Thermal Performance and Economic Feasibility Analysis of a Basin Type Solar Still

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Abstract - With the increased awareness about global warming and environmental constraints it is becoming imperative to use alternative energy sources. Solar energy is one such low grade energy which can be used to save high grade energy. There are many areas where solar energy can be used. Distillation of water using solar still is one such area. By using solar still, the initial investment is low but maintenance is much more difficult as compared to other conventional method where electricity is used for distillation of water. In the present work variation of, thermal losses and temperature of water, ambient air and basin plate are observed with time. The variation of solar radiation is also observed for a day. In second part previous parameters of a financial analysis of the solar still has been carried out taking the initial capital investment, maintenance cost and distillate output over the life period of the solar still at Pantnagar, India. The cost of distillate output per liter during first year is found to be Rs. 0.98, it decreases year by year and its value for the fifteenth year is Rs. 0.38. A comparison of the cost has been made with electrical distillation unit in which distillate output cost (considering operating cost i.e. electricity bill only) is coming to be Rs. 5.16 per liter of distillate output. Thus, the pay-back period of solar still when compared with electrical distillation unit is coming two years only.

Keywords: Solar energy, Solar still, Water distillation, Global warming, Economic feasibility.

1. Introduction

There are many parts of the world like arid and semi-arid areas and coastal areas where plenty of underground water is available but this highly saline and therefore unfit for human consumption. The acceptance of impurities level in water for industrial purposes varies to great extent. In some industries like steam power plants ultra-pure water with a dissolved salt only 10ppm is used.

Solar distillation is a relatively simple treatment of brackish (i.e. contain dissolved salt) water supplies. Distillation is one of many processes that can be used for water purification and can use any heating source. Solar energy is a low tech option. In this process, water is evaporated; using the energy of the sun and then the vapor condenses as pure water. This process removes salt and other impurities.

Solar distillation is used to produce the drinking and pure water for lead acid batteries, laboratories, hospitals and in producing commercial products such as rose water. It is recommended that drinking water has 100 to 1000mg/l of salt to maintain electrolyte levels and for taste. Some saline water may need to be added to the distilled water for acceptable drinking water.

Solar stills have proven to be highly effective in cleaning up water supplies to provide safe drinking water. The effectiveness of distillation for producing safe drinking water is well established and recognized. Systems can be sized for one person, up to community sized systems. They have no moving parts, relying only on the sun for energy, and should last 20 years or more. Larger disinfecting systems which generate chlorine and other gases can be operated in remote locations, using solar energy.

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.

There are many methods for converting saline water into potable water. Distillation process is considered to be one of the simplest and widely adopted techniques for converting saline water into fresh water. One of the best and cheap methods for water distillation is by using solar still.

Solar distillation uses the heat of the sun directly in a simple piece of equipment to purify water. The solar still, consists primarily of a shallow basin with a transparent glass cover. The sun heats the water in the basin, causing evaporation. Moisture rises, condenses on the cover and runs down into a collection trough, leaving behind the salts, minerals, and most other impurities including germs. Although it can be rather expansive to build a solar still that is both effective and long-lasting, it can produce purified water at reasonable cost if it is built, operated, and maintain properly.

Solar distillation techniques also have considerable financial advantage over other small scale distillation processes primarily due to free availability of solar energy. However, solar distillation technology is relatively capital-intensive and a detailed financial evaluation and comparison with other competing options is necessary to decide upon its utility as an alternative.

Present work focuses mainly on small-scale basin-type solar still which can be used as suppliers of potable water for families and other small users. Of all the solar still designs developed thus far, the basin-type continues to be the most economical. In this work a basin type solar still o $1m^2$ is constructed in the college workshop. Experiments on the solar still set-up has carried out for the different time period and total daily output from solar still has taken for the performance analysis of solar still.

In this project we have carried out an economic analysis and performance analysis of solar still. Maintenance of solar still set-up is relatively difficult as compare to the other conventional methods such as distillation by using electricity. Water output per day from solar still has measured by conducting the experiments on solar still set-up in Pantnagar at different time. A compromise has been made of 250 sunny days out of 365 days in one year and after taking a mean value of distillate output in whole year we calculate the cost per liter of distillate output. Since the operating cost is zero due to free availability of solar energy but output cost mainly is due to the maintenance cost and depreciation of the solar still components. Hence cost per liter of output is estimated by dividing the total output in a year to total annual coat on the solar still and a comparison is made with the electric distillation unit.

2. Construction of Solar Still

A solar still consists of shallow basin made up of a GI sheet. This basin is placed inside the wooden frame and glass wool is filled between basin and wooden frame. Glass wool acts as an insulator, which minimizes thermal losses. Bottom of the basin is painted black so as to absorb solar radiation effectively. Top of the basin is covered with transparent glass tilt fitted so that maximum radiation can be transmitted in to the still. Edges of the glass are sealed with the basin using tar tape so that the entire basin becomes air tight. Entire assembly is placed on a stand. Outlet is connected with a storage container. Provision has been made to fill water in the still basin. Water is charged into the basin in thin layer.

3. Working of system

The basic principles of solar water distillation are simple yet effective, as distillation replicates the way nature makes rain. The sun's energy heats water to the point of evaporation. As the water evaporates, water vapor rises, condensing on the glass surface for collection. This process removes impurities such as salts and heavy metals as well as eliminates microbiological organisms. The end result is water cleaner than the purest rainwater. In the still that we have constructed have no moving parts to wear out.

Operation is simple: water should be added (either manually or automatically) once a day through the still's supply fill port. Excess water will drain out of the overflow port and this will keep salts from building up in the basin. Purified drinking water is collected from the output collection port.

The still is filled each morning or evening, and the total water production for the day is collected at that time. The still will continue to produce distillate after sundown 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.

4. Experimentation

4.1 Experimental set-up: For the thermal performance analysis of solar still a number of experiments are carried out on solar still setup. In present work experimental set-up is installed in solar lab where a number of instruments were connected to the solar still set-up. Pyranometer is used to measure the global solar radiation intensity. Thermocouples made of copper constantan are used to measure the absorber plate temperature, water temperature and ambient temperature. Brackish water is poured in the basin in the evening up to a certain height. All the thermocouples are connected to a voltmeter which gives temperature in terms of millivolt which can be converted into °C by calibration chart of thermocouple.

4.2 Experimental Procedure: The solar still is properly oriented, and directly exposed to the solar radiation. All the measuring instruments are installed in position and thermocouple connection are made. Then thermocouple is tested before filling the water in the basin. Water is filled via inlet port to a depth so that it does not come out from overflow port. All the key quantities are carefully measured and recorded at a time interval of every 15 working minutes. The measured parameters and quantities are; solar radiation intensity (I), the plate temperature (T_p), the basin water temperature (T_w), and the ambient air temperature (T_a). The designed system has the following important characteristics:

1. The negative effect of scale formation on the absorption efficiency, and the increased cost of cleaning the white scale are two important causes of reducing the solar still efficiency. So, basin should be clean after some time to maintain good absorptivity of basin surface.
2. The water surface level was precisely adjusted to avoid the dry spots, mainly at shallow water depths.
3. The proper material selection and fabrication of the absorbing plate has a positive effective on the increased basin water temperature. In order to ensure an efficient capturing of solar irradiation, the absorbing plate is made of G.I. sheet because of its thermal conductivity and avoids pitting effect in case of aluminium sheet.

4.3 Observation of the Experiment done in Solar Lab at Pantnagar:

First Day: Distillate output **=** 6 liters for whole day

Second Day: Distillate output **=** 5.3 liters for whole day

Seventh Day: Distillate output **=** 3.9 liters for whole day

5. Thermal Performance Analysis of Solar Still

The performance of solar still can be predicted by writing energy balance equations on various components of the still. A steady state analysis of solar still is described here. The heat losses from the still can also be determined.

The instantaneous heat balance equation on basin water can be written as

$$I\alpha_w \tau = q_e + q_r + q_c + q_b + q_s + C_w \, dT_w/dt$$

Where, I is the solar radiation on surface.

Similarly the instantaneous heat balance equation for glass cover can be written as

$$I\,\alpha_g + q_e + q_r + q_c = q_{ga} + C_g \, dT_g/dt$$

Where, q_{ca}(=q_{ra} + q_{ca}) is the heat loss from glass cover to the atmosphere.

Heat balance equation on the still can be written as

$$I\alpha_w \tau + I\alpha_g = q_{ca} + q_{ra} + q_b + q_s + C_w dT_w/dt + C_g dT_g/dt$$

The parameters like $(1- \alpha_g - \tau)I$ and $(1- \alpha_w)\tau I$ are not included in equations since these do not add to evaporation or condensation of water.

The heat transfer by radiation,

$$q_r = F\sigma\,(T_w^4 - T_g^4)$$

Where, F is the shape factor which depends on the geometry and the emissivity of water and glass cover.

Here F is assumed as 0.7.

$$q_r = 0.7\,\sigma(T_w^4 - T_g^4)$$

The convective heat loss from hot water surface in the still to the glass cover can be calculated from the following expression:

$$q_c = h_c\,(T_w - T_g)$$

The value of convective heat transfer coefficient depends on many parameters like temperature of water and glass, density, conductivity, specific heat, viscosity, expansion coefficient of fluid, and spacing between water surface and glass cover.

The heat transfer coefficient between plate of the basin and glass is calculated by using the Dunkel's empirical relation as follows:

$$h_c = 0.884\left[\left[T_w - T_g + \frac{(Pw - Pg)}{268.9 \times 10^3 - P_w} T_w\right]\right]^{1/3}$$

For determining T_g (glass cover temperature) a semi-empirical relation has been used (Sharma and Mullick, 1991)

$$T_g = \frac{\{(0.02612T_w{}^2 - 15.76T_w + 2392)T_w + A_r h_w T_a + A_r(0.048T_a - 9)T_s\}}{\{(0.02612T_w{}^2 - 15.76T_w + 2392) + A_r h_w + A_r(0.048T_a - 9)\}}$$

$$A_r = \frac{A_g}{A_w} = \frac{1.04*1}{1*1} = 1.04$$

$$h_w = 5.7 + 3.8 \text{ X } V_w$$

Assuming wind velocity $V_w = 1m/s$

Therefore, $h_w = 5.7 + 3.8 = 9.5\ W/m^2K$

$$T_s = 0.0552 \text{ X } T_a{}^{1.5}$$

The evaporative heat loss q_e from water to the glass cover can be calculated by knowing the mass transfer coefficient and convective heat transfer coefficient. The empirical expression for q_e as given by Dunkle and converted into SI unit is given by:

$$q_e = \frac{h_{ewg}}{U_i} \text{ x } U_t\,(T_w - T_s)$$

Where U_t is the upward heat loss coefficient and U_i is the sum of h_{ewg}, h_c and h_{rwg}

$$h_{ewg} = \frac{9.15 \text{ X } 10^{-5} h_c \text{ X } (p_w - p_g) h_{fg}}{(T_w - T_g)}$$

Now the bottom and side loss coefficient can be calculated by using the formula as:

$$U_b = \frac{K_{ins}}{\delta_b}$$

The value of δ_b and δ_s is 4 cm each.

Thermal conductivity of insulating material is the resulting conductivity of both glass wool and wood as they are in series for heat transfer.

K_{ins} for wood = 0.052 W/mK, and

$K_{ins.}$ for glass wool = 0.03 W/mk

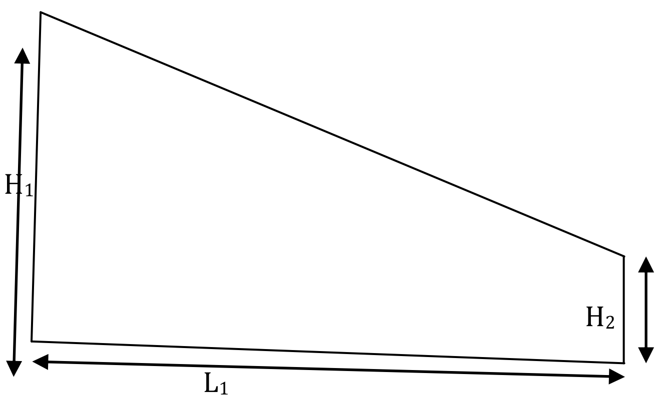
$$\frac{1}{U_b} = \frac{0.02}{K_{wood}} + \frac{0.02}{K_{glass\ wool}}$$

U_b = 0.9512 w/m^{2}K

Now the bottom heat loss from the basin can be calculated as :

$$q_b = U_b(T_w - T_a)$$

For calculating side losses consider the following figure:



The basin area is $(L_1\ X\ L_2)\ m^2$

So side surface area = $L_2H_1 + L_2H_2 + L_1(H_1 + H_2)$

$$U_s = \frac{side\ surface\ area\ X\ U_b}{base\ area}$$

$$= \frac{1\ X\ (.33+.05)+1(0.33+0.05)}{1X1}\ X\ 0.9512$$

U_s = 0.723 W/m^{2}K

Now the side heat loss from the basin can be calculate as:

$$q_s = U_s(T_w - T_a)$$

The convective heat loss q_{ca} from glass to ambient air can be calculated from the following expressions;

$$q_{ca} = h_w(T_g - T_a)$$

The radiative heat loss q_{ra} from glass to sky can be determined if the radiant sky temperature is known because the ultimate sink is sky. The sky temperature is very much dependent on atmospheric conditions such as the presence of clouds etc. Generally for practical purposes the average sky temperature is taken as per the relation:

$$T_s = 0.0552\ X\ T^{1.5}{}_a$$

Thus the radiative heat loss q_{ra} from glass cover to the atmoshere is given as:

$$q_{ra} = \epsilon_q\ \sigma(T^4{}_g - T_s{}^4)$$

6. Economic Analysis

The value of a solar thermal application must be ultimately being judged on the basis of its economy. It is quite evident that solar thermal devices and systems are characterized by high initial costs. However they bring long term benefits in term benefits in form of lower annual operating costs. An economic evaluation of a solar system has to consider both these aspects.

Initial cost: The cost of a solar system is the cost of buying the equipment and installing it. Solar collectors contribute significantly to the initial cost. It is denoted by (C).

Annual cost: The annual cost of a solar system installed by an individual or organization is the sum of a number of factors. These include the cost of fuel consumed by an auxiliary energy source, repayment on the loan taken to install the system, maintenance of the system, electrical energy consumed by the subsidiary equipment like pumps and the blowers, local taxes, etc.

Consider a solar thermal energy system installed for an application like water heating, space heating, etc. in order to evaluate the economic viability of the system. We are interested in calculating the savings which will accrue annually and on a long term basis as a result of installing the solar system.

Annular solar savings (ASS) = Fuel savings – Payment on a loan – Maintenance charges + Electric energy bill – Local taxes + Tax deductions.

Cumulative solar saving (CSS) over a certain number of years (n) is the sum of annual solar savings over the period minus the initial down payment made at the time of installation of the solar system.

Life cycle savings (LCS) is the cumulative solar savings calculated over the life time (n_t) of a system plus the resale value of the system at the end of its life time.

$$CSS = \sum_{j=1}^{n} (ASS)_j - (initial\ down\ payment)$$

$$LCS = \sum_{j=1}^{n} (ASS)_j - (initial\ down\ payment) + resale\ value$$

Since the value of money keeps changing with time, the usual practice is to obtain the sum of the annual power savings in above equations in terms of money value at the present instant of time. The present worth of money required sometimes in future is obtained by calculating how much would have to be invested at the market interest rate today in order that the required money would be available when required in future.

It is obvious that if a solar system is to be economically beneficial, the value of CCS over a reasonable period of time or the value of LCS must be positive. It is obvious that in a given situation these values will decrease as the market rate increases. The discount rate at which the value of CSS or LCS is zero is called as the rate of return on investment (ROI).

Also an important term payback period is used during analysis which is the time needed for the cumulative fuel savings to become equal to the total investment on the system.

Depreciation and maintenance cost can be calculated on per year basis to determine the cost of obtaining distillate by solar still. Once distillate cost is determined it is used it can be compared with the cost of obtaining same amount of distillate by conventional methods (like by firewood, CNG, electricity, etc.).

In this section an economic analysis is carried out to check the economic feasibility of basin type solar still and a comparison is made with distillate output by electricity.

6.1 Initial cost: The initial cost of solar still is the cost of the components used for the construction of basin type solar still.

Total Raw material cost= Rs. 3295

Approximate total initial set up cost= Raw material cost+ fabrication cost=Rs. 4500. (Excluding raw water supply cost, transportation costs, installation cost etc.)

Some additional costs also have to take into account for analysis such as cost of raw water, cost of land available for installation of solar still, cost of labors for construction of solar still and transportation cost. Raw water is available everywhere free of cost so we can ignore the raw water and its supply cost. In present work we are not considering the cost of land available for installation, transportation cost etc. for our convenience because these costs vary from one place to other.

6.2 Maintenance cost: Generally the life of a solar still is 15 years. For the continuous and undisrupted supply of distillation water we have to repair or replace some components of solar still. Glass cover is assumed to replace once in 5 years, paint on the body is done after each year, we have also replace/repair some other parts so for economic analysis we have to consider the maintenance costs of these components.

The initial cost of those components which are replaced/ repaired in whole life of solar still is equal to Rs. 1460.

Total maintenance cost per year for 1m × 1m basin type solar still=Rs 350 (also accounting some unforeseen maintenance cost that might occur during operation)

6.3 Operation cost: Operation cost is the major factor to determine the performance of any conventional processes but solar still make use of solar energy for water distillation. Solar energy is available everywhere free of cost and in abundant hence we may ignore the operation cost of solar still.

Operation cost of solar still (per year) = Rs. 0.0

6.4 Output: The solar still output (distillate) is a strong function of solar radiation on horizontal surface the distillate output increases linearly with the solar radiation for a given ambient temperature. A compromise has been made for still output that total sunny days available in a year are 280 days and rest of 85 days are cloudy. As solar radiation available in summer and winter for whole day is different so we have to consider a mean value of distillate output for one year.

According to experiment done in solar lab Pantnagar average output of one day in summer are 6.0 liters and for winter are 2.0 liters.

Mean value of summer and winter output= (6.0+2.0)/2= 4.0 liters

Therefore, total output in one year = 250*4=1000 liters

6.5 Description on Solar Still Components:

To calculate the annual cost of a solar still set-up one has to calculate the depreciation per year on those components which are not replaced with in the economical life of set-up of solar still.

Economical life of solar still set-up (N) =15 years

Initial capital investment (C_s) = Rs 4500-1460 = Rs 3040

(Excluding the cost of those components which are replacing or repairing)

Salvage value: Salvage value in case of solar still set-up can be assumed as its scrap value because after 15 years it will be sold as a scrap so we can take its scrap value into account as

Salvage value (S) = Rs 100 (as per according to today scrap market price)

Applying the declining balance method to determine the depreciation at the end of each year of solar still components cost which are not replaced in its whole life.

All the cost has been taken in Rs, economical life (N) of set-up in year and period (P) is the time after which we have calculated the depreciation in year.

Depreciation at the end of each year has been calculated by using MS EXCEL (by declining balance method) in following table:

6.6 Annual cost and distillate output cost (Rs. /liter)

To estimate the cost of per liter of distillate output one has to predict the annual expenditure on solar still set-up. Annual cost of a solar still apparatus is the sum of maintenance cost per year, depreciation in that year of set-up components, overheads and operation cost in that particular year.

In case of solar still operation cost is zero and overheads can be ignored because they vary from one place to other.

For each year cost per liter has been determined as follows:

Total distillate output per year = 1000 liters

As per the calculations, we get Rs. 0.98/ liter in first year and the cost/liter decreases in the next years within the economical life of still.

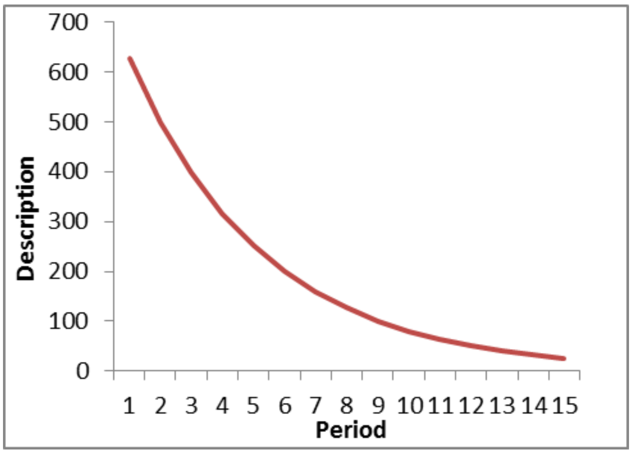


Fig. 6.1 Variation of depreciation value of solar still with time

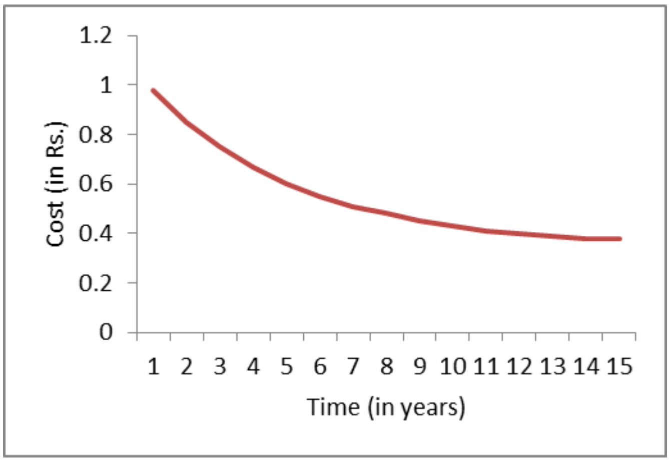


Fig. 6.2: Variation of cost with time

6.7 Comparisons with electricity unit

Total annual savings for an output of 1000 liter is calculated as follows

Distillate output of standard distillation unit = 2.5 liter per hour

Rating of unit = 4.3 kW

Cost of electricity per kW in Pantnagar= Rs 3.00

Thus cost of obtaining per liter distilled water = Rs. (4.3 ×3.00)÷2.5 = Rs. 5.16 per liter

Cost of obtaining distilled water from a solar still accounting for maintenance costs, depreciation costs, etc. = Rs. 0.98 (calculated earlier)

Thus annual saving for an output of 1000 liter = 5.16 × 1000 – 0.98 ×1000 = Rs. 4180 (for first year)

Payback period is the period by which we start to obtain cumulative savings above the value of the initial capital investment.

As cumulative savings at the end of second year is = Rs. 4180 + Rs. 4310 = Rs. 8490

Clearly CSS > Initial investment (Rs. 4500)

Thus Payback period = 2 year.

7. Results and Discussion

7.1 Results of Experiment: In the present experimental study, for calculating the various heat losses from the water in the basin, the experiments were conducted in Solar Laboratory Pantnagar.

The variations of water temperature, ambient temperature, plate temperature and solar intensity with time on a particular day are shown in Figs.7.1-7.4. The variation of heat loss by radiation time of the day is shown in Fig. 7.5. In this work various heat losses are calculated.

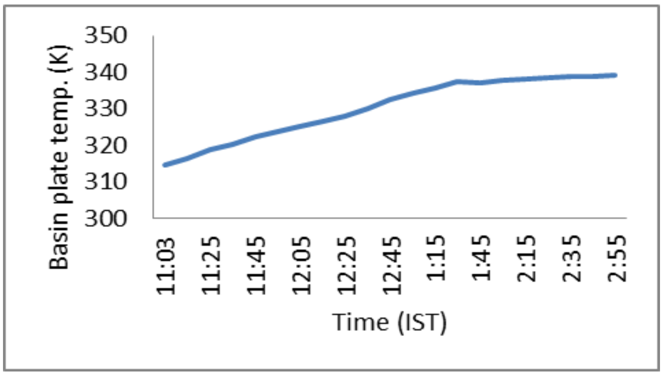


Fig.7.1 Variation of basin plate temp (K) with time (on 1st day)

7.2 Discussion

From the fig. 7.1 and 7.2 it is observed that the basin plate temperature and water temperature increases continuously with time and their between 2 pm to 3 pm (IST) and after that it decreases.

As shown in fig. 7.3 the ambient temperature does not have any straight relation with time (i.e. increase or decrease) but it attains maximum value between 1 pm to 2 pm (IST). Practically ambient temperature variation over a period of day is small which follows from our results.

Fig. 7.4 shows the variation of solar radiation intensity with time and it reveals from graph that the maximum value solar intensity occur between 12 pm to 12:30 pm (IST) thereafter it decreases as time is elapsed.

Variations of various heat losses are observed with temperature of water in the basin and all the graphs show that the losses increases with increase in water temperature. Since losses roughly depend upon the temperature difference of water and ambient and thus their increase in value is justified in our results.

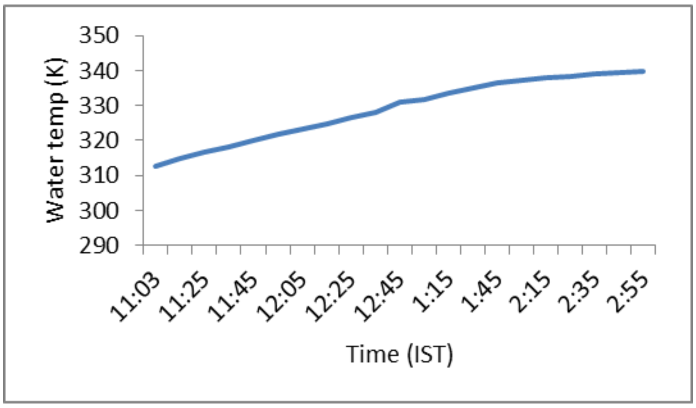


Fig.7.2: Variation of water temperature (K) with time (on 1st day)

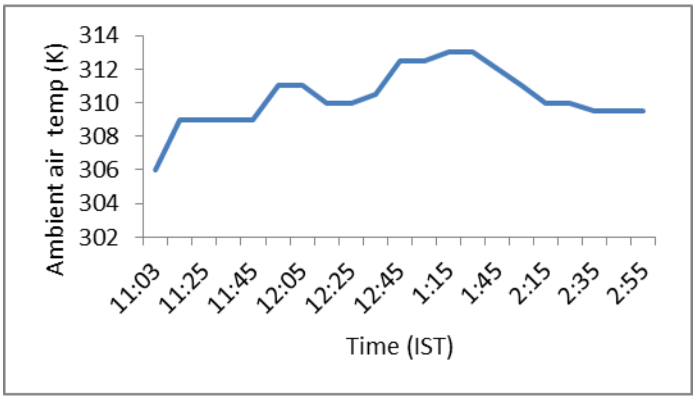


Fig.7.3 Variation of ambient air temperature (K) with time (on 1st day)

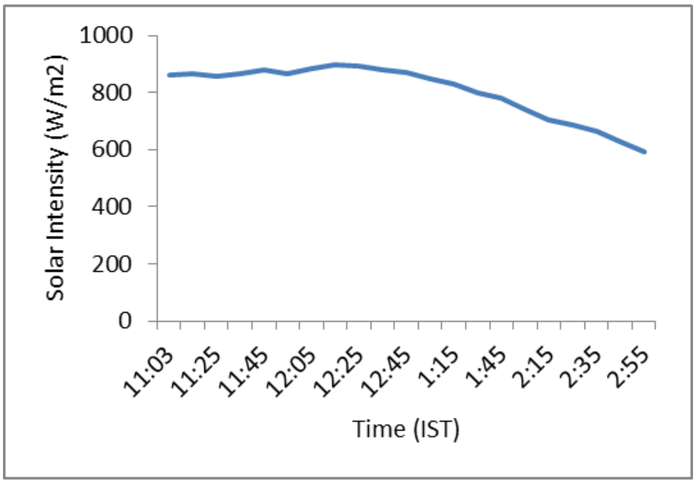


Fig.7.4 Variation of intensity of solar radiation with time on a particular day (on 1st day)

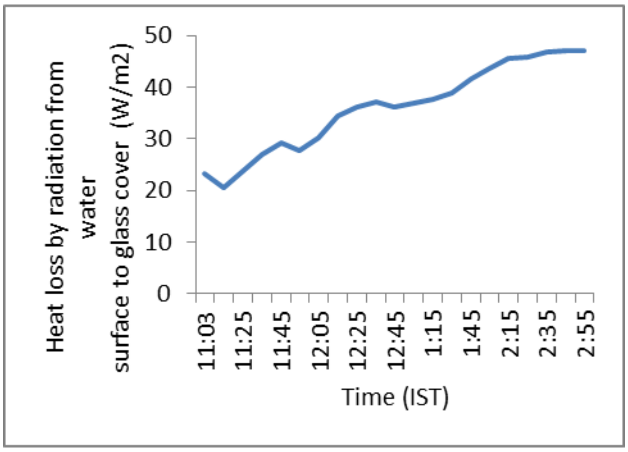


Fig.7.5 Variation of heat loss by radiation from water surface to glass cover with time on a particular day (on 1st day)

8. Conclusion

In thermal analysis the radiative losses etc. increases with increase in water temperature however these losses can be minimized by using better insulation and by improvement in design characteristics. The pattern of solar intensity observed over period of a day satisfies the general trend that is observed in different other studies.

By mean of economic analysis it can be established that within a period of two years the value of initial cost can be recovered and after that there is positive value for cumulative solar savings. Thus the distillation by solar still is much better than the current electric systems used in practice. It not only minimizes cost but also help in saving a high grade energy which can be utilized for other purposes. However the only drawback is limited amount of distillate that can be collected over a period of a day as compared to conventional electric distillation unit.

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