hour steady state condition is reached

3.4.1 Energy Balance for Passive Solar Still

The energy balance of different components of a passive solar still is as follows:

3.4.1.1 Energy Balance of Inner Glass Cover for Passive Solar Still

The sum of the radiation absorbed by the inner glass cover surface and heat transferred from the water to glass surface is equal to the rate of conductive heat transfer from inner glass cover surface to outer glass cover surface. Fig. 3.12 shows an energy balance diagram for glass cover.

\[
\alpha_g \dot{I}(t) + [q_{rg} + q_{ew} + q_{ew}] = q_{cg} 
\]

or

\[
\alpha_g \dot{I}(t) + h_i(T_w - T_{ci}) = \frac{K_g}{L_g}(T_{ci} - T_{co})
\]

An expression of the total heat transfer coefficient \( h_i \) is as given in Appendix – II.

3.4.1.2 Energy Balance of Outer Glass Cover for Passive Solar Still

Rate of conductive heat transfer from inner glass cover surface to outer glass cover surface is equal to the sum of radiative and convective heat transfer of glass cover to ambient.

\[
\frac{K_g}{L_g}(T_{ci} - T_{co}) = q_{rg} + q_{cg}
\]
\[
\frac{K_g}{L_g} (T_{ci} - T_{co}) = h_2 (T_{ci} - T_a)
\]

Hence, put value of (3.14) in Eq. (3.11)

\[
\alpha'_{g} I(t) + h_1 (T_w - T_{ci}) = h_2 (T_{ci} - T_a)
\]

Expressions of convective and radiative heat transfer coefficients are given in Appendix-II.

**Fig. 3.12 Energy balance equation for glass cover in passive solar still**

### 3.4.1.3 Energy Balance of Water Mass for Passive Solar Still

The amount of radiation absorbed by water mass and heat stored from basin liner to water equals to the amount of heat stored in water and high temperature transfer from water surface to glass surface. Fig. 3.13 shows an energy balance diagram for water mass.

\[
\alpha'_{w} I(t) + q_b = (MC)_w \frac{dT_w}{dt} + [q_{rw} + q_{cw} + q_{ew}]
\]
or \[ \alpha_w I(t) + h_3(T_b - T_w) = (MC)_w \frac{dT_w}{dt} + h_i(T_w - T_c) \] 

(3.7)

Fig. 3.13 Energy balance equation for water mass inside passive solar still

3.4.1.4 Energy Balance of basin Liner for Passive Solar Still

Solar radiation absorbed by the basin liner is equal to the amount of heat transmitted to the water by convection and heat transferred from basin side surface to the ambient. Here, side loss is small, hence; it is not taken into consideration. Fig. 3.14 shows the energy balance equation for basin liner.

\[ \alpha_b I(t) = q_w + [q_{bb} + q_{bs}] \] 

(3.8)

or

\[ \alpha_b I(t) = h_3(T_b - T_w) + U_b(T_b - T_a) \] 

(3.9)

Expression for \( h_3 \) is shown in Appendix II.
Fig. 3.14 Energy balance equation for basin liner inside passive solar still

Where,

\[ \alpha_b' = (1 - R_g) \alpha_g \]

\[ \alpha_w' = (1 - \alpha_g)(1 - R_g)(1 - R_w)[(1 - \sum \mu_j \exp(-\eta_j d_w)) \]

And

\[ \alpha_b' = \alpha_b(1 - R_g)(1 - \alpha_g)(1 - R_w)[\sum \mu_j \exp(-\eta_j d_w)] \]

Here, \( \sum \mu_j \exp(-\eta_j d_w) \) is the attenuation factor, the value of which depends on water depth. As per Tiwari et al., (2003), it is 0.5490 (for 0.01 m).

For determining expression for \( T_{ci} \) (3.2) can be rearranged as:

\[ \alpha_s I(t) = h_1(T_w - T_{ci}) = h_2(T_{ci} - T_a) \]
\[
\alpha_s I(t) + h_1 T_w - h_1 T_g = h_2 T_g - h_2 T_w \\
\alpha_s I(t) + h_1 T_w + h_2 T_a = (h_1 T_w + h_2 T_a) \\
\alpha_s I(t) + h_1 T_w + h_2 T_a = (h_1 + h_2) T_{ci} \\
T_{ci} = \frac{\alpha_s I(t) + h_1 T_w + h_2 T_a}{h_1 + h_2} \tag{3.10}
\]

For determining expression for \( T_b \), (3.9) can be written as:
\[
\alpha_s I(t) = h_3 (T_b - T_w) + U_b (T_b - T_a) \\
\alpha_s I(t) = h_3 T_b - h_3 T_w + U_b T_b - U_b T_a \\
\alpha_s I(t) + h_3 T_w + U_b T_a = h_3 T_b + U_b T_w \\
T_b = \frac{\alpha_s I(t) + h_1 T_w + U_b T_a}{h_3 + U_b} \tag{3.11}
\]

Now put values of \( T_{ci} \) and \( T_b \) in (3.7)
\[
\alpha_w I(t) + h_3 (T_b - T_w) = (MC)_w \frac{dT_w}{dt} + h_1 (T_w - T_{ci}) \\
\]
Divide whole equation by \((MC)_w\) then it becomes
\[
\frac{\alpha_w I(t) + h_3 (T_b - T_w)}{(MC)_w} = \frac{dT_w}{dt} + \frac{h_1 (T_w - T_{ci})}{(MC)_w} \tag{3.12}
\]
\[
\alpha_w I(t) + \left( h_3 \frac{\alpha_s I(t) + h_1 T_w + U_b T_a}{(h_3 + U_b)} - T_w \right) = \frac{dT_w}{dt} + \frac{h_1 (T_w - \left[ \alpha_s I(t) + h_1 T_w + h_2 T_a \right])}{(h_3 + U_b)} \tag{3.13}
\]
rearranging above equation (3.13) to
\[
\frac{\alpha_w h_w}{h_w + h_3} + \alpha_g \frac{h_1}{h_1 + h_2} I(t) + \left( \frac{h_w h_3}{h_w + h_3} + \frac{h_w h_2}{h_1 + h_2} \right) \times T_a = \frac{dT_w}{dt} + \frac{h_1 (h_w h_3 + h_w h_2)}{(h_w + h_3)(h_1 + h_2)} \tag{3.14}
\]
\[
\frac{\alpha \tau_{eff} I(t) + U_L T_a}{(MC)_w} = \frac{dT_w}{dt} + \frac{U_L T_w}{(MC)_w} \tag{3.15}
\]
Eq (3.15) can be rewritten as:

\[ f(t) = \frac{dT_w}{dt} + aT_w \]  

Hence, Eq (3.16) can be rearranged as:

\[ \frac{dT_w}{dt} + aT_w = f(t) \]  

where, \( f(t) = \frac{(\alpha \tau)_{\text{eff}} I(t) + U_L T_a}{(MC)_w} \)  

where, \( (\alpha \tau)_{\text{eff}} = \alpha_w h_w + \alpha'_w + \alpha'_g \frac{h_1}{h_1 + h_2} \)  

\[ a = \frac{U_L}{(MC)_w} \]  

where, \( U_L = U_b + U_t \)  

where, \( U_b = \frac{h_w h_3}{h_w + h_3}, \) \( U_t = \frac{h_t h_2}{h_1 + h_2} \)  

3.4.2 Approximate Solution of \( T_w \) for Varying Glass Cover Thicknesses in Passive Solar Still

In order to obtain an approximate solution of Eq. (3.17) with above initial conditions, the following assumptions are made.

- The time interval \( \Delta t (0 < t < \Delta t) \) is small.
- The function \( f(t) \) is constant, i.e. \( \bar{f}(t) = f(t) \) for the next time interval, \( \Delta t \)
- \( a \) is constant during the time interval

The value of \( h_1 \) can be determined by considering known values of water and glass temperatures at,

\[ t=0, \text{i.e, } T_w (t=0) = T_{w0} \text{ and } T_{ci} = T_{ci0}(t=0) \]
The solution of Eq (3.17) can be written as

\[ T_w = \frac{\bar{f}(t)}{a} \left[ 1 - \exp(-a\Delta t) \right] + T_{w0} \exp(-a\Delta t) \]  

(3.23)

Where, \( T_{w0} \) is the temperature of the basin at \( t=0 \) and \( f(t) \) the average values of water and \( f(t) \) for the time interval 0 and \( t \).

The rate of evaporative heat loss and the hourly yield of the solar still are given as:

\[ q_{ew} = h_{ew}(T_w - T_{ci}) \]

And

\[ m = \frac{h_{ew}(T_w - T_{ci})}{L} \times 3600 \]  

(3.24)

The daily distillate output is given by

\[ M_{ew} = \sum_{i=1}^{24} M_{ew} \]  

(3.25)

Efficiency is determined by:

\[ \eta = \frac{h_{ew}(T_w - T_{ci})}{I \times A} \]  

(3.26)

3.4.3 Statistical Tools Used

Following is the relation used to evaluate the root mean square of percentage deviation:

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

(3.27)

Where,

\[ e_i = \frac{X_i - Y_i}{X_i} \times 100 \]  

(3.28)

The coefficient of correlation has been evaluated by (AK Tiwari and GN Tiwari (2007))

\[ r = \frac{N \sum X_i Y_i - (\sum X_i)(\sum Y_i)}{\sqrt{N \sum X_i^2 - (\sum X_i)^2} \times \sqrt{N \sum Y_i^2 - (\sum Y_i)^2}} \]  

(3.29)

Where, \( N \) is the number of observations, \( X_i \) is the theoretical or predicted value obtained from thermal modeling; \( Y_i \) is the experimental value of different observed parameters.
3.5 Experimental Setup of Passive Solar Still with Vacuum Tubes

Generally a distillate output of passive solar still is lower; hence it is not widely used in the industrial and domestic purposes. There is a way of to increase the distillate output of passive solar still is the attachment of vacuum tubes at bottom of the solar still basin. Hence, due to natural circulation, water circulates inside the basin through temperature difference within the vacuum tubes. Vacuum tube possesses lower heat losses compared with flat plate collector, hence water remains at higher temperature and distillate output of passive solar still is increased. A schematic diagram of the experimental setup of passive solar still with vacuum tubes is shown in Fig. 3.15. Fig. 3.16 shows thermo-syphon arrangement in vacuum tubes. Fig. 3.17 represents the experimental setup of passive solar still with vacuum tubes. The system consists of a solar still and water in tube evacuated tubes. The passive solar still with an effective basin area of 1 m$^2$ used in this study and mounted on an iron base. The passive solar still consists of an airtight basin, usually constructed out of Galvanized iron (GI) sheet as fabrication material and Fiber reinforced plastic (FRP) of better insulating materials. The FRP thickness is about 0.05 m and thermal conductivity is about 0.351 W/mK (Bilal et al., 1998) has been considered in the present analysis. The basin liner is painted black to increase absorptivity to radiation. Transparent glass cover (thermal conductivity of 0.76 W/m K (Bilal et al., 1998) with thickness of 0.004 m with an inclination of 23° (latitude of Mehsana) to the horizontal fixed to the top and sealed with Silicon rubber to make it airtight to prevent vapor leakage. Fourteen numbers of double-walled hard borosilicate glass tube with 1.6 mm thickness, inner diameter of 0.047 m, outer diameter of 0.058 m, and length of 1.5 m used for present experiment. Fig. 3.18 shows a detailed drawing of passive solar still with vacuum tubes and Fig. 3.19 shows all three views of passive solar still with vacuum tubes for better understanding of set up. The outer tube of evacuated tube is transparent and allowing light rays to pass through it. The inner tube is coated with a selective coating of aluminum nickel alloys compound (Al-Ni/Al) for better solar radiation absorption (>93%) and minimum emittance (<6%). An evacuated tubes or vacuum tubes consist of number of concentric borosilicate tubes inclined at angle of 45° from horizontal. Fourteen numbers of tube coupled with lower curved portion of solar still with help of rubber bush.
Fig. 3.15 Schematic arrangement of single basin passive solar still with vacuum tubes
To prevent breakage of glass tube at bottom, cap is provided hence, direct contact of floor and tube is minimized. These tubes transfer the heat to water filled inside through its contact peripheral surface. The hot water rises up due to low density, whereas; the cold water takes its place due to gravity and high density of solar still as shown in Fig. 3.16. The circulation flow rate inside the collector loop is influenced by the instantaneous solar energy input, fluid temperature and the collector configuration. The orientation of the complex system is assumed to be kept south in order to receive maximum solar radiation throughout the year. Specification of complete system the solar still under study is given in Table 3.3. This setup requires three thermocouples for measurement of water, inner glass cover and ambient temperature. Here, vacuum tubes are attached with passive solar still; hence solar intensity falling on vacuum tube is also required along with radiation falling on passive solar still. Fig. 3.18 shows a detailed drawing of passive solar still with vacuum tubes and Fig. 3.19 shows three views of passive solar still with vacuum tubes.

Fig. 3.16 Schematic diagram of thermo-syphon arrangement in evacuated tube
Fig. 3.17 Experimental set up of passive solar still coupled with vacuum tubes
Fig. 3.18 Detailed drawing of passive solar still coupled with vacuum tubes
3.6 Working of Passive Solar Still coupled with Vacuum Tubes

Passive solar still contained water supplied by the water tank from the rear through a feeder tube to passive solar still, hence due to the high density of water, it flows into the basin. A bottom curved portion of a basin, is coupled with vacuum tubes, hence due to the high density of water, it flows to the inner side of vacuum tube. During daytime, radiation absorbs by the vacuum tubes and passive solar still and the temperature of water inside vacuum tube rides and lifted automatically upward towards the basin by natural circulation and then cold water inside the basin moves downward to make hot water. This process will be remain continue during sunshine hours. Hence, hot water in the still quickly forms a vapor and distillate output is increased by passive solar still.
3.7 Main Components of Passive Solar Still with Vacuum Tubes

There are two main components in the present system like vacuum tubes and single basin passive solar still, which are explained below:

3.7.1 Vacuum Tubes

Fig. 3.20 shows vacuum tubes. It is made of two concentric tubes made of borosilicate glass. Conductive and convective heat losses are eliminated because there is no air to conduct heat or to circulate and cause convective losses. There is, however, some radiant heat loss, i.e. heat energy will move through space from warmer to cooler surface even across a vacuum. But, this loss is small and of little consequence compared with the amount of heat transferred to the liquid in the absorber tube. In this vacuum tube, radiation passes through the outer glass tube and the coated absorber receives the heat. Heat energy is transferred to the fluid flowing through the absorber. Evacuated tubes possess advantages like: work in both direct and diffuse radiation, no tracking is required and higher efficiency and temperature compared with flat plate collectors (Sampathkumar et al. 2013). Fig. 3.20 shows three views of vacuum tubes used in the present experiment.

![Diagram of vacuum tubes](image)

Fig. 3.20 Three views of vacuum tubes used in passive solar still with vacuum tubes
3.7.2 Passive Solar Still without Attachment of Vacuum Tubes

A schematic diagram of a passive solar still is shown in Fig. 3.21. The height of the lower and the higher vertical side was kept 0.50 m and 0.924 m, respectively from giving 23° inclination to the condensing cover. The basin is designed to accommodate a maximum depth of 0.50 m. Here, 0.50 m means maximum 50 kg water can be stored inside the still. Vacuum tubes are attached to lower portion of the still, hence water can come easily due to density and become hot and flow of solar still by natural circulation. Fig. 3.21 shows a detailed drawing of passive solar still basin used in the present experiment. Other components are solenoid control valve, suryampai, thermocouples, data logger and distillate jar. They all are explained in (3.2.2) to (3.2.6).

Fig. 3.21 Detailed drawing of passive solar still used in passive solar still with vacuum tubes
Fig. 3.22 Flow chart of computer model for passive solar still with vacuum tubes for measurement of inner glass cover thickness, water temperature and distillate output.

- Start
- Read system design parameters
- Initialize (i=0)
- Read I(s), T_i, Initial Value of T_w, T_ci
- Initialize m = 0
- Is t > 3600
  - t = t + 1
  - Calculation of Theoretical values of m, T_w and T_ci using excel programme
  - Read Experimental value of m, T_w and T_ci
  - Calculate r and e
- Display m, T_w, T_ci, r, e
- I = I + 1
- Is I = N
  - YES
  - STOP
  - NO
### Table 3.3 Dimension of Experimental Setup of Passive Solar Still with Vacuum Tubes (K Sampathkumar, 2013)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of basin in solar still</td>
<td>1 m²</td>
</tr>
<tr>
<td>Outer area of solar still</td>
<td>1.05 m × 1.05 m</td>
</tr>
<tr>
<td>Inclination of glass cover</td>
<td>23°</td>
</tr>
<tr>
<td>Length of evacuated tube</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Inner diameter of vacuum tube</td>
<td>0.047 m</td>
</tr>
<tr>
<td>Outer diameter of vacuum tube</td>
<td>0.058 m</td>
</tr>
<tr>
<td>Glass thickness of vacuum tubes</td>
<td>0.0016 m</td>
</tr>
</tbody>
</table>

### Table 3.4 Thermo-physical values of passive solar still attached with vacuum tubes (K Sampathkumar, 2013)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>αₜ₀</td>
<td>0.36</td>
</tr>
<tr>
<td>αₜ₉</td>
<td>0.05</td>
</tr>
<tr>
<td>αₜ₆</td>
<td>0.34</td>
</tr>
<tr>
<td>F_R</td>
<td>0.831</td>
</tr>
<tr>
<td>M_w</td>
<td>30 kg</td>
</tr>
<tr>
<td>εₜₑ</td>
<td>0.82</td>
</tr>
<tr>
<td>L_i</td>
<td>0.05 m</td>
</tr>
<tr>
<td>K_1</td>
<td>0.57 W/m K</td>
</tr>
<tr>
<td>h_w</td>
<td>250 W/m² K</td>
</tr>
<tr>
<td>Δt</td>
<td>3600 s</td>
</tr>
<tr>
<td>C_w</td>
<td>4190 J/Kg K</td>
</tr>
<tr>
<td>σ</td>
<td>5.67 × 10⁻⁸ W/m²K</td>
</tr>
<tr>
<td>(ατ)ₐ</td>
<td>0.8</td>
</tr>
<tr>
<td>U_LC</td>
<td>2.44 W/m² K</td>
</tr>
<tr>
<td>h₂</td>
<td>5.7 + 3.8 V, V = 3 m/s</td>
</tr>
</tbody>
</table>
3.8 Thermal Modeling of Passive Solar Still with Vacuum Tubes

Fig. 3.22 shows a flow chart of calculations of the theoretical value of passive solar still with vacuum tubes. Procedure of calculating theoretical values is shown in (3.3.2). Experimental procedure will remain same as explained in (3.3.1) but only one parameter solar intensity on vacuum tubes is added to the measurement. The energy balance for each component of the present system in thermo-syphon mode has been carried out with the following assumptions.

a) The solar still unit is vapor leakage proof.
b) Heat capacities of glass and basin material are negligible.
c) Temperature dependent heat transfer coefficients have been considered in the present experiment.
d) Side heat loss from the solar still is neglected.
e) There is no thermal stratification across the water depth.
f) Attenuation of solar radiation within the water mass is considered.
g) Initial values of water and inner glass cover temperatures have been used to determine internal heat transfer coefficients.
h) The system operates in a quasi-steady state regime during day time.
i) Water level in the basin of a solar still kept constant.
j) The condensation that occurs through the inner glass cover is film wise.
k) Quasi steady-state analysis is carried out.

Table 3.3 shows the dimensions of passive solar still with vacuum tubes and Table 3.4 shows thermo-physical values of passive solar still attached with vacuum tubes.

3.8.1 Energy Balance of Passive Solar Still with Vacuum Tubes

The energy balance of different components of a passive solar still with vacuum tubes is as follows:
The amount of the radiation absorbed by the inner glass cover surface and heat transferred from the water to glass surface is equal to the rate of conductive heat transport from the inner glass cover surface to the outer glass cover surface. Fig. 3.23 shows energy balance for glass cover in passive solar still with vacuum tubes.

### 3.8.1.1 Energy Balance of Glass Cover in Passive Solar Still with Vacuum Tubes

![Diagram of glass cover in passive solar still with vacuum tubes]

Fig. 3.23 Energy balance of glass cover in passive solar still with vacuum tubes

Hence, energy balance equation is given by

\[
\alpha_g I(t) + [q_{rg} + q_{cw} + q_{ev}] = q_{cg}
\]

(3.30)
The expression of total internal heat transfer coefficient \( h_1 \) is given in Appendix II.

### 3.8.1.2 Energy Balance of Outer Glass Cover surface of Passive Solar still with Vacuum Tubes

Rate of conductive heat transfer from inner glass cover surface to the outer glass cover surface is equal to summation of radiative and convective heat transfer of glass cover to ambient.

\[
\frac{K_g}{L_g} (T_{ci} - T_{co}) = h_2 (T_{co} - T_a)
\]  

(3.32)

The expression for total external heat transfer coefficient \( h_2 \) is given in appendix II.

### 3.8.1.3 Energy Balance of Water mass in Passive Solar Still with Vacuum Tubes

The sum of radiation absorbed by water mass and heat stored from basin liner to water equals to the sum of heat stored in water and heat transfer from water surface to glass surface. Fig 3.24 shows the energy balance for water mass in passive solar still with vacuum tubes.

Hence, the energy balance equation is given by

\[
\alpha_w (1 - \alpha_g') I(t) + h_2 (T_b - T_w) + Q_u = (MC)_w \frac{dT_w}{dt} + h_i (T_w - T_{ci})
\]  

(3.33)

Where,

\[
Q_u = F_R (\alpha \tau)_{ci} I(t) - U L_c \left( \frac{A_L}{A_{ET}} \right) (T_w - T_a)
\]  

(3.34)
3.8.1.4 Energy Balance of Basin Liner in single basin Solar Still with Vacuum Tubes

Fig. 3.24 Energy balance of water mass in passive solar still with vacuum tubes

Fig. 3.25 Energy balance of basin liner in passive solar still with vacuum tubes
Solar radiation absorbed by the basin liner is equal to the sum of heat transfer to the water by convection and heat transfer from basin side surface to the ambient. Here, side loss is small, hence it is not taken into consideration. Fig. 3.25 shows energy balance on

The energy balance equation for the basin liner of the passive solar still with vacuum tubes is given by:

\[
\alpha_b (1-\alpha_g')(1-\alpha'_w) I(t) = q_w + [q_{bb} + q_{bs}]
\]

or

\[
\alpha_b (1-\alpha_g')(1-\alpha'_w) I(t) = h_3 (T_b - T_w) + U_b (T_b - T_a)
\]

From the energy balance equation of the outer surface of a glass cover, \(T_{co}\) is derived from Equation (3.32)

\[
\frac{K_g}{L_g} (T_{ci} - T_{co}) = h_2 (T_{co} - T_a)
\]

\[
\frac{K_g}{L_g} T_{ci} - \frac{K_e}{L_g} T_{co} = h_2 T_{co} - h_2 T_a
\]

\[
\frac{K_g}{L_g} T_{ci} + h_2 T_a = \frac{K_e}{L_g} T_{co} + h_2 T_{co}
\]

\[
\frac{K_g}{L_g} T_{ci} + h_2 T_a = \left( \frac{K_g}{L_g} + h_2 \right) T_{co}
\]

\[
T_{co} = \frac{\frac{K_e}{L_g} T_{ci} + h_2 T_a}{\frac{K_g}{L_g} + h_2}
\]

Substituting the value of \(T_{co}\) in Equation (3.37) in the energy balance equation of the inner surface of a glass cover and \(T_{ci}\) is derived as:

\[
\alpha_g (T_{ci}) + h_1 (T_w - T_{ci}) = \frac{K_g}{L_g} (T_{ci} - T_{co})
\]
\[
\alpha' g I(t)_s + h_t T_w - h_i T_{ci} = \frac{K_s}{L_g} (T_{ci} - \left( \frac{K_s}{L_g} T_{ci} + h_s T_a \right) + h_t T_w - h_i T_{ci})
\]

Multiply and divide right side by \( h_t \), hence result will be

\[
\alpha' g I(t)_s + h_t T_w - h_i T_{ci} = \frac{K_s}{L_g} T_{ci} - U_{cga} T_{ci} - T_a U_{cga}
\]

(3.39)

\[
\alpha' g I(t)_s + h_t T_w + T_a U_{cga} = T_{ci} (h_t + U_{cga})
\]

(3.40)

Because, here \( U_{cga} = \frac{h_t}{h_t + \frac{K_s}{L_g}} \)

Expression for the \( U_{cga} \) is given by Appendix – II.

From the energy balance equation of the basin liner, the basin liner temperature \( T_b \) is derived as:

(See 3.11)

\[
T_b = \frac{\alpha'_w I(t)_s + h_t T_w + h_b T_a}{h_w + h_b}
\]

(3.41)

Put values of \( T_{ci} \) and \( T_b \) in Eq. (3.33)

(3.42) can be rearranged as
Using equation (3.23), one can get first order differential equation is obtained, and equation is as follows:

\[ f(t) = \frac{dT_w}{dt} + aT_w = \frac{dT_w}{dt} + aT_w = f(t) \]  

(3.44)

Where,  \[ f(t) = \left[ \frac{I_{\text{eff}} + U_{\text{eff}} T_a}{(MC)_w} \right] \text{and } a = \left[ \frac{U_{\text{eff}}}{(MC)_w} \right] \]  

(3.45)

Expressions for \( I_{\text{eff}} \) and \( U_{\text{eff}} \) are given in appendix II.

3.9 Approximate Solution of \( T_w \) for Single basin Solar Still with Vacuum Tubes

The following assumptions have been made to find an approximate analytical solution:

1. The time interval \( \Delta (0<t<\Delta) \) is small.
2. \( a \) is constant during the time interval \( \Delta t \).
3. The function \( f(t) \) is constant, i.e. \( f(t) = f(t) \) for the next time interval \( \Delta t \) for time interval between 0 and t.

By using the following boundary condition \( t=0 \), i.e. \( T_w(t=0) = T_{w0} \) and \( T_{ci} = T_{ci0} (t=0) \). The solution of Equation (9) is derived as follows:

\[ T_w = \frac{f(t)}{a} \left[ 1 - \exp(-a\Delta t) \right] + T_{w0} \exp(-a\Delta t) \]  

(3.46)

The hourly yield is given by the equation:
The daily distillate output is given by:

\[ M_{cw} = \sum_{i=1}^{24} M \]  

(3.48)

The efficiency is given by:

\[ \eta = \frac{h_{cw}(T_w - T_{ci})}{I(t)_s \cdot A_s + I(t)_c \cdot A_{ET}} \]  

(3.49)
3.10 Experimental Setup of Double basin Passive Solar Still with Vacuum Tubes

Fig. 3.26 Experimental Setup of double basin solar still with vacuum tubes
Double basin passive solar still with vacuum tubes gained distillate output from lower basin and upper basin; hence the total distillate output is higher. The experimental setup of present solar still is shown in Fig. 3.26. The data logger attachment to the passive solar still is demonstrated in Fig. 3.27. The overall size of the top basin used is 1.0*1.0*0.500 m\(^3\), and the upper basin is 1.06 *1.0 *0.500 m\(^3\). The lower basin is black coated to increase radiation absorption. Two window
glass of 4 cm thickness provided in the present experimental set up. The lower glass cover is fixed at 8 mm above the basin bottom and upper cover was fixed at 0.010 m above lower cover. An insulation of 0.050 m in thickness was provided on all sides to reduce heat losses. Here polyurethane foam (PUF) with a thermal conductivity of 0.025 W/m² K was used in the present experiment. The evaporated water in the lower basin and the upper basin was condensed by plane glass about 4 mm in thickness. The condensed water of the lower and upper basins was collected by measuring jar A silicone rubber sealant was provided to hold the toughened glass in contact with the still surfaces. A total of 4 holes was made on the lower and upper basins for the location of thermocouples. Here, 14 vacuum tubes were coupled with a hole about 6 cm in diameter in the lower side of the top basin. The inside pipe is coated with a selective coating of aluminum, nickel alloy compound (Al-N/Al) for better solar radiation absorption (>93%) and minimum emittance (<6%) The vacuum tubes were linked up to the still stand at an angle of 45° with respect to the horizontal axis. Rubber gaskets were provided to secure the vacuum tubes attached to the top basin of the solar still. The bottom part of the vacuum tube was connected to a sponge cloth to prevent breakage of vacuum tubes.

Here, the main characteristic is the application of the double basin passive solar still is for the enhancement of distillate output. Compared with conventional passive solar still, it has following merits:

- The generated freshwater can quickly drip because of flow distance of the condensed water on the condensation surface is short and the inclination of condensation surface is large.
- The condensation resistance of the water vapour is reduced due to water inside upper basin.
- The area of condensation surface is increased, which leads to heat transfer efficiency of water vapour.
- Lower basin is coupled to vacuum tubes, hence it continuous receives hot water from vacuum tubes, hence the distillate output of lower basin is higher.
- Latent heat of condensation of lower basin is utilized to evaporate water of the upper basin, which already receives solar energy, hence the distillate output of upper basin will also enhanced compared with conventional solar still.
The total distillate output of present solar still will be summing of lower and upper solar still and it will be remains higher compared with conventional single basin passive solar still.

Fig. 3.28 Detailed drawing of double basin solar still with vacuum tubes

3.11 Working Principle of Double basin Solar Still with Vacuum Tubes

In this present passive solar still, the vacuum tubes which attached with lower basin firstly absorbs the solar insolation and heats the water inside and it supplies hot water in the lower basin under the legal philosophy of natural circulation. Generated water vapour within the lower basin
due to supply of hot water from vacuum tubes, condenses on the inner glass cover surface of the upper basin and released latent heat of condensation consequently to heat water in the upper basin, which also gained solar intensity on it. Hence, it enhances hot water and condensation of vapour for increment in distillate output. The heat then transfers from the lower to upper basin with small proportions dissipating into the surrounding through insulation and also an upper basin receiving heat from the solar radiation. Hence, in this passive solar still distillate output is considerable because it is picked up from the lower and upper basin and total distillate output of the present still is a summation of lower and upper distillate output.

3.12 Experimental Procedure for Calculation of Double basin Passive Solar Still with Vacuum Tubes

A number of experiments have been carried out for a 24h period starting from 7 am to next day 6 am in clear sky conditions from July-2012 to June-2013. Here, lower basin and upper basin is filled with 0.03 m and 0.01 m water depth, which remains constant throughout the experiments. For each experiment, the glass cover was cleaned to avoid dust concentration on the top of the glass cover of the top basin solar still. The variables measured in the present experiments where the water temperature of the top basin, the inner glass cover temperature of the top basin, ambient temperature, solar radiation on evacuating tubes, solar radiation with glass cover and distillate output. Here, cloudy days are not preferred and various temperatures have measured with the help of data logger and suryampai used for measurement of solar intensity on passive solar still and vacuum tubes. Here, hot water of lower basin is coming from the vacuum tubes; hence it is assumed that, temperature in the lower basin is equal to the temperature of vacuum tubes. Hence, vacuum tube temperature is not considered in the present experiment. Detailed drawing of the present system is shown in Fig. 3.28.

3.13 Main Components used in Double Basin Passive Solar Still with Vacuum Tubes

There are two main components in the present system like vacuum tubes and double basin chamber. They are explained below:
3.13.1 Vacuum Tubes: Vacuum tubes explanation is discussed in (3.7.1).

3.13.2 Double basin Passive Solar Still

A schematic diagram of present solar still is as shown in Fig. 3.29. It is consists of two chambers like upper basin and lower basin. Lower basin is attached with vacuum tubes and upper basin attached with lower basin for getting heat and upper basin is exposed to sunlight. It is consists of two glass covers and one basin liner. First glass cover is kept upper side of the upper basin and second glass cover is kept between lower and upper basin. Second glass cover transfers the excess heat of lower basin towards the upper basin for enhancement of water temperature of the upper basin.
Other components are solenoid control valve, suryampai, thermocouples, data logger and distillate jar. They all are explained in (3.2.2) to (3.2.6).

3.14 Thermal Modeling of Double basin Solar Still with Vacuum Tubes

The following assumptions have been made for thermal analysis of the double basin solar still with vacuum tubes:

- The system is in a quasi-steady state condition.
- There is no vapour leakage.
- There is no temperature gradient along the thickness of glass cover and water column.
- The heat capacity of the glass covers, insulation and the flowing water is negligible.
- The radiative, convective and evaporative heat losses are linearized during the time interval $\Delta t = t_0$.
- The time interval $(\Delta t)$ is small, i.e. $\Delta t = 3600$ s for the present experiment.
- The heat transfer coefficients are constant during the $(\Delta t)$ time interval.
- The physical properties of the water and vapour are constant in the operating temperature range of the present system.
Fig. 3.30 Flow chart of computer model for double basin solar still with vacuum tubes for measurement of inner glass cover thickness, water temperature and distillate output of lower and upper basin.

Energy balance for various components of the double basin passive solar still with vacuum tubes is given below. Fig. 3.30 shows a computer model for theoretical values of the present still. Procedure of theoretical values remains same as explained in earlier passive solar still.


![Diagram of energy balance for upper glass cover](image)

Fig. 3.31 Energy balance of upper glass cover in double basin passive solar still with vacuum tubes
The energy gained by the upper glass cover (from the sun and convective, radiative and evaporative heat transfer from water to glass) was equal to the summation of energy lost by radiative heat transfer between glass and sky, convective heat transfer between glass and sky and energy gained by glass cover. Hence, the energy balance of upper glass cover is shown in Fig. 3.31.

\[ \alpha_w' I(t)_s + h_1' (T_w' - T_{ci}') = h_2' (T_{ci}' - T_a) \]  

(3.50)

\[ \alpha_w' I(t)_s + h_1' T_w' - h_1' T_{ci}' = h_2' T_{ci}' - h_2 T_a \]  

(3.51)

\[ T_{ci}' = \frac{\alpha_w' I(t)_s + h_1' T_w' + h_2 T_a}{h_1' + h_2} \]  

(3.52)


![Energy balance of upper basin water mass in double basin solar still with vacuum tubes](image)

Fig. 3.32 Energy balance of upper basin water mass in double basin solar still with vacuum tubes
Energy gained by the upper glass cover (from sun and convective, radiative and evaporative heat transfer from water to glass and convective heat transfer of lower basin) was equal to the summation of energy lost by radiative heat transfer between glass and sky, convective heat transfer between glass and sky and energy gained by glass. Hence, energy balance of water inside upper basin is shown in Fig. 3.32.

\[ \alpha_w I(t) + h^\prime_2 (T_{ci} - T_w) = m_w C_{pw} \frac{dT^\prime_w}{dt} + h^\prime_1 (T^\prime_w - T^\prime_{ci}) \]  

(3.53)


The energy gained by the lower glass cover (from sun and convective heat transfer between water and glass, radiative heat transfer between water and glass, evaporative heat transfer between water and glass) is equal to the energy lost by convective heat transfer between lower glass cover to upper basin glass cover. Hence, the energy balance of lower glass cover is given below.

\[ h^\prime_1 (T^\prime_w - T^\prime_{ci}) = h^\prime_2 (T^\prime_{ci} - T^\prime_w) \]  

(3.54)

\[ h^\prime_1 T^\prime_w - h^\prime_1 T^\prime_{ci} = h^\prime_2 (T^\prime_{ci} - h^\prime_2 T^\prime_w) \]

\[ T^\prime_{ci} = \frac{h^\prime_1 T^\prime_w + h^\prime_2 T^\prime_{ci}}{h^\prime_1 + h^\prime_2} \]  

(3.55)


The energy received by water in the lower basin (from sun and base) is equal to the summation of energy lost by convective heat transfer between water and glass, radiative heat transfer between water and glass, evaporative heat transfer between water and glass and energy gained by water. Hence, the energy balance of lower water mass is shown in Fig. 3.33.

\[ \alpha^\ast_w I(t) + Q_w + h^\prime_3 (T_b - T_w) = m_w C_{pw} \frac{dT^\prime_w}{dt} + h^\prime_1 (T^\prime_w - T^\prime_{ci}) \]  

(3.56)

Where,
\[ Q_u = F_R(\alpha \tau) \varepsilon(t) - U_L C \left( \frac{A_L}{A_E} \right)(T_w - T_a) \]  

\[ (3.57) \]

Fig. 3.33 Energy balance of upper lower basin water mass in double basin solar still with vacuum tubes


Solar radiation absorbed by the basin liner is equal to the sum of heat transferred to the water by convection and heat transferred from basin side surface to the ambient. Here, side loss is small
hence; it is not taken into consideration. Hence, energy balance of basin liner is shown in Fig. 3.34.

\[
\alpha_b^* I(t) = h_i (T_b - T_w) + h_b (T_b - T_w) \\
T_b = \frac{\alpha_b^* I(t) + h_i T_w + h_b T_a}{h_w + h_b}
\]

After obtaining expression for \(T_{ci}'\) and \(T_{ci}\) from Eq. (3.52) and (3.55) put it in (3.53)

![Diagram of energy balance of basin liner in double basin solar still with vacuum tubes]

Fig. 3.34 Energy balance of basin liner in double basin solar still with vacuum tubes
\[ \alpha_w' I(t) + h_2' \left[ \frac{\alpha'_s I(t) + h_1 T + h_2 T'}{h_1 + h_2} \right] = m_w' \frac{d(\alpha_0')}{dt} \] 

Divide the whole equation by \( m_w' C_{pw'} \)

\[ \frac{\alpha_w' I(t)}{(m_w' C_{pw'})} + \frac{h_2' \left[ \frac{\alpha'_s I(t) + h_1 T + h_2 T'}{h_1 + h_2} \right]}{(m_w' C_{pw'})} = \frac{m_w' \frac{d(\alpha_0')}{dt}}{(m_w' C_{pw'})} \]

Hence, Eq. (3.61) can be rearranged as:

\[ \frac{dT}{dt} + aT = f(t) \] 

where,

\[ f(t) = \frac{(\alpha T)_{df} I(t) + U_T T}{(MC)_w} \] 

where,

\[ (\alpha T)_{df} = \alpha_w' + \alpha'_s \frac{h_1 h_2'}{h_1 + h_2} \]

where,

\[ a = \frac{U_L'}{(m_w' C_{pw'})} \]

Where, \( U_L' = U_b' + U_L' \)

where,

\[ U_b' = \frac{h_1 h_2'}{h_1 + h_2} \]

\[ U_T' = \frac{h_1 h_2'}{h_1 + h_2} \]

Approximate solution of Eq. (3.62) is

\[ T_w = \frac{f_0}{a_0} (1 - e^{a_0 t}) + T_{w0} e^{-a_0 t} \]
Now for determining equation for lower basin, put values in (3.56)

\[ \alpha''_w I(t)_s + h_3(T_b - T_w) + Q_w = (MC)_w \frac{dT_w}{dt} + h_1(T_w - T_a) \]  

(3.68)

\[ \alpha'_w I(t)_s + h_3 \left[ \alpha'_3 I(t)_s + \frac{h_2 T_b + h_3 T_w}{h_3 + h_b} \right] - T_w + F_R \left[ (\alpha \tau)_c I(t)_c - U_{\text{LC}} \left( \frac{A_L}{A_{\text{ET}}} \right) (T_w - T_a) \right] =  \]

(3.69)

\[ (MC)_w \frac{dT_w}{dt} + h_1(T_w - \left[ \alpha'_3 I(t)_s + \frac{h_2 T_b + U_{\text{eff}} T_w}{U_{\text{eff}} + h} \right]) \]

(3.69) can be rearranged as

\[ \left( \frac{U_{\text{eff}} h_2}{U_{\text{eff}} + h_2} \times \frac{h_1 h_b}{h_3 + h_b} + F_R A_L U_{\text{LC}} \right) T_a = \frac{dT_w}{dt} + \left[ \left( \frac{U_{\text{eff}} h_2}{U_{\text{eff}} + h_2} \times \frac{h_1 h_b}{h_3 + h_b} \right) + F_R A_L U_{\text{LC}} \right] \]

(3.70)

Using equation (3.70), one can get first order differential equation is obtained, and equation is as follows:

\[ f(t) = \frac{dT_w}{dt} + aT_w = \frac{dT_w}{dt} + aT_w = f(t) \]  

(3.71)

Where,  \( f(t) = \left[ \frac{L_{\text{eff}} + U_{\text{eff}} T_a}{(MC)_w} \right] \) and  \( a = \left[ \frac{U_{\text{eff}}}{(MC)_w} \right] \)

(3.72)

Expressions for \( L_{\text{eff}} \) and \( U_{\text{eff}} \) are given in appendix II.

### 3.15 Approximate Solution of \( T_w \) for Double Basin Solar Still with Vacuum Tubes

The approximate solution of \( T_w \) for double basin solar still with vacuum tubes is given below:

\[ T_w = \frac{f(t)}{a} \left[ 1 - \exp(-a \Delta t) \right] + T_{w0} \exp(-a \Delta t) \]  

(3.73)

The following assumptions have been made for the solution of Equation (3.24):

1. The time interval \( \Delta \) (0 < \( t < \Delta \)) is small.
2. \( a \) is constant during the time interval \( \Delta t \).
3. The function \( f(t) \) is constant, i.e. \( \bar{f}(t) = f(t) \) for the next time interval \( \Delta t \) for time interval between 0 and \( t \).
The rate of mass of distilled water obtained from the lower and upper basin can be determined as:

\[
m_{\text{lower}} = \frac{h_{ew} (T_w - T_{ci})}{L} \times 3600, \text{kg/m}^2\text{h} \tag{3.74}
\]

\[
m_{\text{upper}} = \frac{h'_{ew} (T_w' - T_{ci}')}{L} \times 3600, \text{kg/m}^2\text{h} \tag{3.75}
\]

Hence, Total distillate output is given by:

\[
m = m_{\text{lower}} + m_{\text{upper}} \tag{3.76}
\]
3.16 Experimental Set up of Various Energy Storage Materials on Top Basin of Double Basin Solar Still with Vacuum Tubes

Fig. 3.35 Experimental set up of energy absorbing materials with double basin passive solar with vacuum tubes
Fig. 3.36 Schematic diagram of energy absorbing materials inside upper basin of double basin passive solar still with vacuum tubes
Fig. 3.37 Calcium Stone used as Energy Absorbing Materials inside Top Basin of DBSWVT

Fig. 3.38 Black Granite Gravel used as Energy Absorbing Materials inside top basin of DBSWVT
The top basin of double basin passive solar still with vacuum tubes gained lower distillate output compared with lower basin in spite of getting heat from the lower basin. Hence, to increase distillate output of the upper basin, different energy storage materials like pebbles, black granite gravel and calcium stones introduced to decrease the quantity of water and increase the surface area of water for increment in distillate output. The main purpose of using such energy storage materials inside water of the upper basin is to reduce the quantity of water in the basin and increase the surface or exposure area of water. Also such material can act as an energy storage medium during sunshine hours and release of-sunshine hours.

Fig. 3.35 shows the experimental setup of vacuum tubes coupled double basin solar still with energy absorbing materials in top basin. Fig. 3.36 represents a schematic diagram of energy absorbing materials used in the upper basin of vacuum tube coupled double basin passive solar still. Fig. 3.37 shows various energy absorbing materials like pebbles, black granite gravel and calcium stones. Fig. 3.38 shows black granite gravel inside the top basin solar still of double basin passive solar still with vacuum tubes.