CHAPTER III

EXPERIMENTAL SETUP AND PROCEDURE

3.1 GENERAL

Solar energy is the most ancient source and the greatest advantage of solar energy is renewable source of energy compared with other forms. It is clean and can supply drinking water without causing any environmental pollution. In the recent years, a number of models for solar distillation have been presented in literature by various investigators. Mainly, they have single and double slope solar collectors. In either case, they operate on absorbing solar radiation through a transparent cover, usually made of glass, which is then transmitted to the water. The conventional single basin single slope passive type solar still was chosen for this research work due to its simplicity in design and fabrication, easy handling and low cost of water per kg. Further, due to low operation and maintenance cost it is most suitable for the rural areas in this region.

The experimental setup was developed to conduct the experiments in the following five modes of operation namely,

1. Passive Solar Still with Galvanised Iron sheet (PSS - GI)
2. Passive Solar Still with of Black coated Copper sheet (PSS - Cu, B)
3. Passive Solar Still with Black coated Copper sheet with Pebbles (thermal storage) (PSS - Cu, B, S)
4. Passive Solar Still with Black coated Copper sheet with Pebbles and integrated with stainless steel Fins (PSS - Cu, B, S, F)
5. Passive Solar Still with Black coated Copper sheet with Pebbles, stainless steel Fins and Vacuum pump (PSS - Cu, B, S, F, V)
The above solar stills were fabricated and experimentally tested at Jayaraj Annapackiam CSI College of Engineering, Nazareth, Tamil Nadu, India (Latitude: 9°N; Longitude: 77°E and an altitude of 9 m above sea level) throughout the year from April 2011 to March 2012. The details of the experimental setup, instrumentation, experimental procedure and experimental uncertainties are discussed in this chapter.

3.2 DESCRIPTION OF THE EXPERIMENTAL SETUP

Figure 3.1 Schematic of experimental setup

Figure 3.1 shows the schematic of experimental setup. In this work, two passive solar stills with galvanised iron sheet and black coated copper sheet of same basin size were fabricated. Two single basin passive solar stills of size of 0.9 m × 0.3 m of 0.27 m² basin area made up of galvanised iron sheet and black coated copper sheet were fabricated for experimental study. They were made of 1.5 mm galvanised stainless steel sheet/copper sheet. The basin is enclosed inside a wooden box of inner cross section 1050 x 350 x 430 mm and thickness 20 mm. The top of the basin was covered with a transparent glass of 5 mm thick transparency (transmissivity of about 0.88).
The glass was tilted to the angle of latitude of Nazareth, 9° and fixed to ensure maximum transmission of solar radiation into the still enabling condensed vapor to trickle down the trough built in the still basin. The silicon rubber sealant was used to maintain contact between the glass cover and solar still to prevent vapor leaks. The glass cover was sealed with silicon rubber which plays an important role to promote efficient operation as it can accommodate the expansion and contraction between dissimilar materials.

![Figure 3.2 Passive solar stills with GI and black coated copper sheets](image)

Figure 3.2 shows the experimental setup of passive solar stills with GI and black coated copper sheets. All sides and bottom of the solar still were well insulated with thermocol of 25 mm thickness with thermal conductivity of 0.045 W/m K and it was used to minimize the heat loss from the sides and bottom of the basin to the surroundings. An inlet pipe was fixed at the rear side of the solar still and used to supply the brackish/saline water. The distillate water condensed from the glass cover was collected by a collecting vessel fixed to the lower end of the glass cover. Further, a flexible pipe was connected to the collection tray for collecting desalinated water in a narrow necked collecting jar to avoid evaporation during distillate collection.
The entire setup was made of quality material designed to withstand the harsh conditions produced by water and sunlight and it stands on four legs. The design incorporated a supply fill port through which water was added into the still. Purified drinking water was collected from the distilled output collector. There was an overflow port, which would flow out excess water into the still. The contaminated water was poured into the still to partially fill the basin through the supply fill port. Care was taken in adding the water at a slow enough rate to prevent splashing onto the interior of the still glazing or overflowing into the collection trough. Two pipes of 10 mm diameter were fitted to the basin; one for filling the brackish water into the basin and the other for flushing the brackish water out from the basin of the solar still. A condensate channel ran along the lower edges of the glass cover which collected the distillate and carried it outside the still. Thermocouples were fixed in different positions to measure the temperatures of the inside and outside glass cover, solar basin, water, ambient air and vapor. The distillate yield was collected by a jar every hour and weighed in an electronic balance.

The working of the solar still is similar to the natural hydrological cycle. In the solar still, saline water is stored in the basin of the still, where it gets evaporated by means of the sunlight through clear glass. The pure water vapor condenses inside the glass surface and the pure water is collected in the collecting vessel. The incident solar radiation on the glass cover is partially reflected and absorbed by the glass cover and the rest is transmitted into the airtight enclosure of distillation unit. The transmitted radiation comes into contact with the water surface and part of it gets reflected and absorbed in the water mass. Consequently, the water mass gets heated, leading to an increased temperature of water and glass cover. The heat transfer from the water surface to the glass cover takes place mainly by convection, evaporation and radiation. The evaporated water gets condensed over the inner surface of the glass after releasing the latent heat. The condensed water trickles under gravity into the channels provided at the lower end of the glass cover. The distilled water is collected from the distillate channel to an appropriate jar through the plastic or rubber pipe for the end use. The thermal energy received by the inner surface of glass cover is lost to the atmosphere by radiation and conduction heat transfer.

The various factors affecting the productivity of the solar still are solar intensity, wind velocity, ambient temperature, water glass temperature difference and fro
surface area of water, absorber plate area, temperature of inlet water, glass angle and depth of water. The solar intensity, wind velocity and ambient temperature cannot be controlled as they are metrological parameters, whereas the remaining parameters, free surface area of water, absorber plate area, temperature of inlet water, glass angle and depth of water can be varied to enhance the productivity of the solar stills. By considering the various factors affecting the productivity of the solar still, various modifications are being made to enhance the productivity of the solar still.

In this work, the passive solar stills with galvanised iron and black coated copper sheets of same basin size were tested for atmospheric conditions. Then in the passive solar still with black coated copper sheet various modifications were made to enhance the productivity of the still by use of pebbles, introduction of fins and by providing with low pressure of 0.1 bar inside the still basin.

3.2.1 Passive Solar Still with GI Sheet

The material selection and design specification of the passive solar still with GI sheet is shown in Table 3.1.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parts name</th>
<th>Material</th>
<th>Size</th>
<th>Purpose of selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Still outer box</td>
<td>Plywood (Water proof)</td>
<td>1050 x 350 x 430 mm</td>
<td>Low cost and ability</td>
</tr>
<tr>
<td>2</td>
<td>Still basin</td>
<td>Galvanised Iron sheet</td>
<td>900 x 300 x 50 mm 1.5 mm thickness</td>
<td>Low cost and stability</td>
</tr>
<tr>
<td>3</td>
<td>Top glass cover</td>
<td>Glass</td>
<td>1175 x 320 x 5 mm</td>
<td>Highly transparent</td>
</tr>
<tr>
<td>4</td>
<td>Insulation</td>
<td>Thermocol</td>
<td>25 mm thickness</td>
<td>Good Insulator, low cost</td>
</tr>
</tbody>
</table>

Figure 3.3 shows the pictorial view of the passive solar still with galvanised iron sheet of size 900 x 300 x 50 mm and thickness 1.5 mm. The galvanised iron sheet is fabricated into a rectangular tray by sheet metal work of bending and cutting. The galvanised iron sheet is selected for its easy availability at low cost and stability. In order to ensure an efficient capturing of solar irradiation, the absorbing plate is made...
of galvanized iron sheet. The entire assembly is placed on a stand. The experiment is carried out keeping a water depth of 1 cm. During the experiment every day the solar radiation, atmosphere temperature and day time wind speed were also measured. The feed water is changed and the distilled water product measured at 7.00 h every morning. The hourly productivity of fresh water is collected through a collecting vessel and weighed. Day by day the salts deposited are removed manually. Each and every hour the potable water output is measured correspondingly and the prevailing conditions are noted down. Eventually the output of the solar still is increased hour by hour in the mid period of 11.00 h to 14.00 h.

![Image of a solar still with a GI sheet](image)

**Figure 3.3 Passive solar still with GI sheet**

The solar radiation, I(t) after reflection and absorption by the glass cover is transmitted inside the still enclosure. This transmitted radiation is further partially reflected and absorbed by the water mass. The attenuation of solar flux in water mass depends on its absorption and depth. The solar radiation finally reaches the basin, generally known as the basin liner, where it is mostly absorbed. After absorption of solar radiation at the basin liner, most of the thermal energy is converted to water mass and a small quantity is lost to the atmosphere, by conduction. Consequently, the water gets heated, leading to an increased difference of water and glass cover temperatures. The heat transfer takes place by radiation, and
evaporation from the water surface to the glass cover. After releasing the latent heat, the condensed water vapor trickles down the inclined glass cover to an interior collection trough and from there it is collected into the storage container through a distilled output collection port. The thermal energy received by the glass cover, through radiation, convection and latent heat, is lost to the ambient by radiation and convection.

3.2.2 Passive Solar Still with Black Coated Copper Sheet

The material selection, reason for selection and design specification are shown in Table 3.2.

Table 3.2 Specification of the passive solar still with black coated copper sheet

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parts</th>
<th>Material</th>
<th>Size</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Still outer box</td>
<td>Plywood (water proof)</td>
<td>1050 x 350 x 430 mm</td>
<td>Low cost and easy availability</td>
</tr>
<tr>
<td>2</td>
<td>Still Basin</td>
<td>Copper</td>
<td>900 x 300 x 50 mm 1.5 mm thickness</td>
<td>High thermal conductivity</td>
</tr>
<tr>
<td>3</td>
<td>Top Cover</td>
<td>Glass</td>
<td>1175 x 320 x 5 mm</td>
<td>Highly transparent</td>
</tr>
<tr>
<td>4</td>
<td>Insulation</td>
<td>Thermocol</td>
<td>25 mm thickness</td>
<td>Insulation, Low cost</td>
</tr>
</tbody>
</table>

The proper material selection and fabrication of the still basin has a positive effect on the increased basin water temperature. In this work the material used for this second still basin is copper sheet because of its high thermal conductivity. The solar still with black coated copper sheet consists of a shallow rectangular basin made up of copper sheet instead of galvanised iron sheet. Copper has thermal conductivity of 401 comparatively higher than galvanised iron sheet; the rate of heat transfer to water in the still is more. A single basin solar still with copper sheet was designed for the same basin size of 900 x 300 x 50 mm and 1.5 mm thick. The basin is enclosed in a wooden box of inner cross section 1050 x 350 x 430 mm and thickness 20 mm. Plywood is used as outer cover to keep the still basin inside. The gap of 25 mm between the sides of the tray and the wooden box is filled with thermocol to prevent heat loss. Therefore the rate of heat transfer to water in the still is more for the still
basin with copper sheet instead of galvanised iron sheet. Thus the water temperature is increased.

Copper sheet is made into a rectangular tray by sheet metal work of bending and cutting. The effective area of the solar still for saline water is 0.27 m². The inner part of the basin consists of an absorber plate made of copper sheet and painted to form a matt black surface (absorptivity of about 0.98 and emissivity of about 0.08 from absorbed energy). The still basin is insulated from the bottom to prevent heat losses. The solar radiation finally reaches the blackened surface, generally known as the basin liner, where it is mostly absorbed. After absorption of solar radiation at the basin liner, most of the thermal energy is converted to water mass and a small quantity is lost to the atmosphere, by conduction. Figure 3.4 shows the experimental setup consisting of a passive solar still with black coated copper sheet.

![Figure 3.4 Passive solar still with black coated copper sheet](image)

The condensing surface in the still is simply a glass cover. The glass of size 1175 x 320 mm is used as the roof for the still. The top of the basin is covered with a 5 mm thick transparent glass. It should have minimum amount of heat absorption, minimum amount of reflection for solar radiation energy, maximum transmittance for solar radiation energy and high thermal resistance for heat loss.
ambient. As evaporation takes place, the saline water level in the solar still decreases. To compensate the loss of water, for every half an hour, the makeup water is added to the still from the storage tank. Provision is made to change water in the basin. The amount of produced potable water is collected by a jar and weighed. The water produced in solar still is pure water and can be used for cooking, drinking and for industrial usage. The cover is sealed tightly using silicon sealant to reduce the vapor leakage and the basin becomes air tight.

A small feeding tank 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 a floating ball. The outlet is connected to a storage container through a pipe. Provision is made to change water in the stills. The still is filled with the brackish water in a thin layer. The solar still productivity is strongly dependent on the design and operational conditions; the accepted thermal performance is achieved was due to the improved design parameters and optimized operational technique. The solar stills are properly oriented and directly exposed to the solar radiation. The measured parameters and quantities are; the solar radiation intensity ( ) the glass temperature ( ), the basin water temperature ( ) and the ambient air temperature ( ). The remarkable results and visual observations during the initial investigations are due to the accurate adjustments and calibrations. Based on these observations, the system of measurement is carefully established during the testing period; all the key quantities are carefully measured and recorded at a time interval of every 15 working minutes.

The various factors affecting the productivity of solar still are solar intensity, wind velocity, ambient temperature, water-glass temperature difference, free surface area of water, still basin area, temperature of inlet water, glass angle, inside pressure and depth of water. The solar intensity, wind velocity and ambient temperature cannot be controlled as they are metrological parameters, whereas the remaining parameters, free surface area of water, still basin area, temperature of inlet water, glass angle, inside pressure and depth of water can be varied to improve the productivity of the solar still. By considering the various factors affecting the productivity of the solar still, various modifications are being made to enhance the productivity of the solar still. Various aspects such as temperature, productivity are to be measured once every hour and also the percentage of salt concentration is added to w
20% depending upon the water depth into the still basin. For different water levels of basin 1 cm, 3 cm and 5 cm, readings are taken to find the variation in yield. When solar radiation is falling on the solar still, the glass cover is heated. And due to heating of glass cover temperature of the water inside the solar still is increased and it forms vapor. Such vapor has low density so goes upward and sticks to the glass cover i.e., it condenses. And due to slope it goes downward and collects in glass. The water produced in solar still is pure water and can be used for cooking, drinking and for industrial usage.

![Black coated copper sheet](image)

**Figure 3.5 Black coated copper sheet**

The bottom of the basin is usually painted black to absorb the sun’s heat which in turn increases the evaporation rate. Figure 3.5 shows the black coated copper sheet. The copper sheet is painted by red-lead primer then by matt-type black paint.

### 3.2.3 Passive Solar Still with Black Coated Copper Sheet with Pebbles

To store the thermal energy in solar still, some energy storing materials are used. Black rubber, gravel, metallic wiry sponges and surfactant additives are some of the energy storing materials widely used in solar stills. The solar still with pebbles (gravel) is shown in Figure 3.6. To absorb and retain the heat obtained by solar
radiations, sensible heat storage materials like gravels or pebbles are used in this modification to increase the temperature of water. Black Pebbles of 20-30 mm size are used. Pebbles absorb more energy due to its highest volumetric heat capacity. Addition of pebbles in the basin surface increases the water temperature thereby increasing the evaporation rate.

![Schematic of solar still with pebbles](image)

**Figure 3.6 Schematic of solar still with pebbles**

To absorb and retain the heat obtained by solar radiation, heat absorbing materials like stones are placed inside the still as shown in Figure 3.7. The evaporation rate of the water in the solar still is directly proportional to the exposure area of water in the still, absorber area and temperature of water in the basin. Pebble is one of the highest solar thermal energy storage materials as it has high sensible heat. A pebble of uniform diameter 20 mm is used. Addition of pebbles in the basin surface increases the water temperature thereby increasing the evaporation rate. The area productivity of the solar still increases with the increase in absorber area.

Figure 3.7 and 3.5 shows the setup with and without pebbles (heat storage) medium of the still basin. Various aspects such as temperat
should be measured once every hour and also the percentage of salt concentration is added to water like 0%, 10% and 20% depending upon the water depth into the still basin. The different water levels of basin are 1 cm, 3 cm and 5 cm respectively and the experiments are conducted. When sun radiation is coming on the solar still, the glass cover is heated. And due to the heating of glass cover the temperature of the water inside the solar still is increased and it forms vapor. Such vapor has low density, so goes upward and sticks to the glass cover which means it condenses. And due to slope it goes downward and collects in glass. The water produced due to solar still is called pure water.

Figure 3.7 Black coated copper basin with pebbles

3.2.4 Modifications on the Passive Solar Still with Black Coated Copper Sheet with Pebbles and Fins

The schematic and pictorial views of the solar still with black coated copper sheet with fins are shown in Figure 3.8 and 3.9 respectively. The bottom of the rod is joined by brazing at the top surface of the trays. In the present work the productivity is improved by integrating the solar still with fins at the basin plate. The diameter and length of the fins are 10 mm and 50 mm respectively. Totally 30 fins are used. Depending on the level of water in the basin a portion of the fin is used inside the
saline water and remaining is exposed over the water level. The passive solar still with black coated copper sheet with fins and pebbles is shown in Figure 3.10.

Figure 3.8 Schematic of solar still with fins

Figure 3.9 Black coated copper still basin with fins
3.2.5 Passive Solar Still with Black Coated Copper Sheet with Pebbles, Fins and Vacuum Pump

Figure 3.10 Black coated copper still basin with fins and pebbles

Figure 3.11 shows the schematic of vacuum solar still. The boiling of water takes place when the ambient temperature equals that of the vapor pressure of the liquid. If the working pressure inside the still is reduced, then the boiling point of water in the basin is decreased. Due to this, the water evaporates at lower temperature and increases the evaporation rate in turn increases the yield. This will ensure higher rates of evaporation even at low temperatures and hence the increase in efficiency. One more additional feature in the distiller that we propose is the latent heat which is released during condensation to heat up the water at lower temperature. In the design we incorporate a pump which is a simple vacuum pump to reduce air pressure inside the distillation chamber. The operating condition of this still is about 60°C and ensures low heat transfer losses. At this temperature the vapor pressure of water is 0.1 bar. So we need to operate the pump to reduce the pressure to this value and then leave it in the sun for distillation. This will ensure boiling of water inside the still as soon as the temperature reaches 60°C, which is
pretty low and easily achievable by using simple designs. This still is most suitable when there is not ample sunlight. Given the highly erratic supply of sunlight which depends greatly on weather conditions we have to over design it for high factor of safety.

![Diagram of vacuum solar still](image)

**Figure 3.11 Schematic of vacuum solar still**

Figure 3.12 shows the vacuum solar still setup with solar cell. A small sized innovative vacuum pump is fitted with the still to reduce pressure inside the distillation chamber which will be operated intermittently to maintain the vacuum constantly. This pump is driven by a small D.C motor which is powered by a 12 V battery. The battery is charged by a solar cell with renewable energy. At that time a separate condensation chamber is used to condense the vapor leaving through the vacuum pump. Vacuum enables the distillation of water at lower temperature, requires less thermal energy. This experimental setup eliminates the need of larger size still unit. The additional condensation chamber is used to condense and collect the water vapor coming out of the vacuum pump. Around 10-20% of the total distillate output is collected in the additional condensation chamber.
Figure 3.12 Vacuum solar still setup

Figure 3.13 Vacuum solar still setup with solar cell

Figure 3.13 shows the vacuum solar still coupled with vacuum pump set up with solar cell. To drive the vacuum pump motor a D.C supply of 12 V is needed. A 12 V,
5 Amps. Battery is used and it is recharged by a solar cell arrangement as shown in the Figure. As the solar still works in the sunny hours so that charging the battery is not a problem because of the functioning of the solar cell during that time.

### 3.2.5.1 Vacuum Pump – Specification

![Vacuum pump unit](image)

**Figure 3.14 Vacuum pump unit**

A reciprocating piston type vacuum pump is used in our work to produce low pressure inside the still basin. Figure 3.14 shows the vacuum pump unit for fitting in the still basin. A smaller sized motor of 1/16 H.P is mounted over the pump. To drive the motor a D.C supply of 12 V is needed. The motor has the specification of minimum pressure limit of 0.1 bar and speed 300 rpm. It has a capacity of 3 litres per minute. This can be operated intermittently for 30 minutes OFF and 10 minutes ON. The piston has a diameter of 15 mm and stroke length of 25 mm.

The reciprocating piston type vacuum pump consists of two parts namely an electric motor and a pump. The motor windings are mounted over the spindle and placed inside the casing. When the motor is switched on, the current passing through the coil makes the armature to rotate and thus the spindle rotates. Thus the electrical energy is converted into mechanical work. The principle of an electric motor is the
current carrying coil in a magnetic field causes rotation. The spindle is connected with an eccentric through gear wheel arrangement and the eccentric starts rotating. The eccentric rotation makes the smaller sized piston to move up and down inside the cylinder arrangement is shown in Figure 3.15.

Figure 3.15 Pump unit

Figure 3.16 Motor unit
The downward movement of piston creates vacuum inside pump and the suction valve opens and the fluid gets in. The upward movement of piston creates compression of already sucked fluid inside the pump and the delivery valve opens and the compressed fluid gets out. Thus a vacuum is created in the input side. Motor unit of vacuum pump is shown in Figure 3.16.

![Image of vacuum pump unit mounted on the still](image)

Figure 3.17 Vacuum pump unit mounted on the still

In this work, the vacuum pump casing is removed for the ease of fitting. The pump unit is fitted on the inside wall of the still basin and the motor is fitted on the outside wall of the still basin. Vacuum pump unit mounted on the still is shown in Figure 3.17. The motor is connected with a D.C supply of 12 V Battery. The provision is made for battery re-charging. The pump is made operative for 10 minutes continuously and then it is stopped for another 20 minutes and thus the desired low pressure of 10 (0.1 bar) is maintained inside the still basin. The boiling point of water decreases with the decrease of pressure. At 10, the boiling point of water is around 60°C. Thus the boiling of water takes place even at low temperature inside the still basin. Hence the increase in evaporation rate of water and the distillate output. There is an increase in efficiency of the vacuum still working at lower pressure than atmospheric pressure.
The evaporation rate of water and the distillate output of the vacuum still efficiency is higher as the distillate output is more due to vacuum in the morning and evening i.e. during low ambient temperature and it is high in the noon as the ambient temperature is on its peak. Accordingly, the vacuum still efficiency is higher as the efficiency is more due to vacuum in the morning and evening i.e. during low ambient temperature and it is high in the noon as the ambient temperature is on its peak. It is essential to provide necessary arrangement for air tightness and leak proof. For this a smaller still area is fabricated and tested.

3.2.6 Water Storage Tank and Distillate Collection Trays

3.2.6.1 Water Storage Tank

Figure 3.18 Water storage tank

Figure 3.18 shows the water storage tank made up of a white color syntax tank which is used to supply brackish water to the solar still.

3.2.6.2 Distillate Collection Tray

Distillate collection tray is used to store condensed water trickling on the bottom side of the Glass. It has a small opening at the bottom to trip out the condensate as and when required. It is made up of 3” PVC cylindrical pipe 320 mm length of capacity 2 litres. It is placed over a wooden stand which is mounted on the inside outer cover. For this, a portion of the pipe is cut and the sides covered with end cap of same
diameter as shown in Figure 3.19. It has a small opening on the topside for collecting the condensate.

![Figure 3.19 Distillate collection tray](image1.png)

Figure 3.19 Distillate collection tray

Figure 3.20 shows the distillate collection tray (before cutting). The bottom side has a small opening of 10 mm diameter. A tube is inserted and controlled by a valve. By opening and closing this valve the required water level is maintained inside the basin. A small portion of water is always inside this collection tray not to leak out the vapor inside the still basin. The tray is kept inside in such a way that the larger end touches the glass cover and which makes the condensate trickling on the slope of the glass cover to fall inside the distillate collection tray.

![Figure 3.20 Distillate collection tray (before cutti](image2.png)
3.2.6.3 Additional Condensation Chamber

This additional condensation chamber is a vacuum flask normally used in radiator cooling system of cars. It has a capacity of 2 litres and it is made up of PVC and can withstand for high pressure and temperature. Around 1/10\textsuperscript{th} of the total distillate collected is obtained from this chamber. There is a provision if pressure exceeds the safe limit. Figure 3.21 shows the additional condensation chamber which is used for cooling and condensing and collecting the condensate coming from the vacuum pump outlet. The vacuum pump sucks the vapour inside the vacuum still basin in order to maintain low pressure inside the still. This vacuum is allowed to mix with water inside the tank and it is condensed and collected.

![Figure 3.21 Additional condensation chamber](image)

3.3 MEASURING DEVICES

In order to measure the various physical conditions there is a need for certain equipment to trace out the parameter prevail. Basically the ambient temperature is most important, solar radiation from the sun, wind velocity. To measure such factors solar meter, Anemometer, hygrometer are used. Various parameters have to be measured simultaneously and periodically in order to investigate the performance of a solar still e.g. water temperatures, cover temperatures, solar
speed. Temperatures were measured in various positions of the still using thermocouples. For measuring temperatures, Copper-Constantan thermocouples, integrated with a temperature indicator and selector switch are used. Thermocouples are fixed at the following locations: still basin plate, water, inside and outside of the glass cover. To measure solar radiation a calibrated pyranometer is used. Wind velocity is measured by a calibrated vane type digital anemometer and collected water is measured by an electronic weighing machine.

3.3.1 HYGROMETER

A hygrometer is an instrument used for measuring the moisture content in the environmental air in addition a dry bulb indicator is also provided which describes the existing temperature. A hygrometer is shown in Figure 3.22. The evaporation rate is depending upon the prevailing temperature to describe the evaporation rate its most need to have the hygrometer. Two mercury thermometers with a range from 0 to 99.9°C are used to measure the temperatures of the various components of the still system. The above snap which is a hygrometer which we had brought to measure the wet bulb temperature and dry bulb temperature. The wet bulb temperature
indicates the amount of moisture content in the atmospheric air. The thermometer bulb is wrapped by a cotton tie which is dipped inside the water.

### 3.3.2 SOLARIMETER

![Solarimeter Image](image)

**Figure 3.23 Solarimeter**

A solarimeter is also called as Sunmeter and it is used to measure the solar radiation is shown in Figure 3.23. This device measures the instantaneous intensity of radiation in (W/m²), Range 0-1999 Watt/m². The transfer of energy without any contact medium is termed as radiation. It used to measure broadband solar irradiance on a planar surface and is a sensor that is designed to measure the solar radiation flux density (in watts per meter square) from a field of view of 180 degrees. The solar radiation is more essential for energizing the solar still. The intensity of solar radiation was measured with the help of a solarimeter (Suryamapi make). This instrument is manufactured by Central Electronics Ltd., India. The working principle of suryamapi is almost same as pyranometer. As the intensity of the radiation increases, the current induced in the meter varies linearly and accordingly the needle deflects and shows the exact radiation. It was calibrated with the help of a standard pyranometer.
3.3.3 **ANEMOMETER**

An anemometer is a device for measuring wind speed and is a common weather station instrument. It is shown in Figure 3.24. In this process the condensation is takes place on the inner surface of the glass. The cool breeze from outside makes the hot steam inside the solar still to condense. So it is necessary to know about the wind velocity. The yield also depends upon the velocity of wind. The yellow point is pointed against the wind flow; the leaf inside the anemometer would rotate when there’s a flow of wind usually the wind velocity is measured in metre/sec. In this device we can changes the term’s according to our need it also shows the reading in km/h

3.3.4 **THERMOCOUPLLE**

Copper-Constantan (T-type) thermocouples and digital temperature indicator were used to measure the temperature of water, water vapor and condensing cover. When the two ends of thermocouple wires are kept at different temperatures, electromagnetic force is generated, which is proportional to the temperature difference between the two ends of thermocouple. The hot junction of thermocouple
is kept in contact with the place where the temperature is to be measured and other end is connected to digital temperature indicator. Thermocouples used in the experiments were calibrated with the standard Zeal thermometer (0-110 °C).

3.3.5 ELECTRONIC WEIGHING MACHINE

The distillate yield was collected in a narrow necked glass bottle to reduce the evaporation losses. The mass of the distilled water is measured an electronic weighing machine and the output value is adjusted for two digit. The photograph of the electronic weighing machine used in this work is shown in Figure 3.25.

![Figure 3.25 Electronic weighing machine](image)

3.4 EXPERIMENTAL PROCEDURE

The solar still is operated from 7:00 hr to 17:00 hr during the months of April 2011 to March 2012. Brackish or saline water was poured into the basin of the solar still to partially fill the basin. The depth of water in the basin was maintained at 0.01 m, 0.03 m and 0.05 m respectively and the experiments were conducted. During the experiment, various temperatures such as ambient, glass inside, glass outside, vapor, basin, basin water, solar intensity, wind velocity and distillate yield are taken hourly basis and recorded. The above experimental
both the passive solar stills PSS – GI and PSS – Cu, B. The stills are positioned in such a way that the sloping sides always face the sun. The whole experimental setup was kept in the north–south direction, with the inclination of 9°. The solar stills were properly oriented and directly exposed to solar radiation. The measured parameters and quantities were; the solar radiation intensity I(t), the glass temperature (Tg), the basin water temperature (Tw) and the ambient air temperature (Ta). Then the same experimental study is also made over the modified passive solar still with black paint coated copper sheet using pebbles, stainless steel fins and vacuum pump (PSS – Cu, B, S, F, V). During that period, the intensity of solar radiation, temperature of the atmosphere, water, water vapor, glass inside, glass outside and basin, amount of distilled water collected and wind velocity were recorded on hourly basis. The amount of water collected was measured and the same amount of brackish water was added gently through the rear inlet pipe of the solar still in order to maintain a constant water depth. The accumulated yield during the night was measured at 7.00 h (next day) to determine the daily yield of the solar stills.

3.5 EXPERIMENTAL UNCERTAINTIES

Table 3.3 Experimental uncertainties

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Instrument</th>
<th>Range</th>
<th>Accuracy</th>
<th>Expected Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solarimeter</td>
<td>0 - 120</td>
<td>±5</td>
<td>5%</td>
</tr>
<tr>
<td>2</td>
<td>Thermocouple (J-Type)</td>
<td>0 - 100°C</td>
<td>±0.1°C</td>
<td>0.4%</td>
</tr>
<tr>
<td>3</td>
<td>Electronic Weighing Machine</td>
<td>0 – 10 kg</td>
<td>±1 g</td>
<td>2%</td>
</tr>
<tr>
<td>4</td>
<td>Anemometer</td>
<td>0 – 15 m/s</td>
<td>±0.1 m/s</td>
<td>10%</td>
</tr>
<tr>
<td>5</td>
<td>Vacuum gauge</td>
<td>0.01-100</td>
<td>±0.01</td>
<td>1%</td>
</tr>
</tbody>
</table>

The details of the measuring devices such as range, accuracy and expected error are given in Table 3.3. To measure the temperatures of basin plate, saline water, glass and vapor, copper constantine thermocouples (T-type) integrated with a temperature indicator and selector switch were used. To measure solar radiation a calibrated Kipp–Zonen pyranometer was used. An electronic weighing machine of 5 kg capacity was used to measure the hourly yield. Vane type digital anemometer was used to measure the wind velocity. The thermocouples were fixed at the following locations: still basin
plate, basin water, water vapor, inside and outside glass cover. The accuracy of various measuring instruments used during experimentation is given in Table 3.3. The hourly reading of wind velocity, wet bulb temperature, dry bulb temperature, anemometer and pyrometer were tabulated. Experimental uncertainties for all temperatures namely glass inside, glass outside, basin liner, vapor and ambient and yield were also evaluated in similar manner and the values are given in Table 3.4. Moreover, all these experimental uncertainties for the above mentioned parameters for other experimental studies of passive solar still made up of GI and black coated copper sheet and passive solar still with black coated copper sheet using pebbles, fins and vacuum pump have also been evaluated.

Table 3.4 Percentage of uncertainty in measured parameters

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameter</th>
<th>Percentage of uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PSS - GI</td>
</tr>
<tr>
<td>1</td>
<td>Basin water temperature</td>
<td>±4.5</td>
</tr>
<tr>
<td>2</td>
<td>Glass inside temperature</td>
<td>±1.20</td>
</tr>
<tr>
<td>3</td>
<td>Glass outside temperature</td>
<td>±6.00</td>
</tr>
<tr>
<td>4</td>
<td>Basin temperature</td>
<td>±7.44</td>
</tr>
<tr>
<td>5</td>
<td>Vapor temperature</td>
<td>±9.30</td>
</tr>
<tr>
<td>6</td>
<td>Ambient temperature</td>
<td>±2.18</td>
</tr>
<tr>
<td>7</td>
<td>Yield</td>
<td>±2.50</td>
</tr>
<tr>
<td>8</td>
<td>Wind velocity</td>
<td>±2.4</td>
</tr>
<tr>
<td>9</td>
<td>Solar intensity</td>
<td>±4.5</td>
</tr>
</tbody>
</table>

3.6 THERMAL MODELING

The thermal modeling was developed for the passive solar still made up of GI sheet PSS- GI, passive solar still with black coated copper sheet PSS - Cu, B and passive solar still with black coated copper sheet with modifications PSS - Cu, B, S, F, V and results are validated with the experimental results. The following assumptions have been made while writing the energy balance equations

1. There is no vapor leakage in the solar still.
2. The water mass in the solar still basin is assumed to be constant.
3. The evaporative loss of water mass is negligible.
4. The temperature gradient along water mass depth is negligible.
5. The heat capacity of the glass cover and insulating material is negligible.
6. The inclination of the glass cover with horizontal is small.
7. The areas of water surface, glass cover and basin are equal.

3.7 ENERGY BALANCE EQUATIONS

The energy balance equations at various portions of the solar still are described as follows:

The rate of energy gained by the glass and the rate of energy gained from the water surface to the glass by radiation, convection and evaporation are equal to the rate of energy lost to air.

3.7.1 Outside Surface of Glass Cover

Rate of energy received from inner glass cover by conduction = Rate of energy lost to the ambient by convection and radiation

\[ (\text{rate of energy}) \] \hspace{1cm} (3.1) \]

By substituting Equations (2.18) and (2.21) into Equation (3.1), the energy balance equation of the outside surface glass cover becomes,

\[ (\text{rate of energy}) \] \hspace{1cm} \text{(3.2)} \]

By simplifying Equation (3.2), the glass outside temperature is written as,

\[ (\text{temperature}) \] \hspace{1cm} (3.3) \]

3.7.2 Inner Surface of Glass Cover

Rate of energy + Rate of energy received from water mass by convection, = Rate of energy absorbed from solar radiation evaporation and radiation = transferred to glass outside surface
By substituting Equation (2.12) into Equation (3.4), the energy balance equation of
the inside surface of the glass becomes,

\[
\begin{align*}
( & ) & - & ( ) \\
\end{align*}
\]  

(3.5)

By substituting Equation (3.3) into Equation (3.5), the temperature of the inside
surface of the glass is written as,

\[
\begin{align*}
( ) & - ( & - & ) \\
\end{align*}
\]  

(3.6)

By rearranging Equation (3.6), it becomes,

\[
\begin{align*}
( ) & - & ( ) \\
\end{align*}
\]  

(3.7)

where

\[
\begin{align*}
( ) & - & \\
\end{align*}
\]

By simplifying the above equation can be re-written as

\[
\begin{align*}
& ( ) \\
\end{align*}
\]  

(3.8)

3.7.3 Basin Liner

Rate of energy absorbed from solar radiation + Rate of energy lost to water mass by convection = Rate of energy lost to the ambient by conduction and convection

\[
\begin{align*}
( ) & + ( ) & = ( ) \\
\end{align*}
\]  

(3.9)

By substituting Equations (2.21) and (2.22) into Equation (3.9), it becomes

\[
\begin{align*}
( ) & + ( ) & = & ( ) \\
\end{align*}
\]  

(3.10)

After simplifying Equation (3.10), the basin temperature of the solar still is,

\[
\begin{align*}
& ( ) \\
\end{align*}
\]  

(3.11)

where

\[
\begin{align*}
( ) & - & ( ) \\
\end{align*}
\]
3.7.4 Water Mass

<table>
<thead>
<tr>
<th>Rate of energy absorbed from solar radiation</th>
<th>Rate of energy received from basin liner by convection</th>
<th>Rate of energy received from external devices</th>
<th>Rate of energy stored</th>
<th>Rate of energy lost to the glass inner surface by convection and evaporation and radiation</th>
</tr>
</thead>
</table>

\[
\begin{align*}
(\text{Rate of energy absorbed}) & + (\text{Rate of energy received from basin liner by convection}) & + (\text{Rate of energy received from external devices}) & = (\text{Rate of energy stored}) + (\text{Rate of energy lost to the glass inner surface by convection and evaporation and radiation}) \\
& & & & (3.12)
\end{align*}
\]

Substituting Equations (1.12) and (1.21) into Equation (3.12), the energy balance equation of the water mass in the solar still becomes,

\[
(\text{Rate of energy absorbed}) + (\text{Rate of energy received from basin liner by convection}) + (\text{Rate of energy received from external devices}) = (\text{Rate of energy stored}) + (\text{Rate of energy lost to the glass inner surface by convection and evaporation and radiation})
\]

(3.13)

By substituting values of \( g \), \( \dot{Q}_n \), and \( b \) from Equations (3.8) and (3.11) into Equation (3.13), it becomes

\[
(\text{Rate of energy absorbed}) + [\text{Rate of energy received from basin liner by convection}] + [\text{Rate of energy received from external devices}] = [\text{Rate of energy stored}] + [\text{Rate of energy lost to the glass inner surface by convection and evaporation and radiation}]
\]

(3.14)

\[
(\text{Rate of energy absorbed}) + \left[\frac{\text{Rate of energy received from basin liner by convection}}{\text{Rate of energy received from external devices}}\right] = \left[\frac{\text{Rate of energy stored}}{\text{Rate of energy lost to the glass inner surface by convection and evaporation and radiation}}\right]
\]

(3.15)

where

\[
(\text{Rate of energy absorbed}) + \left[\frac{\text{Rate of energy received from basin liner by convection}}{\text{Rate of energy received from external devices}}\right] = \left[\frac{\text{Rate of energy stored}}{\text{Rate of energy lost to the glass inner surface by convection and evaporation and radiation}}\right],
\]

and

\[
\text{Rate of energy absorbed} + \left[\frac{\text{Rate of energy received from basin liner by convection}}{\text{Rate of energy received from external devices}}\right] = \left[\frac{\text{Rate of energy stored}}{\text{Rate of energy lost to the glass inner surface by convection and evaporation and radiation}}\right]
\]

In the case of a passive solar still, additional thermal energy becomes zero, \( \dot{Q}_n = 0 \)

The above equations can be expressed in simplified form as follows:

\[
(\text{Rate of energy absorbed}) + (\text{Rate of energy received from basin liner by convection}) + (\text{Rate of energy received from external devices}) = (\text{Rate of energy stored}) + (\text{Rate of energy lost to the glass inner surface by convection and evaporation and radiation})
\]

(3.16)

where
The following assumptions have been made to find the approximate analytical solution for the above equation:

1. The time interval $\Delta t$ ($0 < t < \Delta t$) is small
2. The value of “$a$” is constant during the time interval $\Delta t$
3. The function “$f(t)$” is constant for the time interval between 0 and $t$, i.e. $\bar{f(t)} = f(t)$

By using the boundary condition, $T_{w(t=0)} = T_{w0}$, the solution for above first order differential equation is

\[
\begin{align*}
\frac{\partial q}{\partial t} &= \frac{\partial}{\partial t} \left( \sum \right) \\
&= \text{(3.17)}
\end{align*}
\]

The hourly yield is given as follows,

\[
\begin{align*}
\frac{\partial q}{\partial t} &= \frac{\partial}{\partial t} \left( \sum \right) \\
&= \text{(3.18)}
\end{align*}
\]

The total daily yield is given as follows,

\[
\begin{align*}
\sum \frac{\partial q}{\partial t} &= \frac{\partial}{\partial t} \left( \sum \right) \\
&= \text{(3.19)}
\end{align*}
\]

3.7.5 **Overall Thermal Efficiency of the Solar Still**

The instantaneous thermal efficiency is calculated as

\[
\begin{align*}
\frac{\partial q}{\partial t} &= \frac{\partial}{\partial t} \left( \sum \right) \\
&= \text{(3.20)}
\end{align*}
\]

The overall thermal efficiency of passive solar still is determined by the following expression:

\[
\frac{\sum \left( \sum \right)}{\sum (3.21)}
\]

where $m_{kw} =$ mass of distillate collected in kg/h

$A =$ Area of the basin in m$^2$
I (t) = Solar radiation with respect to time W/m² and
L = Latent heat of vaporization in KJ/kg.

The still efficiency is defined as the ratio of heat energy used for vaporizing the
water in the basin to the total Solar Intensity of radiation absorbed by the still. The
daily efficiency (\( \eta_d \)) is obtained by summing up the hourly condensate production
\( (m_w) \), multiplied by the latent heat of vaporization (L) and divided by the daily
average solar radiation (I) over the still area \( (A_s) \).

3.7.5.1 Still with Pebbles

The theoretical results are compared with the experimental results and found that
the theoretical results agreed well with the experimental ones. All the above equations
are used for theoretical analysis but in addition to the heat capacity of the basin
\( (M_wC_{p_w}) \), the heat capacity of the pebbles \( (M_pC_{p_p}) \) is also added. The surface area of
basin \( A_b \) is taken as 0.27 m² and the saline water surface \( A_w \) is taken as 0.22 m². The
mass of the pebble taken for experimental analysis is 0.5 kg. The density and specific
heat capacity of the pebble are taken as 2500 kg/m³ and 850 J/kgK respectively.

3.7.5.2 Still with Fins

The area of the basin plate and the area of the free surface water are taken as 0.30
m² and 0.22 m² respectively. Now the mass of the basin plate \( (m_b) \) with fin is taken as
1.5 kg.

3.7.5.3 Still with Vacuum Pump

In this study, a complete vacuum was assumed for the conventional solar still. The
effect of vacuum inside the passive solar still made of black coated copper sheet with
pebbles, fins and vacuum pump (PSS-Cu, B, S, F, V) helps to avoid any heat transfer
due to convection in the still. So, the heat loss from the water in an insulated still is
due to evaporation and radiation only. In the presence of vacuum, the effect of non-
condensable gases (such as air) inside the still which reduces the rate of condensation
is also avoided.

In case of vacuum, the rate of evaporation is found from

\[
\frac{(\ )}{(\ )} \quad (3.22)
\]
Where $P_v$ is vapor pressure (torr), $M$ is molecular weight and $f$ is the sticking coefficient.

A steady state heat transfer through the glass is assumed at the glass cover without any appreciable error. So, $h_v$ is found by,

\[(\quad \quad \quad \quad) (\quad \quad \quad \quad) \quad (\quad \quad \quad \quad) \quad (3.23)\]

Where $\quad$ and $\quad$ are the end of the intervals.

Here, there is a high amount of water evaporation which is not equal to the rate of condensation. The glass cover is considered as a thermal resistance to the heat transfer between the vapor region and the internal surface of the glass cover so that the condensation process is prevented and hence the rate of condensation will not be equal to the rate of evaporation. So the analysis in the case of vacuum is done by using the thermal balance of the glass cover. It is assumed that due to vacuum which reduces the boiling temperature to a very low value, the vapor always exists near the glass cover, but the rate of condensation is found from the glass cover thermal balance equation.

Hence in the case of vacuum, the heat transfer coefficient due to convection becomes zero. Since there is no diffusion of vapor through the air, the evaporation heat transfer coefficient is calculated using the thermal balance equation at the glass cover plays the important role in the water productivity augmentation. The existence of non-condensable gases, such as air, greatly reduces the heat transfer coefficient for condensation. When the vapor containing non-condensable gas condenses, the non-condensable gas is left at the surface and the incoming condensable vapor must diffuse through this body of vapor-gas mixture collected in the vicinity of the condensate layer before it reaches the cold surface to be condensed. So, the existence of the non-condensable gas adjacent to the condensate surface behaves as a thermal barrier to the heat transfer. The condensation heat transfer coefficient is reduced by 50% or more with a few per cent decrease in the volume of air.

Also, the existence of air between the water and glass surfaces causes the vapour evaporated from the water surface to be diffused through the body of vapour-air mixture to reach the glass surface. So, the air is considered as a resistance to the motion of vapour to reach the top surface. The resistance to
causes a drop in the partial pressure of the vapour which, in turn, drops the saturation temperature. The water temperature in the case of vacuum is slightly lower than the water temperature in the case without vacuum. In the case with vacuum, there is more evaporation, hence the water temperature is reduced; but at the same time, the lower temperature of the water causes less heat loss due to radiation from the water surface, increasing the water temperature. Generally, the difference in water temperature between the cases with vacuum and without vacuum is small. The same results are obtained for the glass temperature.

Table 3.5 Design parameters used in thermal modeling

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Area of still</td>
<td>A_s</td>
<td>0.27 m²</td>
</tr>
<tr>
<td>2</td>
<td>Specific heat of water</td>
<td>C_w</td>
<td>4190 J/kg°C</td>
</tr>
<tr>
<td>3</td>
<td>Total mass productivity/day</td>
<td>M_w</td>
<td>2.7 kg</td>
</tr>
<tr>
<td>4</td>
<td>Test duration</td>
<td>t</td>
<td>3600 sec</td>
</tr>
<tr>
<td>5</td>
<td>Absorptivity of water</td>
<td>α_w</td>
<td>0.34</td>
</tr>
<tr>
<td>6</td>
<td>Absorptivity of glass</td>
<td>α_g</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>Absorptivity of basin</td>
<td>α_b</td>
<td>0.36</td>
</tr>
<tr>
<td>8</td>
<td>Glass thickness</td>
<td>L_g</td>
<td>0.005 m</td>
</tr>
<tr>
<td>9</td>
<td>Thermal conductivity of glass</td>
<td>K_g</td>
<td>0.78 W/m°C</td>
</tr>
<tr>
<td>10</td>
<td>Insulation thickness</td>
<td>L_i</td>
<td>0.05 m</td>
</tr>
<tr>
<td>11</td>
<td>Thermal conductivity of thermocol</td>
<td>K_i</td>
<td>0.08 W/m°C</td>
</tr>
<tr>
<td>12</td>
<td>Wind velocity</td>
<td>v</td>
<td>0-6 m/sec</td>
</tr>
<tr>
<td>13</td>
<td>Stefan–Boltzmann constant</td>
<td>σ</td>
<td>5.67×10⁻⁸ W/m²K⁴</td>
</tr>
<tr>
<td>14</td>
<td>convective heat loss coefficient from water</td>
<td>h_w</td>
<td>250 W/m²K</td>
</tr>
<tr>
<td>15</td>
<td>Emissivity effectiveness</td>
<td>e_eff</td>
<td>0.82</td>
</tr>
</tbody>
</table>

A computer model has been developed using MATLAB 10.0 to calculate various heat transfer coefficients, glass temperature, water temperature and hourly yield of solar still, by providing the initial values of water and glass temperature. The solar radiation and ambient temperature values have been taken from the daily experimental observation. The design parameters used for the thermal modeling is given in Table 3.5.
3.7.6 Statistical Analysis

The correlation between the theoretical and experimental results was calculated using the coefficient of correlation (r). The expression is given below.

$$\sqrt{\frac{\sum (x_{i} - \bar{x})(y_{i} - \bar{y})}{\sum (x_{i} - \bar{x})^2 \sum (y_{i} - \bar{y})^2}}$$  \hspace{1cm} (3.24)

The closeness between the theoretical and the experimental results are presented in terms of the root mean square percentage deviation.

$$\sqrt{\frac{\sum (y_{i} - \bar{y})^2}{n}}$$  \hspace{1cm} (3.25)

where

3.8 LIFE CYCLE COST ANALYSIS

The economic payback and the cost per litre on investment are the two important parameters to be verified in the any solar system. The economics of solar distillation system can be improved by the selection of cheap durable materials, proper structure and operation. The life cycle cost analysis of solar still depends on many variables such as initial investment, interest rate, annual distillate yield, maintenance cost, selling price, salvage value and payback period.

The initial investment depends on the system size. In some countries, like India the government provides subsidy or rebate towards the cost of the system, which will obviously improve the economic payback on the purchase. The salvage value of scrap in developed countries is almost negligible, whereas the electricity charges and inflation rates in developing countries are higher than in developed countries.

The better economic return of the investment depends on the production cost of the distilled water and its applicability. The annual cost of the above said solar stills were calculated using annualized life costing method. Annualized uniform cost is defined as a product of present value of the system and capital recovery factor (CRF) and it is expressed as,
\[
\begin{pmatrix}
- & - \\
- & -
\end{pmatrix}
\]  

(3.26)

where \( CR_{i,n} \) \( F \) is a capital recovery factor and \( SR_{i,n} \) \( F \) is known as sinking fund factor. These factors are expressed as:

\[
\frac{1}{(1+i)^n} \quad \text{and} \quad \frac{i}{(1+i)^n} \quad (3.27)
\]

\[
(1+i) \quad (3.28)
\]

The cost of distilled water per kg (CPK) can be calculated by dividing the net annualized cost of the system by annual yield of solar still and it is expressed as:

\[
(\_\_\_) \quad (3.29)
\]

where \( M_{AY} \) is annual yield of the solar still.

The scrap value is considered after 10 years for GI sheet is Rs.30/kg and copper is Rs.450/kg. The scrap value after 20 years for GI sheet is Rs.50/kg and copper is Rs.800/kg.

3.8.1 Capital Cost of Solar Still

The initial capital cost (Ps) investment for purchasing solar still varies for different design, size, types and materials used for construction.

The initial capital cost of passive solar still with GI is expressed as:

\[
(3.30)
\]

The initial capital cost of passive solar still with copper is expressed as:

\[
(3.31)
\]

The initial capital cost of solar still with copper coupled with vacuum pump is expressed as:

\[
(3.32)
\]
3.8.2 Interest Rate

In India, different agencies have proposed the following interest rate (\(i\%\)) for borrowing the fund for promoting the renewable energy system: For house uses, government sector offers subsidized interest rate at 2%,

- For institutional uses, government sector offers subsidized interest rate at 3%,
- For commercial uses, government sector offers subsidized interest rate at 4%,
- Nationalized banks offers the interest rate at 7-8%,
- Private bank offers the interest rate at 11-12%.

Therefore, four interest rates i.e. 4%, 8%, 12% and 16% are considered for this present analysis.

3.8.3 Maintenance Cost

The maintenance of solar still is needed for cleaning of glass cover, removal of salt deposited and maintenance of still basin and vacuum pump. The maintenance cost (\(M_S\)) may be lower by increasing higher water depth and it directly influences the yield of solar still. The maintenance cost of 5%, 10% and 15% of investment cost is expected and has been considered in the economic analysis of solar stills.

3.8.4 Life of the Solar Still

The life of solar still (\(n\)) is the duration in years to produce distilled water successfully. The life of the solar stills purely depends on the materials used, maintenance and local climatic conditions etc. For the present case, the life of the solar stills has been taken as 10 years and 15 years in the economic analysis.

3.8.5 Salvage Value

The salvage value (\(S_S\)) of solar still is the future amount we get by selling the solar still as scrap after completion of its life. In present solar stills, glass cover and outer plywood body does not contributes much for its salvage value. The components made of iron shows better salvage value after completion of life of still. The price of scrap also increases with time due to increase in inflation, which is 4% at present in India. The expected salvage value of each component has been calculated.
3.8.6 Selling Price

The current rate of selling price ($S_p$) of distilled water in the market is 12/kg as bottled water that further depends on the transportation cost. The supply to whole seller will be at lower cost than the market rate. Therefore, selling price of distilled water has been taken as Rs. 2/kg to Rs. 12/kg in the analysis.

3.8.7 Payback Period

The payback period ($n_p$) is the time required to bring the investment cost to zero. In other words, the number of years after which the initial investment become equal to the sum of cash flow is known as payback period and after consideration of interest rate over cash flow.

Initial investment cost of solar still = $P_s$

The annual operation and maintenance cost is taken @ $i\%$ of the initial investment, for all years.

Therefore, the annual operation and maintenance cost, = $M_s$

Cost of minerals added to distilled water, = $C_m$

Average daily productivity of solar still, = $m_{yield}$

Expected life time of the solar still, = $n$

No. of clear days in a year, = $N$

The salvage value of the solar after its life time is assumed to be negligible.

The annual yield ($M_{yield}$) can be calculated by multiplying average daily yield and number of clear days in a year as follows:

\[
(3.33)
\]

The annual revenue ($C_R$) can be determined by multiplying the annual yield ($M_{yield}$) with the difference in cost between selling price ($S_p$) and cost of minerals added to distilled water ($C_m$) per liter.

\[
(3.34)
\]

The annual cash flow (CF) of the solar still is determined by subtracting the annual operation and maintenance cost from the annual revenue. It is assumed that the annual cash flow is same for the entire life time of the solar still.
The cash flow can be expressed as

\[
\sum [ ( ) ]
\]  

(3.36)

If the net cash flow (CFt) at the end of each year is assumed same then,

\[
\sum [ ( ) ]
\]  

(3.37)

where

\[

\]  

The below said equation is used to calculate the payback period (\(n_p\)) of the solar still.

\[

\]  

(3.38)

where \(i\) = Interest rate in fraction

---

**Figure 3.26 Cash flow diagram of the solar still**

The cash flow diagram of the solar still is shown in Figure 3.26. This diagram is considered as revenue dominated cash flow diagram since the main focus is to determine the revenues and benefits realized from the solar still. Therefore, the diagram was constructed by taking the revenues from the solar still in the upward
direction (+ ve) and the expenses incurred by the solar still in the downward direction (- ve) on the time horizon line for 10 years (i.e. assumed life time of the solar still). Figure 3.27 shows the payback period diagram of the solar still for different cases.

![Payback period diagram](image)

**Figure 3.27 Payback period diagram of the solar still for different cases**

**Case 1:** The distilled water is sold at the production rate (CPK), then the annual cash flow is expressed as

(3.39)

**Case 2:** The distilled water is sold at rate of selling price (Sp) other than cost of production, then the annual cash flow is expressed as
Case 3: The distilled water is sold at market price considering interest rate to be zero, then the payback period is expressed as

\[
(3.40)
\]

\[
(3.41)
\]

The results obtained using the above equations are discussed in the next chapter.