CHAPTER-III

METHODS AND MATERIALS -THEORY OF SOLAR DISTILLATION AND DESIGN DETAILS OF A SINGLE SLOPE AND A PYRAMID SOLAR STILL AND SIMULATION MODEL FOR SINGLE SLOPE SOLAR STILL

3.1 INTRODUCTION

Solar still is a device to desalinate impure water like brackish or saline water. It is a simple device to get potable/fresh distilled water from impure water, using solar energy as fuel, for various applications in domestic, industrial and academic sectors.

The first "Conventional" Solar Still plant was built in 1872 by the Swedish Engineer Charles Wilson in the nitrate mining community of Las Salinas which is now in northern Chile. This still was a large basin-type still used for supplying fresh water using brackish feed water to a nitrate mining community. The plant used wooden bays which had blackened bottom using logwood, dye and alum. The total area of the distillation plant was 4,700 square meters. On a typical summer day this plant produced 4.9 kg of distilled water per square meter of still surface, or more than 23,000 liters per day. This first still plant was in operation for 40 years!. Over the past century, literally hundreds of solar still plants and thousands of individual stills have been built around the world.

Many people throughout the world do not have access to clean water. Out of the 2.4 billion people in developing countries, only less than 1.5 billion people do not have access to safe drinking water. The answer to the problem is a Solar Still.

3.2 STILL OPERATION

A Solar still operates on the same principle of rain caused by evaporation and condensation. The water from the oceans evaporates, only to cool, condense, and return to earth as rain. When the water evaporates, it removes only pure water and leaves all contaminants behind. Solar stills mimic this natural process.

Solar still has a top cover made of glass, with an interior surface made of a waterproof membrane. This interior surface uses a blackened material to improve absorption of the sun's rays. Water to be cleaned is poured into the still to partially fill the basin. The glass cover allows the solar radiation (short-wave) to pass into the still, which is mostly absorbed by the blackened base. The water begins to heat up and the moisture content of the air trapped between the water surface and the glass cover increases. The base also radiates energy in the infra-red region (long-wave) which is reflected back into the still by the glass cover, trapping the solar energy inside the still (the "greenhouse" effect). The heated water vapour evaporated from the basin condenses on the inside of the glass cover. In this process, the salts and microbes that were in the original water are left behind. Condensed water trickles down the inclined glass cover to an interior collection trough and out to a storage bottle. The end result is clear water better than the purest rainwater.

The still is poured with water to the desired level at a fixed time either in the evening or morning, and the total water production for the day is collected at regular intervals of 30minutes.The still will continue to produce distillate after sunset also until the water temperature cools down. Feed water should be added each day that roughly exceeds the distillate production to provide proper flushing of the basin water and to clean out excess salts left behind during the evaporation process.

The natural hydrologic cycles involved in the solar distillation process are

1. Transport of vapour to cooler region.
2. Phase transfer form liquid to vapour as a result of heating.
3. Phase reversal in precipitation of snow or mist.
4. Return flow of water to source on melting snow.

3.3 DISTILLATION TECHNOLOGY

Solar stills have proven to be highly effective in cleaning up impure water to safe drinking water. The effectiveness of distillation for producing safe drinking water is well established and recognized. Most commercial stills and water purification systems require electrical or other fossil-fueled power sources. Solar distillation technology produces the same safe quality drinking water as other distillation technologies; only the energy source is different: the sun.

3.4 WATER QUALITY

The distilled water produced by solar distillation is of very high quality, normally better than that sold in bottles as distilled water.It is also aerated, as it condenses in the presence of air inside the still. The water may taste a little strange at first because distilled water does not have any of the minerals which most people are accustomed to drinking. Tests have shown that the stills eliminated all bacteria, and that the incidence of pesticides, fertilizers and solvents is reduced by 75 to 99.5%. This is of great importance for many countries where cholera and other water borne diseases are fatal to mankind.

3.5 ADVANTAGES OF SOLAR DISTILLATION

There are several water sources such as ocean, big lakes, inland sears and underground natural reservoirs containing salt or brackish water. The conventional distillation methods such as multi effect evaporation, thin film distillation and electrolysis are not only energy consuming but are also uneconomical. That is, most of the conventional distillation plants are energy intensive and require scarce electric power or fossil fuel for operation. However, solar energy, being low cost and widespread. Solar energy will become increasingly attractive with time on the cost of the steep rise of conventional fuels. More over solar distillation requires simple technology and maintenance, it can be used at any place without many problems and hence it is a suitable method to get fresh water free of fuel cost.

“Solar stills are the devices which yield drinking water from salty or polluted water with the use of solar energy”.

Solar stills have got major advantages over other conventional distillation / water purification /de-mineralization systems as follows:

- Produces pure water
- No prime movers required
- No conventional energy required
- No skilled operator required
- Possibility of Local manufacturing/repairing
- Low investment
- Can purify highly saline water (even sea water)

3.6 HEAT AND MASS TRANSFER COEFFICIENTS

For the most normal range of operation for a conventional solar still, the most commonly used relationship to evaluate heat and mass transfer coefficients is proposed by Dunkle (1961). The study carried out by Adhikari, et. al., (1995) for verifying the applicability of Dunkle's relationships over a wide range of operating temperatures within a solar still reported that Dunkle's relationships behave well in the lower temperature ranges. So Dunkle's (1961) relationship needs the modification in the higher ranges of temperatures. Thus they proposed a relationship for evaluating heat and mass transfer coefficients including higher temperature ranges as follows.

The convective heat transfer is conveniently considered in terms of four dimensionless parameters namely

Grashof number $Gr = (x_1^3 \rho_f^2 g \beta' \Delta T / \mu_f^2)$ (3.1)

Nusselt number $Nu = (h_{ci} x_1 / k_f)$ (3.2)

Prandtl number $Pr = (C_{pf} \mu_f / k_f)$ (3.3)

Reynolds number $Re = (\rho_f v_f x_1 / \mu_f)$ (3.4)

3.6.1 Internal Heat Transfer Mode

The internal heat exchange modes are classified as convection, evaporation and radiation.

a) Convection

Heat is transported across the bulk of the humid air inside the still by free convection of air. It then releases its enthalpy on coming into contact with the top cover. The coefficient of heat transfer is usually incorporated in the Nusselt number. In case of heat transfer by free convection, the Nusselt number is related to the Grashof and Prandtl number i.e.,

$$Nu = f\,(Gr, Pr)$$

For heat flow against forces of gravity

$$Nu = C\,(Gr\,Pr)^n$$

(i.e) $$h_{ci}\, x_1 / k_f = C\,[(x_1^3 \rho_f^2 g \beta' \Delta T / \mu_f^2)\,(\mu_f C_{pf} / k_f)]^n$$

The values of C and n in the various ranges of values of Gr are:

1. For Gr $> 10^3$, n = 0, C = 1
   (Magnitude of convection is negligible)
2. For $10^4 < G_r > 3.2 \times 10^5$, n = ¼, C = 0.21
   (air flow is laminar)
3. For $3.2 \times 10^5 < G_r > 10^7$, n = $^1/_3$, C = 0.075
   (air flow is in the turbulent regime)

In 1961, Dunkle has chosen the values of physical parameters and find the heat transfer per unit area per unit time between the water surface and top cover due to convection, evaporation and radiation. He found the last range was a suitable one.

$$\text{(ie) } h_{ci}\, x_1 / k_f = 0.075\ [(x_1^3\, \rho_f^2\, g\, \beta'\, \Delta T / \mu_f^2)\, (\mu_f C_{pf} / k_f)]^{1/3}$$

Heat transfer inside the still is predicted by using equation proposed by Malik, et al., (1982). Heat is transported inside the still by free convection of air. It releases its enthalpy upon air, which is coming in contact with the top cover. The heat transfer per unit area per unit time due to convection is

$$Q_{ci} = h_{ci}\,(T_w - T_c)\ \text{W/m}^2 \qquad (3.5)$$

where

$$h_{ci} = 0.884\left[\left(T_w - T_c\right) + \frac{\left(P_w - P_c\right)\left(T_w + 273\right)}{268.9x10^3 - P_w}\right]^{1/3} \qquad (3.6)$$

b) Evaporation

Dunkle connects convective and evaporation heat transfer coefficients. The heat transferred per unit area per time by evaporation from the water surface to the glass cover is given by

$$Q_{ei} = h_{ei}\,(T_w - T_c) \qquad (3.7)$$

$$h_{ei} = 16.273 \times 10^{-3}\, h_{ci}\left(\frac{P_w - P_c}{T_w - T_c}\right)\ \text{W/m}^2 \qquad (3.8)$$

c) Radiation

In the usual analysis of solar stills, the water surface and the top cover are considered as infinite parallel planes. Using Stefan Boltzmann's constant, the heat transfer coefficient is given by,

$$h_{ri} = \sigma\varepsilon[(T_w + 273)^4 - (T_c + 273)^4) / (T_w - T_c)] \quad (3.9)$$

$$Q_{ri} = h_{ri}\,(T_w - T_c) \quad (3.10)$$

Absolute values of the total energy transfer rate are obtained by the addition of the above three main equations. Each of the energy transfer mode can be expressed as a fraction of total energy transferred at given water surface and top cover temperature.

The ratio between the heat of evaporation to the total heat transferred from the water to the cover, depends upon T_w and T_c. Computation of this ratio (S) is given by

$$S = h_{ei} / (h_{ei} + h_{ci} + h_{ri}) \quad (3.11)$$

3.6.2 External Heat Transfer Mode

The external heat transfer modes are classified as convection, radiation and conduction through the base.

a) Convection

The external convection loss from top cover to the outside atmosphere is,

$$Q_{ce} = h_{ca}\,(T_c - T_a) \quad (3.12)$$

where h_{ca} is a function of wind velocity and is given by Duffie and Beckman (1974), as,

$$h_{ca} = 5.7 + 3.8\ V$$

where V is the wind velocity

b) Radiation

The external radiation loss from the top cover to the atmosphere is given by,

$$Q_{re} = \varepsilon\sigma\ [(T_c + 273)^4 - (T_{sky} + 273)^4] \quad (3.13)$$

$T_{sky} = (T_a - 12)$ is the apparent sky temperature for long wave radiation.

c) Bottom and Side Loss Coefficient

Heat is also lost from water from the basin to the ambient by convection and radiation and through the insulation from the bottom and side surface of the basin by conduction. The bottom loss coefficient (Q_{be}) can be written as

$$Q_{be} = h_b\left(T_b - T_a\right) \quad (3.14)$$

where

$$h_b = \left[\frac{L_i}{K_i} + \frac{1}{h_{cb} + h_{rb}}\right]^{-1}$$

The side heat loss coefficient (Q_{se}) can be approximated as

$$Q_{se} = \left(\frac{Q_b \, A_{ss}}{A_s} \right) \tag{3.15}$$

Where,

A_{ss} - is the surface area in contact with water

A_s is the area of the basin of the distiller.

A_{ss} is very small in comparison to A_s for small water depth, hence Q_{se} can be neglected.

The rate of heat loss per meter square for basin liner to ambient can be written as

$$Q_{be} = h_b \left(T_b - T_a \right) \tag{3.16}$$

where

$$h_b = \left[\frac{L_i}{K_i} + \frac{1}{h_{cb} + h_{rb}} \right]^{-1} \tag{3.17}$$

3.7 EFFICIENCY OF SOLAR STILL

The daily distilled water output M (kg/m^2 day) is produced the amount of energy Q_e (J/m^2 day)utilized in vaporizing water in the still over the latent heat of vaporization of water h_v (J/kg). Solar still efficiency (η) is the amount of energy utilized in vaporizing water in the still over the amount of incident solar energy on the still Q_t (J/m^2 day).

These can be expressed as:

Total amount of energy used for evaporation $Q_e = M\,L$

Amount of incident solar energy: $Q_t = I\,A\,t$

Solar still efficiency: $\eta = Q_e / Q_t$

The daily thermal efficiency of the solar still is determined by using the following equation

$$\eta = \frac{ML}{I\,A\,t} \tag{3.18}$$

3.8 THERMOPHYSICAL PROPERTIES

Thermophysical properties such as thermal conductivity, dynamic viscosity, density and latent heat are estimated with equations (3.19) to (3.22) by using experimentally measured temperatures of evaporation and condensation surfaces. These equations are given by Toyoma et al., (1983).

$$k = 0.0244 + (0.7673 \times 10^{-4})\, T_{av} \qquad (3.19)$$

$$\mu = (1.718 \times 10^{-5}) + (4.620 \times 10^{-8})\, T_{av} \qquad (3.20)$$

$$\rho = 353.44 / (273.35 + T_{av}) \qquad (3.21)$$

$$L = 2324.6\, [(1.0727 \times 10^{-3}) - (1.0167 T_{av}) + (1.4087 \times 10^{-4})\, T_{av}^{2} - (5.1462 \times 10^{-6})\, T_{av}^{3} \qquad (3.22)$$

The arithmetic mean of the temperatures of evaporation and condensation surface can be expressed as follows:

$$T_{av} = (T_w + T_c) / 2$$

Similarly the values of Saturation Vapour Pressure are predicted under the expression, which is suggested by Brooker. et al., (1978).

$$P = 6893.03 \exp (54.63 - 12301.69/T' - 5.17 \ln T') \qquad (3.23)$$

where $T' = (1.8T + 491.69)$

The Performance Ratio is calculated using the formula

$$PR = (m_{e,i}\, L) / (I) \qquad (3.24)$$

3.9 DESIGN DETAILS OF A SINGLE SLOPE SOLAR STILL

3.9.1 General Setup of the Still

Single solar still of area 0.75m x 0.75m is designed. The still is filled with the water to a height of 0.05m. Top of the system is covered by a 3 mm transparent acrylic cover. It is air tightened using the cushion supports at the interface between the top cover and the sides of sliding support for uniform landing. Bottom of the still is insulated using sawdust, while the side is insulated with glass wool. The specification of different parts of the still is given below.

3.9.2 Water Storage Basin

The water storage basin of the still is constructed with dimension 0.75m x 0.75m x 0.15m of mild steel. Bottom and sides of the basin are painted with black paint for good absorption of solar radiation. ¼ inch pipe is used for pouring water into the still and it is fixed at the height of 0.25 m from the base on the rear of the still. Another ¼ inch pipe is placed at a height of 0.20 m just below the inlet pipe for the inlet of thermocouples into the still to measure the temperature inside the still. Additionally two more pipes are placed at a height of 0.0505 m and 0.1005 m respectively to maintain the water level inside the storage basin as 0.05 m and 0.10 m respectively.

3.9.3 Water Collection Segment

Water collection segment is placed at the end of the still for collecting the evaporated water and it is of dimension 0.85 m x 0.02 m x 0.015 m. The fine gap between the water storage basin and the water collection segment is sealed using chemical adhesives, in order to protect any water leakage between water collection segment and water storage segment.

The mild steel is bent in the required “U’ shape of dimension 0.85m x 0.02m x 0.015m and is fixed at the inner side of front part of still at the height of 0.14 m.

Strips are provided just above the water collection segment at a distance of 0.005 m from it for the uniform landing of top cover and also to effectively collect the condensed distilled water.

3.9.4 Inlet of the Still

Water inlet provision is given by fixing the one ¼ inch pipe of height 0.25m at the base on the rear side of the still. Water is poured to the basin through this inlet by using the funnel and tubing set up.

3.9.5 Water Circulation Provision

A pair of ¼ inch pipes is fixed on the bottom of the base of the still at diagonally opposite to each other for the circulation of water. These pipes are fused exactly at the corners of diagonal end of the basin.

3.9.6 Acrylic Top Cover

At first the top cover is made up of transparent acrylic sheet of 3mm thickness of transmittance 88%. A 15º slope is maintained for top cover from the rear side to the front side of the still. 3 mm acrylic sheet of area 0.75m x 0.75m is used as top cover for the still. The top cover is placed over the grooves which are provided at all sides for uniform resting.

3.9.7 Glass Top Cover

Since the transparent acrylic cover is bent and becomes brittle due to long exposure to sun light. Hence it is replaced by the transparent glass cover of same dimension as that of acrylic.

3.9.8 Fixation of Top Cover

Small pieces of steel strips are welded at the height of 0.005m from the top surface on the inner side of the still basin. Steel strips of dimension 0.01m x 0.01m are welded at various parts around the inner wall of the still basin so that the top acrylic cover / glass cover lands uniformly and the distilled water are collected freely in the water collection segment. Finally this top cover is bolted air tightly using the cushion supports at the interface between the top cover and the sides of sliding support for uniform landing.

3.9.9 Outer box

The outer box of the still is made up of wood of thickness 4mm with the length 0.85 m and breadth 0.85 m. The height of the outer cover box is made slanting from 0.55 m to 0.30 m. Bushes are placed at the base of the still for uniform landing in the ground. Suitable holes are made at the respective places in the outer cover were the inlet, outlet pipes, distilled water collection pipes and waste water flow pipes points out. Handles are provided at the opposite sides of the outer box for easy handling (movement) of the still.

3.9.10 Insulation

The bottom of the basin is filled with the sawdust up to the height of the 0.15m. The side of the basin is insulated with the glass wool. This insulation is made to reduce the conduction heat loss through the base and sides of the solar still.

The cross sectional view and photographic view of single slope solar still is shown in Fig (3.1) and Fig (3.2).

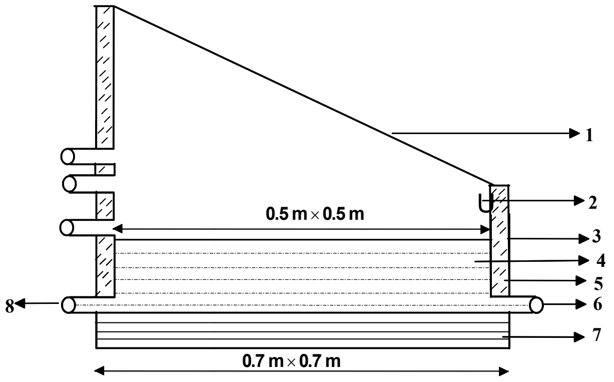

Fig (3.1) Cross sectional view of single slope solar still

1. *Top cover*
2. *Water collection segment*
3. *Wooden box*
4. *Water storage basin*
5. *Glass wool insulation*
6. *Still outlet*
7. *Sawdust insulation*
8. *Still inlet*

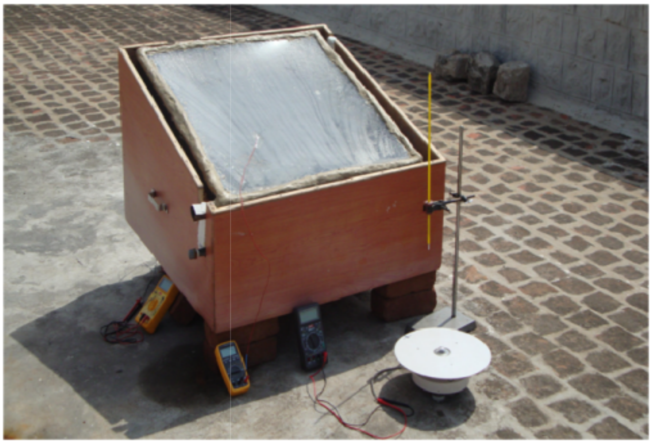

Fig (3.2) Photographic view of single slope solar still

3.10 DESIGN DETAILS OF PYRAMID SOLAR STILL

3.10.1 General Setup of the Still

Pyramid solar still of area 0.75m x 0.75m is designed. The still is filled with the water to a height of 0.05m. Top of the system is covered by a 3 mm transparent acrylic pyramid cover with a height of 0.30m at the middle. It is air tightened using the cushion supports at the interface between the top cover and the sides of sliding support for uniform landing. Bottom of the still is insulated using sawdust, while the side is insulated with glass wool. The specification of different parts of the still is given below.

3.10.2 Water Storage Basin

The water storage basin of the still is constructed with dimension 0.75m x 0.75m x 0.15m of mild steel. Bottom and sides of the basin are painted with black paint for good absorption of solar radiation. ¼ inch pipe is used for pouring water into the still and it is fixed at the height of 0.125 m on the side of the still. Another ¼ inch pipe is placed at a height of 0.1250 m adjacent to the inlet pipe for the inlet of thermocouples into the still to measure the temperature inside the still. Additionally two more pipes are placed at a height of 0.0505 m and 0.1005 m respectively to maintain the water level inside the storage basin as 0.05 m and 0.10 m respectively.

3.10.3 Water Collection Segment

Water collection segment of this system is of dimension 0.75 m x 0.02 m x 0.015 m respectively. Distilled water outlet provision from the water collecting segment is made at diagonally opposite sides by joining two sides collection together. Thus even though there is a water collection segment on all sides of the still, water outlet pipes will be only at the diagonally opposite sides.

The fine gap between the water storage basin and the water collection segment is sealed using chemical adhesives, in order to protect any water leakage between water collection segment and water storage segment.

The mild steel is bent in the required "U' shape of dimension 0.75m x 0.02m x 0.015m and is fixed at the inner side of front part of still at the height of 0.14 m. Strips are provided just above the water collection segment at a distance of 0.005 m from it for the uniform landing of top cover and also to effectively collect the condensed distilled water.

3.10.4 Inlet of the Still

Water inlet provision is given by fixing the one ¼ inch pipe of height 0.125m on the rear side of the still. Water is poured to the basin through this inlet by using the funnel and tubing set up.

3.10.5 Water Circulation Provision

A pair of ¼ inch pipes is fixed on the bottom of the base of the still at diagonally opposite to each other for the circulation of water. These pipes are fused exactly at the corners of diagonal end of the basin.

3.10.6 Acrylic Pyramid Top Cover

At first the top pyramid cover is made up of transparent acrylic sheet of 3mm thickness of transmittance 88%. Pyramid top cover of area 0.75 m x 0.75 m is designed using the 3mm transparent acrylic sheet. It is designed by joining the two portions of the acrylic sheet. Two pieces of molded acrylic sheets are joined by using cyanoacrylate adhesive. The top cover is placed over the strip provision provided at all sides for uniform resting over the water collection segment. The distance between the top of the pyramid to the centre of surface area is 0.30m. Since the cover become brittle due to the long exposure to sun, it is replaced by a glass top cover.

3.10.7 Glass Pyramid Top Cover

Acrylic top pyramid cover is replaced by 3mm thickness of transparent glass. Glass pyramid top cover of area 0.75 m x 0.75 m is designed using the 3mm transparent glass material. It is designed by joining the four side by chemical adhesive (cyanoacrylate) and Silicon adhesive. The top cover is placed over the strip provision provided at all sides for uniform resting over the water collection segment. The distance between the top of the pyramid to the centre of surface area is 0.30m.

3.10.8 Fixation of Top Cover

Small pieces of steel strips are welded at the height of 0.005m from the top surface on the inner side of the still basin. Steel strips of dimension 0.01m x 0.01m are welded at various parts around the inner wall of the still basin so that the top acrylic pyramid cover lands uniformly and the distilled water are collected freely in the water collection segment. Finally this top cover is bolted air tightly using the cushion supports at the interface between the top cover and the sides of sliding support for uniform landing.

3.10.9 Outer box

The outer box of the still is made up of wood of thickness 4mm with the dimension 0.85m x 0.85m x 0.30m. Bushes are placed at the base of the still for uniform landing in the ground. Suitable strips are made at the respective places in the outer cover were the inlet, outlet pipes, distilled water collection pipes and waste water flow pipes points out. Handles are provided at the opposite sides of the outer box for easy handling (movement) of the still.

3.10.10 Insulation

The bottom of the basin is filled with the sawdust up to the height of the 0.15m. The side of the basin is insulated with the glass wool. This insulation is made to reduce the conduction heat loss through the base and sides of the solar still.

The cross sectional view and photographic view of pyramid solar still is shown in Fig (3.3) and Fig (3.4).

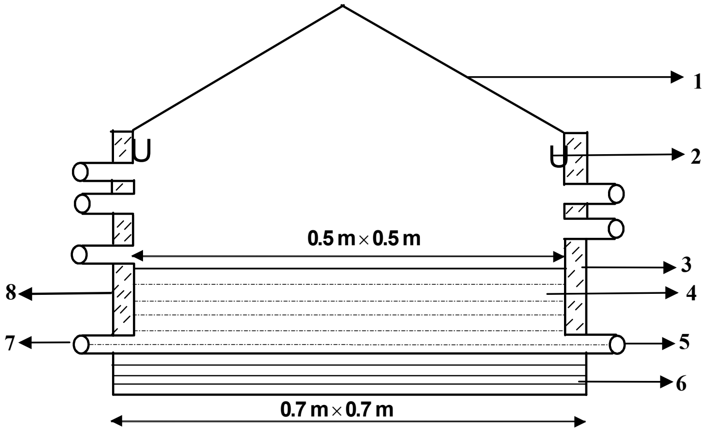

Fig (3.3) Cross sectional view of pyramid solar still

1. *Top cover*
2. *Water collection segment*
3. *Glass Wool Insulation*
4. *Water storage basin*
5. *Still outlet*
6. *Sawdust insulation*
7. *Still inlet*
8. *Wooden box*

Fig (3.4) Photographic view of pyramid solar still

3.11 ELECTRICAL BACKUP:

Electrical backup is made using the circuit as shown in Fig (3.5). Here external temperature controller is connected in between the one side of the coil to control the temperature in it.

Water temperature can be varied by adjusting the input values of the temperature controller. Once if the fixed temperature is attained, circuit open, hence the flow of current is prevented, which results in halt of heat produced in water. When the water temperature drops below the fixed temperature, circuit is switched on and it results in heating of water.

Thus temperature controller circuit switches on and off when the water temperature neutralizes or falls below the fixed temperature. As a result water temperature is maintained always at the fixed set value.

3.11.1. Construction of Electrical Backup

Electrical backup made up of

- Temperature controller,
- Heater coil,
- Thermocouple.

Temperature controller has various plug-in from number 1 to number 20. For temperature controller setting plug-in 1, 2, N1, C, N0, 12 and 13 are used. Temperature of the controller unit can be kept at any temperature by using the set key function (4 digit display), which has two buttons to increase and decrease the temperature. Connections from plug-in 2 and C are interconnected and used as one end of input power supply. Pug-in 1 is used as another end of power supply input. Also a connection is taken from Plug-in 1 and it is connected to one end of the coil. Plug-in N0 is connected to another end of coil. Plug-inn's 12 and 13 are connected to thermocouples. Heater coil is made up of stainless steel and is placed inside the solar still. Sensor thermocouple should be placed near to the heater coil. Schematic representation of electrical backup circuit with temperature controller is shown in Fig (3.5).

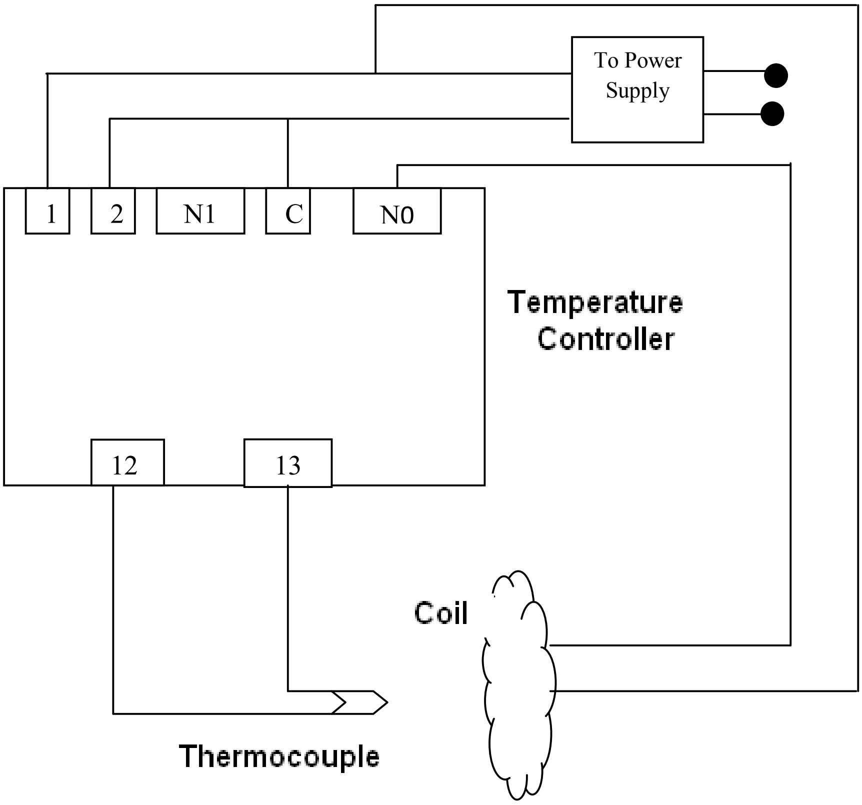

Fig (3.5) Electrical Back Up

Since controller switch is connected to input power supply, once when the fixed temperature is attained, the circuit collapses. As a result power supply is shut down. When the temperature falls below the set value, circuit is switched on and the current flows through the coil, hence it starts heating.

Fig (3.6) and Fig (3.7) shows the experimental set up of the solar still coupled with electrical temperature controller.

Fig (3.6) Experimental Set Up of the Pyramid Solar Still With Electrical Temperature Controller

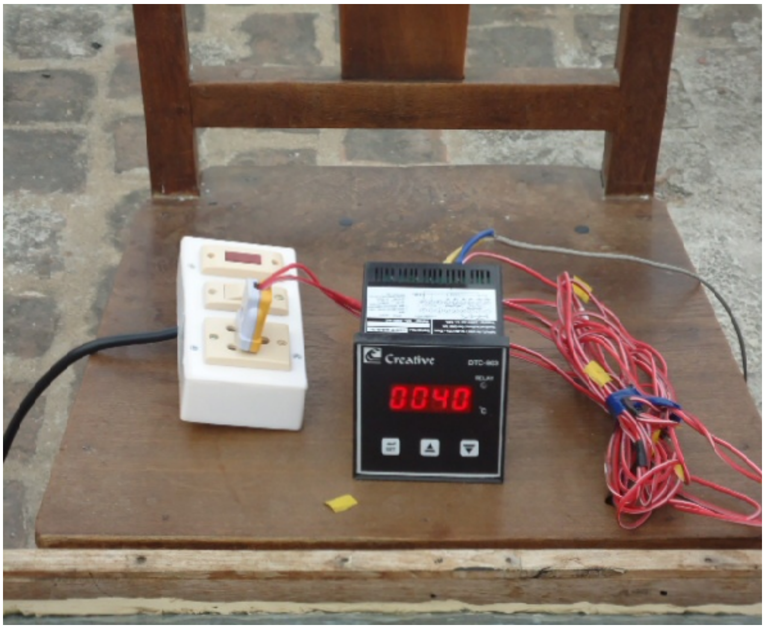

Fig (3.7) Electrical Temperature Controller

3.12 PERFORMANCE EVALUATION

The single slope / pyramid cover solar still was kept facing south on the terrace of the Physics laboratory building of Avinashilingam Deemed University, Coimbatore, where the latitude is 11º00'N and longitude 79º59'E. The stills were evaluated for condensate output with and without thermal absorbing materials. Two sensible energy storage materials namely tar coated blue metal and a phase change material (paraffin wax) kept in a chamber were used for performance evaluation of the stills. The observations desired for analyzing the performance of the stills are measurement of temperature profiles such as water temperature, cover temperature, inside air temperature and ambient temperature, total solar insolation and distillate water output. Evaluation also includes the computation of hourly thermal efficiency and daily average thermal efficiency.

The physical and chemical analysis of the distillate yield was also conducted to assess the quality and purity of water and also for economic analysis for desalination cost.

3.13 EXPERIMENTAL STUDY

The performance of the stills had been carried out on clear sunshine for a number of days.In three consecutive summer seasons (April-June) of 2010 to 2012.Intermittant testing and measurements were also carried out every month on clear sunny days of this period throughout with and w/o storage. The following observations are taken for analyzing the performance of both the stills. The observations carried out are measurement of temperature profiles, total solar insolation and distillate water output, including nocturnal output. These observations are made from 9:00 am to 5:00 pm for every half an hour intervals on selected clear sunny days. To compute the nocturnal output, (from 5:00 pm to 6:00 am) observations were carried out on selected days with and without thermal storage materials.The Pyramid solar still is also coupled to an electrical temperature controller unit and the distillate out put was calculated at desired temperatures 40^0C,50^0C,60^0C by keeping the system unexposed to sunshine,both during day and night time and the results are recorded in tables (4.4) & (4.5)

3.14 MEASUREMENT OF TEMPERATURE PROFILES

The ambient temperature was noted continuously from 9:00 am to 5:00 pm at an interval of half an hour with the help of sensitive thermometer which is fixed near the still. Temperatures of water and glass cover were measured by placing the pre-calibrated k-type thermocouples connected to probes of digital multimeter with thermal display in degree Celsius. Thermocouples are placed at water at two different heights (1cm and 3cm) to measure the water temperatures inside the basin. Similarly, air temperatures inside the still is measured by placing the thermocouple at a height of 22cm, and the cover temperature is measured by the thermocouple fixed at the outer surface of the cover. It is assumed that the temperature of top glass cover is uniform, due to the small thickness of the glass cover. All the temperature measurements are carried out with and without thermal absorbing material of tar coated blue metal and phase change material (paraffin wax) on different days of sunshine and the best observations were recorded.

3.15 TOTAL SOLAR INSOLATION MEASUREMENT

The total solar insolation incident on the acrylic cover was measured at an interval of half an hour from 9 am to 5 pm using a pyranometer. The Pyranometer readings are measured in terms of millivolts (mV) and then converted into watt/m^2.

The value of solar insolation in mV is converted to watt/ m^2 by multiplying the solar insolation in mV with the conversion factor 1000/12.64

12.64 mV = 1000 W/m^2

1 mV = 1000/12.64 W/m^2

1 mV = 79.11 W/m^2.

3.16 DISTILLATE WATER OUTPUT MEASUREMENT

The volume of distilled water collected from the solar still was measured using the measuring jar graduated in milliliters. Measurement was carried out for the two stills without thermal absorbing material, with thermal absorbing material of tar coated blue metal and with a phase change material (paraffin wax).

3.17 SIMULATION MODEL FOR SINGLE SLOPE SOLAR STILL

Basin-type Solar Still is the most widely studied design of all solar stills. It offers unique advantages in simplicity and ease of operation, which has led to simplified heat and mass transfer relations and energy balance equations for its thermal performance modeling. Most of the work done on solar stills by Cooper (1970), Farid and Hamad, (1993) Hirschmann and Roefler, (1970) has used the expressions for internal heat transfer coefficients as developed by Dunkle (1961) under simulated conditions.

However, these expressions are valid only for small inclinations of condensing cover and low operating temperatures and are independent of the average distance between the condensing and evaporating surfaces. Kumar and Tiwari (1996) have recently developed a model, based on regression analysis, to determine the values of C and n using the experimental data obtained from the stills. This method does not impose any limitations on the determination of expressions for internal heat transfer coefficients.

In this chapter, simulation model for the solar still is developed by solving energy balance equation which would be in the form of partial differential equations under suitable initial conditions. The energy balance equation is solved by using finite difference method to evaluate the water temperature and glass temperature in the still.

3.17.1 Physical Model of a Single Slope Solar Still

Fig (3.8) shows the schematic representation of the one dimensional model of a single slope solar still. This model consists a water storage zone of thickness 'Δx'. Thickness of the air above the water storage basin is 'D'. The total depth of the still is L. The still bottom is well insulated and it acts as an isothermal layer of thickness ΔX_I. X=0 indicates the surface of the still covered by top glazing. Δl is the thickness of the top cover. X=L is separating the water storage basin and insulation.

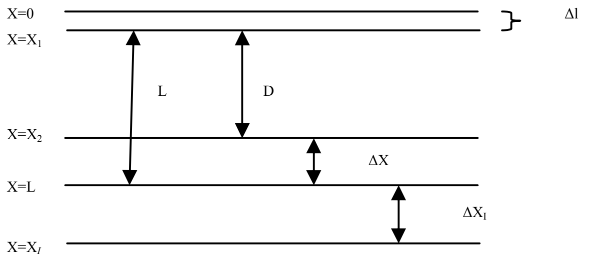

Fig (3.8) Physical Model of a Single Slope Solar Still

3.17.2 Basic Assumption

In writing the heat balance conditions, the following assumptions have been made,

1) The amount of water lost through evaporation is small compared to the amount of saline water in the basin. This is reasonable if the depth of the

water column in the basin is large. If the water column is shallow then the water level may be maintained constant by a steady inflow of saline water at such a rate as to replace the amount of water lost through evaporation. Thus, the mass of saline water in the basin is assumed to be constant in any situation. Further, it is assumed that the heat required to raise the temperature of a particular quantity of the inflowing saline water from ambient to that of water inside the still is negligible compared to the heat required to evaporate the same quantity of water, i.e.,

$C_{pw} (T_c-T_a) << h_v$

This is valid to a good approximation.

2) There is no leakage of water vapor from the still.
3) No temperature gradient exists along the vertical direction in either the top cover or the water in the basin.
4) The surface areas of the top cover, the water surface and the base of the still are equal.
5) The transmittance of the glass cover is not affected by moisture.
6) The wind velocity is constant.
7) All the sides are well insulated.
8) The initial water temperature and ambient temperature are the same.
9) The energy balance is carried out per unit area.

3.17.3 Simulation Model of a Solar Still

- In this case a layer of water of thickness h (Δx) is maintained in solar still basin.
- The simulation is done for water depth of 5 cm thickness respectively.
- The energy balance equation of the solar still is written in the form of finite difference method.
- The initial temperature of the still is assumed as ambient temperature.
- The experimentally measured radiation data is considered for simulation modeling.
- The energy balance equation in all model are solved by involving initial boundary conditions and overall losses.

- The hourly variation of temperature rise in still is predicted by giving number of iteration.

3.17.4 Energy Balance Equation of the Solar Still

A formulation is used to simulate solar still under suitable boundary conditions and to analyze the thermal performance under climatic conditions and ambient temperatures. The energy balance equation is written in the form of the partial differential equation for top cover as

$$M_c C_c\left(\frac{\partial T_c}{\partial t}\right)=\left[\alpha_c \tau_c I(t)+h_{1w}(T_w-T_c)-h_{1g}(T_c-T_a)\right] \tag{3.25}$$

where

$$M_c = A_c d_c \rho$$

$$h_{1w} = h_{ri} + h_{ci} + h_{ei} \quad (Wm^{-2})$$

$$h_{1g} = h_{ca} + \varepsilon_c \sigma \left[\frac{\left(T_c+273\right)^4-\left(T_a+261\right)^4}{T_c-T_a}\right] \quad (Wm^{-2})$$

$$h_{ca} = 5.7+3.8V$$

and the equations for h_{ci}, h_{ei} and h_{ri} are taken from equations 3.6, 3.8 and 3.9 respectively.

The above equation can be written in the form of finite difference form for simulation with initial boundary conditions. The energy balance equation in the form of finite difference equation for the top cover is given by

$$T_{c(i+1)}(c)=T_{ij}(c)+\left(\frac{\Delta t}{M_c C_c}\right)\left\{\left[\alpha_c \tau_c I\right]+\left[h_{1w}(T_w-T_c)\right]-\left[h_{1g}(T_c-T_a)\right]\right\} \tag{3.26}$$

The initial conditions of equations for top cover in solar still is given by

$$T_c\Big|_{initial}=T_c\Big|_{amb}$$

and the boundary conditions is given by

$$T_c\Big|_{x=x1}=T\Big|_{amb}$$

The energy balance equation is written in the form of the partial differential equation for water in the single slope solar still as

$$M_w C_w\left(\frac{\partial T_w}{\partial t}\right)=\left[\alpha\left(I\big|_{x=c}\tau_c-I\big|_{x=L}\tau_w\right)\right]-\left[h_{1w}(T_w-T_c)-h_3(T_{ba\sin}-T_w)\right] \tag{3.27}$$

where

$$M_w = A_s d_w \rho$$

$$h_{1w} = h_{ri} + h_{ci} + h_{ei}$$

$$h_3 = \frac{Ck_f}{x_1}\left[\frac{x_1^3 \rho_f^2 g\beta\Delta T}{\mu_f^2}.\frac{C_{pf}\mu_f}{k_f}\right]^{-1} \quad (Wm^{-2})$$

The above partial differential equation for water in the solar still can be written in the form of finite difference form for simulation with initial boundary conditions. The energy balance equation in the form of finite difference equation for water is given by

$$T_{w(i+1)}(w) = T_{ij}(w) + \left(\frac{\Delta t}{M_w C_w}\right)\left[\alpha(I\big|_{x=c}\tau_c - I\big|_{x=L}\tau_w)\right] - \left(\frac{\Delta t}{M_w C_w}\right)\left[h_{1w}(T_w - T_c) - h_3(T_{ba\sin} - T_w)\right] \tag{3.28}$$

The initial conditions of equations for water in solar still is given by

$$T_w\big|_{initial} = T_w\big|_{amb}$$

$$T_{ba\sin}\big|_{initial} = T_{ba\sin}\big|_{water}$$

and the boundary conditions is given by

$$T_w\big|_{x=L} = T\big|_{water}$$

The amount of distillate per unit area per hour can be given by

$$\dot{m}_e = \left(\frac{h_{ei}(T_w - T_c)}{L}\right) X \;\; 3600 \quad \frac{kg}{m^2 hr} \tag{3.29}$$

3.18 SYSTEM EFFICIENCY

The efficiency of the still is defined as a ratio of useful heat to the total heat input. The hourly performance of the still was studied.

The efficiency of the solar still is

$$\eta = \frac{\text{useful heat}}{\text{total heat input}}(\%).$$

Daily distillate output of the still is $M_e = Q_e / L$

$$\text{Efficiency, } \eta = \frac{M_e \times L}{I \times A \times t}$$

where,

M_e is the distillate output in kg/m^2

I is the solar insolation in w/m^2

t is time in seconds

L is the latent heat of vaporization = 2372000 J/kg

A is the area of the still in m^2

For example if we consider the pyramid solar still, its area is calculated by adding area of four triangular pieces each of base 0.735m and altitude 0.45m adjoined at the apex.

Area of each triangular surface = $\frac{1}{2}$ (bh) m^2

= $\frac{1}{2}$ (0.735 x 0.45) m^2

= 0.165375 m^2

Total area of top cover = 0.165375 x 4

= 0.6615 m^2 (for four sample)

Area of water storage basin = 0.75 x 0.75 m^2

= 0.5625 m^2

An example calculation for the experiment for without storage material for pyramid solar still is given below.

$$\text{Efficiency, } \eta = \frac{M_e \times L}{I(t) \times A \times t}$$

$$= \left(\frac{0.164 \times 2372000}{901.898 \times 0.5625 \times 3600} \right) \times 100$$

Efficiency, η = 21.30%

3.19 THERMAL ANALYSIS OF THE PYRAMID COVER STILL WITHOUT STORAGE MATERIAL

Sample calculation of the thermal analysis of the constructed pyramid cover solar still is as follows.

Readings of the still without thermal storage material:

$T_w = 54.5^o$ C (57 + 52)

$T_c = 45^o$ C

$T_{amb} = 39.5^o$ C

$T_w - T_c = 9.5^o$ C

$T_c - T_{amb} = 5.5^o$ C

$\sigma = 5.67 \times 10^{-8}$

ε = emissivity of the absorbing surface = 0.88
The expression for pressure of the medium is given by

$$P(T) = \exp\left[25.317 - \frac{5144}{T + 273}\right]$$

$$P(W) = P(54.5\,^{o}\,C) = \exp\left[25.317 - \frac{5144}{54.5 + 273}\right]$$

$$\boldsymbol{P_w = 14915.10551}$$

$$P(c) = P(45^{o}\,C) = \exp\left[25.317 - \frac{5144}{45 + 273}\right]$$

$$\boldsymbol{P_c = 9329.151729}$$

$\mathbf{P_w - P_c = 5585.953781}$

3.19.1 Internal heat transfer

3.19.1.1Radiative loss coefficient (h_{rw})

$$h_{rw} = \varepsilon\,\sigma\,[(T_w + 273)^2 + (T_c + 273)^2]\,[T_w + T_c + 546]$$

$\varepsilon = 0.88$

$h_{rw} = 0.88 \times 5.67 \times 10^{-8}\,[(54.5 + 273)^2 + (45 + 273)^2]\,[54.5 + 45 + 546]$

$$\mathbf{h_{rw} = 6.711483587\ w/m^2}$$

$$q_{rw} = h_{rw}\,(T_w - T_c)$$

$= 6.711483587\,(54.5 - 45)$

$$\mathbf{q_{rw} = 63.75909408\ w/m^2\,{}^{o}\,C}$$

3.19.1.2 Convective loss coefficient (h_{cw})

$$h_{cw} = 0.884\left[T_w - T_{ac} + \frac{(P_w - P_c)(T_w + 273)}{268.9 \times 10^3 - P_w}\right]^{1/3}$$

$$h_{cw} = 0.884\left[54.5 - 45 + \frac{(5585.953781)(327.5)}{268.9 \times 10^3 - 14915.10551}\right]^{1/3}$$

$$\mathbf{h_{cw} = 2.259688656\ w/m^2}$$

$$q_{cw} = h_{cw}\,(T_w - T_c)$$

$$q_{cw} = 2.259688656\,(9.5)$$

$$\mathbf{q_{cw} = 21.46704223\ w/m^2\,{}^{o}\,C}$$

3.19.1.3 Evaporative loss coefficient (h_{ew})

$$h_{ew} = 16.273 \text{ x } 10^{-3}\ h_{cw}\ \frac{P_w - P_c}{T_w - T_c}$$

$$= 16.273 \text{ x } 10^{-3} \text{ x } 2.259688656 \text{ x } \frac{5585.953781}{9.5}$$

$$\mathbf{h_{ew} = 21.62170624\ w/m^2}$$

$$q_{ew} = h_{ew}\ (T_w - T_c)$$

$$= 21.62170624\ (9.5)$$

$$\mathbf{q_{ew} = 205.4062093\ w/m^{2\ o}\ C|}$$

3.19.1.4 Total internal heat transfer coefficient (h_{1w})

$$h_{1w} = h_{rw} + h_{cw} + h_{ew}$$

$$= 6.711483587 + 2.259688656 + 21.62170624$$

$$\mathbf{h_{1w} = 30.59287848\ w/m^2}$$

3.19.2 External heat transfer

Since the system is well insulated at the bottom and sides,in the computation of external heat transfer only radiative and convective losses are considered.

3.19.2.1 Radiative heat transfer co-efficient (h_{ra})

$$h_{ra} = \varepsilon_c\ \sigma \left[\frac{(T_c + 273)^4 - (T_{sky} + 273)^4}{T_c - T_{amb}} \right]$$

where, $T_{sky} = T_{amb} - 6$

$T_{sky} = 33.5^o$ C

$T_c = 45\ ^o$ C

T_c - $T_{amb} = 45 - 39.5 = 5.5\ ^o$ C

$$h_{ra} = 0.88 \text{ x } 5.67 \text{ x } 10^{-8} \left[\frac{(54.5 + 273)^4 - (33.5 + 273)^4}{5.5} \right]$$

$$\mathbf{h_{ra} = 24.30168192\ W/m^2}$$

$$q_{ra} = h_{ra}\ (T_c - T_{amb})$$

$$= 24.30168192\ (5.5)$$

$$\mathbf{q_{ra} = 133.6592505\ W/m^{2\ o}\ C}$$

3.19.2.2 Convective heat transfer co-efficient (h_{ca})

$$h_{ca} = 2.8 + 3.10V$$

V = 1.9 m/s

$h_{ca} = 2.8 + 3.0\ (1.9)$

$$\mathbf{h_{ca} = 8.5\ W/m^2}$$

$$q_{ca} = h_{ca}\ (T_a - T_{amb})$$

$q_{ca} = 8.5\ (5.5)$

$$\mathbf{q_{ca} = 46.75\ W/m^{2\ o}\ C}$$

3.19.2.3 Total heat transfer coefficient from top cover to ambient (h_{1a})

$$h_{1a} = h_{ra} + h_{ca}$$

$h_{1a} = 24.30168192 + 8.5$

$$\mathbf{h_{1a} = 32.80168192\ W/m^2}$$

3.19.3 Overall heat transfer

$$U_t = \left[\frac{1}{h_{1a}} + \frac{1}{h_{1w}}\right]^{-1}$$

$$\mathbf{U_t} = \left[\frac{1}{32.80} + \frac{1}{30.59287848}\right]^{-1} \qquad \mathbf{U_t = 15.851126}$$

3.20 THERMAL ANALYSIS OF PYRAMID SOLAR STILL WITH TAR COATED BLUE METAL

Sample calculation of the thermal analysis of the constructed pyramid cover solar still is as follows.

Readings of still with storage material of tar coated blue metal:

$T_w = 49^o$ C (49 + 49)

$T_c = 42^o$ C

$T_{amb} = 38^o$ C

$T_w - T_{ac} = 7^o$ C

$T_c - T_{amb} = 4^o$ C

$\sigma = 5.67 \times 10^{-8}$

ε = emissivity of the absorbing surface = 0.88

$$P(T) = \exp\left[25.317 - \frac{5144}{T + 273}\right]$$

$$P(W) = P(49\,^{o}\,C) = \exp\left[25.317 - \frac{5144}{49+273}\right]$$

$$\mathbf{P_w = 11405.42867}$$

$$P(c) = P(42^{o}\,C) = \exp\left[25.317 - \frac{5144}{42+273}\right]$$

$$\mathbf{P_c = 7997.156099}$$

$\mathbf{P_w - P_c = 3408.27257}$

3.20.1 Internal heat transfer

3.20.1.1Radiative loss coefficient (h_{rw})

$$h_{rw} = \varepsilon\,\sigma\,[(T_w + 273)^2 + (T_c + 273)^2]\,[T_w + T_c + 546]$$

$\varepsilon = 0.88$

$h_{rw} = 0.88 \times 5.67 \times 10^{-8}\,[(49 + 273)^2 + (42 + 273)^2]\,[49 + 42 + 546]$

$$\mathbf{h_{rw} = 6.449209335\ w/m^2}$$

$q_{rw} = h_{rw}\,(T_w - T_c)$

$q_{rw} = 6.449209335\,(49 - 42)$

$$\mathbf{q_{rw} = 45.14446534\ w/m^2\,^{o}\,C}$$

3.20.1.2 Convective loss coefficient (h_{cw})

$$h_{cw} = 0.884\left[T_w - T_c + \frac{(P_w - P_c)(T_w + 273)}{268.9 \times 10^3 - P_w}\right]^{1/3}$$

$$h_{cw} = 0.884\left[49 - 42 + \frac{(3408.272571)(322)}{268.9 \times 10^3 - 11405.4286}\right]^{1/3}$$

$$\mathbf{h_{cw} = 1.981489915 w/m^2}$$

$$q_{cw} = h_{cw}\,(T_w - T_c)$$

$$q_{cw} = 1.981489915\,(7)$$

$$\mathbf{q_{cw} = 13.87042941\ w/m^2\,^{o}\,C}$$

3.20.1.3 Evaporative loss coefficient (h_{ew})

$$h_{ew} = 16.273 \times 10^{-3}\,h_{cw}\,\frac{P_w - P_c}{T_w - T_c}$$

$$h_{ew} = 16.273 \times 10^{-3} \times 1.981489915 \times \frac{3408.27257}{7}$$

$$\mathbf{h_{ew} = 15.69985966\ w/m^2}$$

$$q_{ew} = h_{ew}\,(T_w - T_c)$$

$$q_{ew} = 15.69985966\,(7)$$

$$\mathbf{q_{ew} = 109.8990176\ w/m^2\,{}^{o}C}$$

Now h_{1w}, total internal heat transfer coefficient is given by,

$$h_{1w} = h_{rw} + h_{cw} + h_{ew}$$

$h_{1w} = 6.449209335 + 1.981489915 + 15.69985966$

$$\mathbf{h_{1w} = 24.13055891\ w/m^2}$$

3.20.2 External heat transfer

Since the system is well insulated at the bottom and sides,in the computation of external heat transfer only radiative and convective losses are considered.

The radiative heat transfer co-efficient is given by,

$$h_{ra} = \varepsilon_{ac}\,\sigma \left[\frac{(T_c + 273)^4 - (T_{sky} + 273)^4}{T_c - T_{amb}}\right]$$

where, $T_{sky} = T_{amb} - 6$

$T_{sky} = 32^o\ C$

$T_c = 42\ ^o\ C$

$T_c - T_{amb} = 42 - 38 = 4^o\ C$

$$h_{ra} = 0.88 \times 5.67 \times 10^{-8} \left[\frac{(42+273)^4 - (32+273)^4}{42-38}\right]$$

$$\mathbf{h_{ra} = 14.8683843 w/m^2}$$

$q_{ra} = h_{ra}\,(T_c - T_{amb})$

$= 14.8683843\,(4)$

$$\mathbf{q_{ra} = 59.4735372\ w/m^2\,{}^{o}\ C}$$

$h_{ca} = 2.8 + 3.0V$

$V = 1.9\ m/s$

$h_{ca} = 2.8 + 3.0\,(1.9)$

$$\mathbf{h_{ca} = 8.5\ w/m^2}$$

$$q_{ca} = h_{ca}\,(T_c - T_{amb})$$

$q_{ca} = 8.5\,(4)$

$$\mathbf{q_{ca} = 34\ w/m^2\,{}^{o}\ C}$$

The total heat transfer coefficient from glass cover to ambient (h_{1a}) is given by

$$h_{1a} = h_{ra} + h_{ca}$$

$h_{1a} = 14.8683843 + 8.5$

$$\mathbf{h_{1a} = 23.3683843\ w/m^2}$$

3.20.3 Overall heat transfer

$$U_t = \left[\frac{1}{h_{1a}} + \frac{1}{h_{1w}}\right]^{-1}$$

$$U_t = \left[\frac{1}{23.368} + \frac{1}{24.1305589\!1}\right]^{-1} \quad \mathbf{U_t = 11.934185}$$

3.21 THERMAL ANALYSIS OF PYRAMID COVER SOLAR STILL WITH PARAFFIN WAX

Sample calculation of the thermal analysis of the constructed pyramid cover solar still is as follows.

Readings of still with paraffin wax

$T_w = 33^o$ C (33 + 33)

$T_c = 41^o$ C

$T_{amb} = 35.8^o$ C

$T_w - T_c = -8^o$ C = 8^o C

$T_c - T_{amb} = 5.2^o$ C

$\sigma = 5.67 \times 10^{-8}$

ε = emissivity of the absorbing surface = 0.88

$$P(T) = \exp\left[25.317 - \frac{5144}{T + 273}\right]$$

$$P(W) = P(33\,^o C) = \exp\left[25.317 - \frac{5144}{33 + 273}\right]$$

$$\mathbf{P_w = 4947.029051}$$

$$P(c) = P(41^o C) = \exp\left[25.317 - \frac{5144}{41 + 273}\right]$$

$$\mathbf{P_c = 7591.878944}$$

$$\mathbf{P_w - P_c = 2644.849893}$$

3.21.1 Internal heat transfer

3.21.1.1 Radiative loss coefficient (h_{rw})

$$h_{rw} = \varepsilon\,\sigma\,[(T_w + 273)^2 + (T_c + 273)^2]\,[T_w + T_c + 546]$$

$\varepsilon = 0.88$

$h_{rw} = 0.88 \text{ x } 5.67 \text{ x } 10^{-8} [(33 + 273)^2 + (41 + 273)^2] [33 + 41 + 546]$

$$\mathbf{h_{rw} = 5.946796881 \text{ w/m}^2}$$

$$q_{rw} = h_{rw} (T_w - T_c)$$

$q_{rw} = 5.946796881 (33 - 41)$

$$\mathbf{q_{rw} = 47.57437505 \text{ w/m}^{2\,o} \text{ C}}$$

3.21.1.2 Convective loss coefficient (h_{cw})

$$h_{cw} = 0.884 \left[T_w - T_{ac} + \frac{(P_w - P_c)(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{1/3}$$

$$h_{cw} = 0.884 \left[33 - 41 + \frac{(2644.849893)(306)}{268.9 \times 10^3 - 4947.029051} \right]^{1/3}$$

$$\mathbf{h_{cw} = 1.504921088 \text{ w/m}^2}$$

$$q_{cw} = h_{cw} (T_w - T_c)$$

$$q_{cw} = 1.504921088 (8)$$

$$\mathbf{q_{cw} = 12.0393687 \text{ w/m}^{2\,o} \text{ C}}$$

3.21.1.3 Evaporative loss coefficient (h_{ew})

$$h_{ew} = 16.273 \text{ x } 10^{-3}\ h_{cw} \frac{P_w - P_c}{T_w - T_c}$$

$h_{ew} = 16.273 \text{ x } 10^{-3} \text{ x } 1.504921088 \text{ x } \frac{2644.849893}{8}$

$$\mathbf{h_{ew} = 8.096408166 \text{ w/m}^2}$$

$$q_{ew} = h_{ew} (T_w - T_c)$$

$q_{ew} = 8.096408166 (8)$

$$\mathbf{q_{ew} = 64.77126533 \text{ w/m}^{2\,o} \text{ C}}$$

Now h_{1w}, total internal heat transfer coefficient is given by,

$h_{1w} = h_{rw} + h_{cw} + h_{ew}$

$= 5.946796881 + 1.504921088 + 8.096408166$

$$\mathbf{h_{1w} = 15.54812614 \text{ w/m}^2}$$

3.21.2 External heat transfer

Since the system is well insulated at the bottom and sides, in the computation of external heat transfer only radiative and convective losses are considered.

The radiative heat transfer co-efficient is given by,

$$h_{ra} = \varepsilon_{ac}\,\sigma \left[\frac{(T_c + 273)^4 - (T_{sky} + 273)^4}{T_c - T_{amb}}\right]$$

where, $T_{sky} = T_{amb} - 6$

$T_{sky} = 29.8^{o}$ C

$T_c = 41\ ^{o}$ C

$T_c - T_{amb} = 41 - 35.8 = 5.2^{o}$ C

$$h_{ra} = 0.88 \text{ x } 5.67 \text{ x } 10^{-8} \left[\frac{(41 + 273)^4 - (29.8 + 273)^4}{41 - 35.8}\right]$$

$$\mathbf{h_{ra} = 12.61324066\ w/m^2}$$

$$q_{ra} = h_{ra}\,(T_c - T_{amb})$$

$$q_{ra} = 12.61324066\ (5.2)$$

$$\mathbf{q_{ra} = 65.58885143\ w/m^{2\,o}\ C}$$

$$h_{ca} = 2.8 + 3.0V$$

V = 1.9 m/s

$h_{ca} = 2.8 + 3.0\ (1.9)$

$$\mathbf{h_{ca} = 8.5\ w/m^2}$$

$$q_{ca} = h_{ca}\,(T_c - T_{amb})$$

$q_{ca} = 8.5\ (5.2)$

$$\mathbf{q_{ca} = 44.2\ w/m^{2\,o}\ C}$$

The total heat transfer coefficient from glass cover to ambient (h_{1a}) is given by

$$h_{1a} = h_{ra} + h_{ca}$$

$$h_{1a} = 12.61324066 + 8.5$$

$$\mathbf{h_{1a} = 21.11324066\ w/m^2}$$

3.21.3 Overall heat transfer

$$U_t = \left[\frac{1}{h_{1a}} + \frac{1}{h_{1w}}\right]^{-1}$$

$$U_t = \left[\frac{1}{21.113} + \frac{1}{15.54812614}\right]^{-1}$$

$$\mathbf{U_t = 8.9597557}$$

3.22 DETERMINATION OF DISTILLATE OUTPUT (ml)

The distillate output is observed as well as predicted theoretically with and without thermal storage material.

3.22.1 Determination of distillate output (ml) w/o thermal storage material

Predicted Distillate Output

The predicted distillate output at 12.00 p.m. is given as,

$$M_{ew} = \frac{q_{ew} \times 3600}{L} = \frac{h_{ew}(T_w - T_{ac})}{L} \times 3600$$

$$M_{ew} = \frac{21.30123\ (33-41)}{2372000} \text{x } 3600$$

$\mathbf{M_{ew} = 0.2586172\ Kg/m^2}$

Observed Distillate Output

The observed distillate output at 12.00 p.m.

M_{ew} = 114 ml

= 0.114 litres

M_{ew} = 0.114 Kg

M_{ew} / unitarea = 0.114 / 0.5625

$\mathbf{M_{ew} = 0.20266\ Kg/m^2}$

3.22.2 Determination of distillate output (ml) with tar coated blue metal

Predicted Distillate Output

The predicted distillate output is given by,

$$M_{ew} = \frac{q_{ew} \times 3600}{L} = \frac{h_{ew}(T_w - T_{ac})}{L} \times 3600$$

$$M_{ew} = \frac{25.69985966(49-42)}{2372000} \text{x } 3600$$

$\mathbf{M_{ew} = 0.2730247\ Kg/m^2}$

Observed Distillate Output

The observed distillate output is given by

M_{ew} = 133 ml = 0.133 litres = 0.133 Kg

M_{ew} / unitarea = 0.133 / 0.5625

M_{ew} = 0.2364444 Kg/m^2

3.22.3 Determination of distillate output (ml) with paraffin wax

Predicted Distillate Output

The predicted distillate output is given as,

$$M_{ew} = \frac{q_{ew} \times 3600}{L} = \frac{h_{ew}(T_w - T_{ac})}{L} \times 3600$$

$$M_{ew} = \frac{21.62170624(54.5 - 45)}{2372000} x3600$$

M_{ew} = 0.311746354 Kg/m^2

Observed Distillate Output

The observed distillate output is given by

M_{ew} = 160 ml

= 0.160 litres

M_{ew} = 0.160 Kg

M_{ew} / unitarea = 0.160 / 0.5625

M_{ew} = 0.2844444 Kg/m^2

3.23 DETERMINATION OF THERMAL EFFICIENCY (η)

The thermal efficiency is also observed as well as predicted theoretically with and without thermal storage material.

3.23.1 Determination of thermal efficiency (η) w/o storage material

Predicted Efficiency

$$\eta_{pre} = \frac{M_e \times L}{I(t) \times A \times t} \times 100$$

$$\eta_{pre} = \frac{0.21284 \times 2372000}{905.775 \times 0.5625 \times 3600} \times 100$$

η_{pre} = 27.5246 %

Observed Efficiency

$$\eta_{obs} = \frac{M_e \times L}{I(t) \times A \times t} \times 100$$

$$= \frac{0.183 \times 2372000}{905.775 \times 0.5625 \times 3600} \times 100$$

η_{obs} = 23.6657 %

3.23.2 Determination of thermal efficiency (η) with tar coated blue metal

Predicted Efficiency

$$\eta_{pre} = \frac{M_e \times L}{I(t) \times A \times t} \times 100$$

$$= \frac{0.22105 \times 2372000}{905.775 \times 0.5625 \times 3600} \times 100$$

η_{pre} = 28.5864 %

Observed Efficiency

$$\eta_{obs} = \frac{M_e \times L}{I(t) \times A \times t} \times 100$$

$$= \frac{0.194 \times 2372000}{905.775 \times 0.5625 \times 3600} \times 100$$

η_{obs} = 25.0882 %

3.23.3 Determination of thermal efficiency (η) with paraffin wax

Predicted Efficiency

$$\eta_{pre} = \frac{M_e \times L}{I(t) \times A \times t} \times 100$$

$$= \frac{0.226 \times 2372000}{857.467 \times 0.5625 \times 3600} \times 100$$

η_{pre} = 30.873133 %

Observed Efficiency

$$\eta_{obs} = \frac{M_e \times L}{I(t) \times A \times t} \times 100$$

$$= \frac{0.202 \times 2372000}{857.467 \times 0.5625 \times 3600} \times 100$$

η_{obs} = 27.5945 %

3.24 DETERMINATION OF DISTILLATE GAIN (%)

Distillate gain (%) can be determined using the formula,

$$\text{Distillate gain (\%)} = \frac{M \times L}{A_w \times t} \times 100$$

where,

M is the mass of total distillate / day (8hours) in liters

L is the latent heat in kilojoules

A_w is the surface area of water in m^2

t in seconds for distillate collection

Calculation for distillate gain (%)

Without absorber material

$$\text{Gain (\%)} = \frac{M \times L}{A_w \times t} \times 100$$

$$= \frac{1.6899 \times 2372}{0.75 \times 0.75 \times 8 \times 3600} \times 100$$

Gain (%) = 24.74%

With tar coated blue metal

$$\text{Gain (\%)} = \frac{M \times L}{A_w \times t} \times 100$$

$$= \frac{1.9225 \times 2372}{0.75 \times 0.75 \times 8 \times 3600} \times 100$$

Gain (%) = 28.15%

With paraffin wax

$$\text{Gain (\%)} = \frac{M \times L}{A_w \times t} \times 100$$

$$= \frac{2.2955 \times 2372}{0.75 \times 0.75 \times 8 \times 3600} \times 100$$

Gain (%) = 33.61%

The results of all the sample calculations are presented in the table (3.1), table (3.2) and table (3.3).

Table (3.1): Internal and external heat transfer coefficients of a pyramid cover solar still

Heat transfer coefficients	W/o storage material	With tar coated blue metal	With phase change material (paraffin wax)
h_{rw} (w/m^2)	6.71	6.44	5.94
q_{rw} (w/m^2 ºC)	63.75	45.14	47.57
h_{cw} (w/m^2)	2.25	1.98	1.50
q_{cw} (w/m^2 ºC)	21.46	13.87	12.03
h_{ew} (w/m^2)	21.62	15.69	8.09
q_{ew} (w/m^2 ºC)	205.40	109.89	64.77
h_{1w} (w/m^2)	30.59	24.13	15.54
h_{ra} (w/m^2)	24.30	14.86	12.61
q_{ra} (w/m^2 ºC)	133.14	59.47	65.58
h_{ca} (w/m^2)	8.5	8.5	8.5
q_{ca} (w/m^2 ºC)	46.75	34.00	44.2
h_{1w} (w/m^2)	32.80	23.36	21.11
U_t (w/m^2 ºC)	15.85	11.93	8.95

Table (3.2): Distillate output and efficiency of a pyramid cover solar still

S.No	Specifications	Distillate output (kg)		Efficiency (%)	
		Predicted	Observed	Predicted	Observed
1	W/o storage material	3.2646	3.0043	23.06	21.60
2	With tar coated blue metal	3.7686	3.4178	36.81	35.32
3	With phase change material (paraffin wax)	4.2122	4.0813	34.86	36.61

Table (3.3): Distillate gain (%) of a pyramid cover solar still

S.No	Specifications	Distillate gain (%)
1	W/o storage material	24.74
2	With tar coated blue metal	28.15
2	With phase change material (paraffin wax)	33.61

3.25 TECHNO – ECONOMIC ANALYSIS OF A PYRAMID COVER SOLAR STILL W/O ELECTRICAL BACK UP

The simple techno – economic analysis (Tiwari and Yadav, 1987) of the effectiveness of solar distillation systems considers the capital cost of the system ‘P’ and the rate of capital recovery ‘C’. The first annual cost of the system A’ can be determined by the following formula.

$$A' = \Pr\frac{(1+r)^n}{(1+r)^n - 1}$$

where, r is the rate of interest and n is the life of the system (years)

The salvage value of the system is considered as the cost of usable material saved even after the system’s life is over. The first annual salvage value V can be determined by,

$$V = S \times F$$

where, F a depreciation factor is given by

$$F = \frac{r}{(1+r)^n - 1}$$

If M is the annual maintenance cost of the system then the total annual cost is calculated by A + M – V. The calculation of this analysis for the newly designed pyramid cover solar still of area 0.6615 m^2 is given below.

Calculation

Principal	=	Rs. 5000/-
Expected life span of the system	=	7 years
Rate of interest at 6.5%	=	0.065
Annual maintenance cost M_1	=	Rs. 200/-
Scrap value	=	Rs. 1000/-

FIRST YEAR

The annual cost of the system for the first year,

$$A_1' = 5000 \times \frac{0.065(1+0.065)^7}{(1+0.065)^7 - 1} = 911.7$$

$$\mathbf{A_1' = Rs.\ 912/-}$$

Depreciation factor,

$$F_1 = \frac{0.065}{(1+0.065)^7 - 1}$$

$$\mathbf{F_1 = 0.1173}$$

The annual salvage value for the first year

$$V_1 = S \times F_1$$

$$= 1000 \times 0.1173 = 117.3$$

$$\mathbf{V_1 = Rs.\ 117/-}$$

Total cost for first year

$$= A_1 + M_1 - V_1$$

$$= 912 + 200 - 117$$

$$\mathbf{= Rs.\ 995/-}$$

SECOND YEAR

$\text{Principal} = 5000 - 912 = 4088$

$P_2 = \text{Rs. } 4088/-$

$n = 6 \text{ years}$

$s = \text{Rs. } 1000/-$

$r = 0.065$

$M_2 = 200 + \left(\frac{10}{100}\right)200 = \text{Rs. } 220/-$

The annual cost of the system for second year is given by

$$A_2' = 4088 \times \frac{0.065(1+0.065)^6}{(1+0.065)^6 - 1} = 844.5$$

$$\mathbf{A_2' = Rs.\ 845/-}$$

Depreciation factor is given by

$$F_2 = \frac{0.065}{(1+0.065)^6 - 1}$$

$\mathbf{F_2}$ **= 0.1415**

The annual salvage value for the second year

$V_2 = S \times F_2$

$= 1000 \times 0.1415 = 141.5$

$\mathbf{V_2}$ **= Rs. 142/-**

Total cost for second year

$= A_2 + M_2 - V_2$

$= 845 + 220 - 142$

= Rs. 923/-

THIRD YEAR

Principal = 4088 – 845 = 3243

P_3 = Rs. 3243/-

n = 5 years

s = Rs. 1000/-

r = 0.065

$$M_3 = 220 + \left(\frac{10}{100}\right)220 = \text{Rs. } 242/-$$

The annual cost of the system for the third year is given by

$$A_3' = 3243 \times \frac{0.065(1+0.065)^5}{(1+0.065)^5 - 1} = 780.5$$

A_3' = Rs. 781/-

Depreciation factor is given by

$$F_3 = \frac{0.065}{(1+0.065)^5 - 1}$$

$\mathbf{F_3}$ **= 0.1756**

The annual salvage value for the third year

$V_3 = S \times F_3$

$= 1000 \times 0.1756 = 175.6$

$\mathbf{V_3}$ **= Rs. 176/-**

Total cost for third year

$= A_3 + M_3 - V_3$

= 781 + 242 – 176

= Rs. 847/-

FOURTH YEAR

Principal = 3243 – 781 = 2462
P_4 = Rs. 2462/-
n = 4 years
s = Rs. 1000/-
r = 0.065

$$M_4 = 242 + \left(\frac{10}{100}\right)242 = \text{Rs. } 266/-$$

The annual cost of the system for the fourth year is given by

$$A_4' = 2462 \times \frac{0.065(1+0.065)^4}{(1+0.065)^4 - 1} = 718.7$$

A_4' = Rs. 719/-

Depreciation factor is given by

$$F_4 = \frac{0.065}{(1+0.065)^4 - 1}$$

F_4 = 0.2269

The annual salvage value for the 4th year

V_4 = S x F_4

= 1000 x 0.2269

V_4 = Rs. 227/-

Total cost for fourth year

= $A_4 + M_4 - V_4$

= 719 + 266 – 227

= Rs. 758/-

FIFTH YEAR

Principal = 2462 – 719 = 1743

P_5 = Rs. 1743/-

n = 3 years

s = Rs. 1000/-

r = 0.065

$$M_5 = 266 + \left(\frac{10}{100}\right) 266 = \text{Rs. } 293/-$$

The annual cost of the system for the 5 th year is given by

$$A_5' = 1743 \times \frac{0.065(1+0.065)^3}{(1+0.065)^3 - 1} = 658.2$$

A_5' = Rs. 658/-

Depreciation factor is given by

$$F_5 = \frac{0.065}{(1+0.065)^3 - 1}$$

F_5 = 0.3126

The annual salvage value for the 5th year

V_5 = S x F_5

= 1000 x 0.3126 = 312.6

V_5 = Rs. 313/-

Total cost for fifth year

= $A_5 + M_5 - V_5$

= 658 + 293 – 313

= Rs. 638/-

SIXTH YEAR

Principal = 1743 – 658 = 1085
P_6 = Rs. 1085/-
n = 2 years
s = Rs. 1000/-
r = 0.065

$$M_6 = 293 + \left(\frac{10}{100}\right) 293 = \text{Rs. } 322/-$$

The annual cost of the system for the 6th year is given by

$$A_6' = 1085 \times \frac{0.065(1+0.065)^2}{(1+0.065)^2 - 1} = 596.0$$

A_6' = Rs. 596/-

Depreciation factor is given by

$$F_6 = \frac{0.065}{(1+0.065)^2 - 1}$$

F_6 = 0.4843

The annual salvage value for the 6^{th} year

V_6 = S x F_6

= 1000 x 0.4843 = 484.3

V_6 = Rs. 484/-

Total cost for sixth year

= $A_6 + M_6 - V_6$

= 596 + 322 – 484

= Rs. 434/-

SEVENTH YEAR

Principal = 1085 – 596 = 489

P_7 = Rs. 489/-

n = 1 year

s = Rs. 1000/-

r = 0.065

$$M_7 = 322 + \left(\frac{10}{100}\right)322 = \text{Rs. } 354/-$$

The annual cost of the system for the 7^{th} year is given by

$$A_7' = 489 \times \frac{0.065(1+0.065)^1}{(1+0.065)^1 - 1} = 520.7$$

A_7' = Rs. 521/-

Depreciation factor is given by

$$F_7 = \frac{0.065}{(1+0.065)^1 - 1}$$

F_7 = 1

The salvage value for the 7^{th} year

V_7 = S x F_7

= 1000 x 1

V_7 = Rs. 1000/-

The total life span of the system is assumed as 7 years. Hence at the end of the life span of the system, the scrap value of Rs. 1000 is realized. The amount towards the maintenance of the system is calculated as Rs. 354/- for the seventh year and the annual cost of the system at the seventh year is calculated s Rs. 521/-. Hence the total amount that has to be spent on the system towards the end of the seventh year is Rs. 875/-. Now by deducting the amount spent from scrap value we obtain Rs. 125/-. This amount and the cost incurred from the distilled water is the profit obtained towards the life span of the system.

3.26 TECHNO – ECONOMIC ANALYSIS OF A PYRAMID COVER SOLAR STILL WITH ELECTRICAL BACKUP

Cost of the electrical thermal controller with heating coil of 1500W = Rs.1000/-

If usage of electrical back up is 1 hour/day

Then, the approximate usage of electricity, unit/month = 45 units

Therefore , For unit /day =1.5 units

Units of electricy utilized for 3 ½ hours /day =5.25 units

for 1 unit electricity, Electricity Board charges= Rs.6.50

Therefore for 5.25 units /day = 5.25 units x 6.50

=Rs.34.125

Cost of one month =Rs .34.12x30

=Rs.1023.75/month

Cost of one year =Rs 34.125x365

= Rs.12455.625 /year

Total annual cost of the still without electrical temperature controller per year } =Rs.995

Total annual cost of the still when coupled with electrical temperature controller per year } =Rs.1000 +995+12455.625

= Rs.**14450.625**

The distillate output yield for both solar insolation utilizing solar still and still with electrical temperature controller is more or less same. But the Cost of the solar still utilizing electricity for evaporation is 15 times greater than that of the solar still with the use of solar insolation. This analysis shows that solar still which is exposed to solar energy is highly economical and profitable.

3.27 ANNUAL PRODUCTION OF DISTILLED WATER UNDER SOLAR DISTILLATION

The amount of distilled water produced annually by solar desalination is calculated as follows.

Total number of solar days in a year = 200 days

Average number of operating hours per day = 8 hours

Total solar working hours in a year = 200 x 8

= 1600 hours

Amount of distilled water produced per hour (approximately)

= 270 ml

= 0.270 litres

Amount of distilled water produced in a year = 1600 x 0.270

= 432 litres

Cost of distilled water per litre = Rs. 30/-

Total cost of distilled water obtained in a year = 432 x 30

= Rs. 12960/-

3.28 COST-BENEFIT ANALYSIS

The cost-benefit analysis of the pyramid cover solar still for seven years is shown as follows.

First Year

Annual cost of the system = Rs. 995/-

Total cost of the distilled water obtained in the year = Rs. 12960/-

Profit (benefit) obtained in the first year = 12960 – 995

= Rs. 11965/-

Second Year

Annual cost of the system = Rs. 923/-

Total cost of the distilled water obtained in the year = Rs. 12960/-

Profit (benefit) obtained in the second year = 12960 – 923

= Rs. 12037/-

Third Year

Annual cost of the system = Rs. 847/-

Total cost of the distilled water obtained in the year = Rs. 12960/-

Profit (benefit) obtained in the third year = 12960 – 847

= Rs. 12113/-

Fourth Year

Annual cost of the system = Rs. 758/-

Total cost of the distilled water obtained in the year = Rs. 12960/-

Profit (benefit) obtained in the fourth year = 12960 – 758

= Rs. 12202/-

Fifth Year

Annual cost of the system = Rs. 638/-

Total cost of the distilled water obtained in the year = Rs. 12960/-

Profit (benefit) obtained in the fifth year = 12960 – 638

= Rs. 12322/-

Sixth Year

Annual cost of the system = Rs. 432/-

Total cost of the distilled water obtained in the year = Rs. 12960/-

Profit (benefit) obtained in the sixth year = 12960 – 432

= Rs. 12528/-

Seventh Year

Towards the end of the seventh year we have,

Scrap value – Amount spent = Profit

1000 – 875 = 125 = Rs. 125/-

Total cost of the distilled water obtained in the seventh year = Rs. 12960/-

Total profit obtained in the seventh year = 12960 + 125

= Rs. 13085/-

Table (3.4): Profit obtained from the distilled water

S.No.	Year	Profit obtained (Rs.)
1	1	11965
2	2	12037
3	3	12113
4	4	12202
5	5	12322
6	6	12528
7	7	13085

From the table (3.4), we observe that the profit increases gradually year by year. The cost obtained by marketing the distilled water in the first one year is Rs. 12960/-. This is taken as a constant value for all the years although there may be slight variation due to the variation in the cost of the distilled water in the year. The distillate production may increase or decrease depending upon the climatic parameters. But the amount of Rs. 12960/- is taken constantly for all the seven years. The above techno economic analysis reveals that the pyramid cover solar still is economically viable and profitable.

3.29 PHYSICAL AND CHEMICAL ANALYSIS OF WATER AFTER SOLAR DESALINATION

The physical and chemical analysis for the distilled water was made at the Regional Laboratory of Tamil Nadu Water Board (TNWB), Coimbatore. The sample was tested for colour, turbidity, total dissolved solids, electrical conductivity, pH, alkalinity pH, total hardness calcium, magnesium, manganese, free ammonia, nitrite, nitrate, chloride, fluoride, sulphate, phosphate and the results are tabulated in the tables (3.5) and table (3.6).

Table (3.5): Physical Examination

S. No.	Physical parameters	Test results of solar distillate sample
1	Appearance	Clear
2	Colour (Pt-Co-scale)	Colorless
3	Odour	None
4	Turbidity NT Units	2
5	Total dissolved solids mg/L	678
6	Electrical conductivity (micro mho/cm)	968

Table (3.6) Chemical Examination

S.No.	Chemical parameters	Test results of solar distillate sample
1	pH	7.52
2	Alkalinity pH	0
3	As $CaCo_3$ total	210
4	Total hardness as $CaCo_3$	286
5	Calcium as Ca	76
6	Magnesium as Mg	23
7	Iron as Fe	0
8	Magnese as Mn	0
9	Free Ammonia as NH_3	0
10	Nitrite as NO_2	0
11	Nitrate as NO_3	13
12	Chloride as Cl	108
13	Fluride as F	0.6
14	Sulphate as SO_4	68
15	Phosphate as PO_4	0

Table (3.7) *Total Distillate Output With and W/o Storage*

Type/With and W/O storage	Nocturnal Output (5 pm to 6 am)kg	Day Output (9.30 am to 5pm)kg	Total output kg
Pyramid still W/O	0.0509	1.6399	1.6899
Pyramid still+ TCBM	0.0675	1.855	1.9225
Pyramid still + Wax	0.3685	1.9275	2.2955
Single slope still W/O	0.04825	1.6052	1.6532
Single still+ TCBM	0.064	1.810	1.874
Single still+ Wax	0.3497	1.8567	2.2057