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DESIGN, FABRICATION AND THERMAL ANALYSIS OF ROTATING SOLAR BOILER

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Abstract -*The solar energy has the greatest potential of all the sources of renewable energy. To use the solar energy, solar collectors are integral part. Different types such as flat plate collector, evacuated tube type collector, parabolic trough collector and dish type collectors are used. Larger space requirement and less thermal efficiency are the problem with the present solar collectors systems. These problems can be handled with the new idea of solar collector. In the present study, the innovative and novel design of the solar collector, known as Rotating Solar Boiler is discussed. The rotating solar boiler is nothing but the modified parabolic trough solar collector in which the absorber is larger in size and rotating with certain speed. It's construction, working principle, thermal analysis, heat losses, performance study to understand and to make comparison with other existing solar collectors are given in the paper. The detail and extensive design of the device was done. As per design, system was manufactured for experimental investigation. The device was tested for different speeds i.e. stationary, 40 rpm, 60 rpm, 80 rpmand 100 rpm to check its performance. Experimental results are studied to determine the optimum speed for Rotating Solar Boiler. Calculated efficiency of device is compared with stationary parabolic trough collector. It was found that rotating solar boiler is performing with higher efficiency when it is rotating with 80 rpm. This efficiency is more by 9 % to 15 % than that of stationary collector. Area of Rotating Boiler is also less by 20% in comparison with conventional flat plate collector and trough collector. In winter season, the maximum temperature of water obtained in device is around 53^{o}C at 450 – 500 W/m^{2} solar radiation which is greater than 8 ^{o}C compare to flat plate collector. This high temperature water can be used for any industrial as well as domestic purpose. Therefore present study is ended with conclusion that the rotating solar boiler may be contributed in the future of solar energy application considerably.*

Key words*- Solar Energy, Rotating Solar Boiler, Flat Plate Collector, Stationary Absorber and Instantaneous Efficiency*

I. INTRODUCTION

As the power demand is going on increasing day by- day, it increases responsibility on the shoulders of our engineers to find and invent the new resources of the energy to make it available as per the demand. At present, many of the power generation plants are using non-renewable sources as their primary sources. But these may become extinct at any time and before facing the situation, we have to choose an alternative to avoid the power crisis. One of the best alternatives is choosing non-conventional sources like solar energy, wind energy, tidal energy, bio-mass energy etc. as the primary sources for power generation in power station.

Solar power is also known as being "eco-friendly" since it doesn't emit toxic gases into the environment. In some countries like India, it has great potential and available throughout the year. To utilize solar energy, different collectors and photovoltaic cells are required. Solar collectors are devices that produce heat from sun radiation. At this moment, there are five different types of solar collectors in use namely flat plate solar collectors, concentrating solar collectors, evacuated tube collectors, uncovered absorbers, solar ponds.

Rotating solar boiler is a new emerging idea of solar collector to generate high temperature water / steam with the higher thermal efficiency. The rotating boiler consists of two concentric tubes. The inner tube is called the absorber which is placed inside another transparent tube which acts as cover. This entire assembly is rotating with certain speed to get better performance. The present work is dedicated to design and fabricate the Rotating solar boiler for industrial and home appliances.

II. LITERATURE REVIEW

J.P.H.van Luijtelaer has given theory behind the rotating solar boiler in his research work [1]. In his study, three different rotating solar boilers were designed and manufactured. Their thermal performances were also tested through the experimental work. The effects of conduction, convection, radiation and mechanical losses were described. The boilers typically produced 1KW of steam at 100 ^{o}C. The efficiencies of the different boiler were measured. Models were developed to predict their performances. The all models were having an efficiency of around 68 – 70 %. It was concluded that Rotating solar boiler has a high efficiency, produces high temperature steam and has a low cost per unit surface area. In this thesis, a new design is proposed and evaluated both theoretically and experimentally. Sai Manoj Rompicherla described the significance of the solar energy as it will be the energy source of future for mankind [2]. The solar energy is one of the important non-conventional sources of energy. World's dependence on crude oil will continue for most part of the 21st century but the continued dependence on crude oil is loaded against it with inherent price volatility linked to finite global reserves. This paper is useful to get the basic information about the conventional methods which are widely used in solar energy applications.

Lixi Zhang and Chunlei Li have designed a new solar-heated generation system with capacity of 10 kW. The system is based on solar-heated Rankine cycle [3]. The CPC solar energy collector array is used as the main heat source, and the gas boiler as the assistant heat source. The heat storage facility provides heat for put-off 24 hours generating without sun's radiation. The paper is focused on the analysis of four typical working processes under the different climatic conditions. The shape of the CPC solar collector is designed, and the thermal efficiency is analyzed, and the collector array is ranged suitably. The paper is useful to understand the how to consider design and performance parameters for practical design/ analysis of the solar collectors. George O.G. et al conducted on solar desiccant cooling system at the Solar Energy Applications Laboratory, Colorado State University [4]. The system comprises an air heating/ desiccant evaporative cooling unit, a evacuated tube solar collector, hot water solar storage tank, auxiliary electric boiler, controls, and accessories. The cooling unit is operated in the ventilation mode, fresh air being dried in a rotating desiccant matrix, and cooled by heat exchange and evaporative cooling. The solar-driven system provided over 90 % of the seasonal cooling requirements in an experimental, residence type building at average COP levels of 1.0 and solar collection efficiencies of 50 percent when supplied with solar heated water at temperatures of 50 to 65°C. The paper gives the useful information about the different components used in the solar heating and cooling system. It focuses the more and throws different light on the solar cooling application.

III. PROBLEM OF CONVENTIONAL SOLAR COLLECTORS AND SOLUTION

1. The flat plate collectors, Evacuated tube collectors etc. are heavy in construction and more space is required for installation. Also initial manufacturing costs of these collectors are very high. The researchers have been doing lot of research to overcome the mentioned problems by modifying present devices to increase the thermal performance or by inventing the new design for the solar collectors.

2. In the present paper, same problem is considered and work is aimed to design new concept of solar collector known as 'Rotating Solar Boiler'. The present paper work addresses the research in the solar energy which is one of the hot issues about need of the today's world. Therefore, present work will contribute at different level in this field.

The main purpose of this solar rotating boiler is to generate the hot water or steam of high temperature by absorbing maximum available solar energy. The device may work with high efficiency with less space for the installation and at comparatively moderate manufacturing cost. It consists of two concentric tubes. The inner absorber tube made up of copper or aluminium is rotating continuously with certain speed inside the outer cylindrical cover, made up of transparent glass. Due to this arrangement, the centrifugal force will be acting on the cold water in absorber. Thus, the cold water comes continuously in contact with hot surface and gets heated at high temperature by absorbing large amount of solar energy. Finally steam is generated. Therefore, Rotating Solar Boiler will generate the steam or hot water at higher thermal efficiency.

IV. WORKING PRINCIPLE OF ROTATING SOLAR BOILER

1. In Stationary Solar Collector

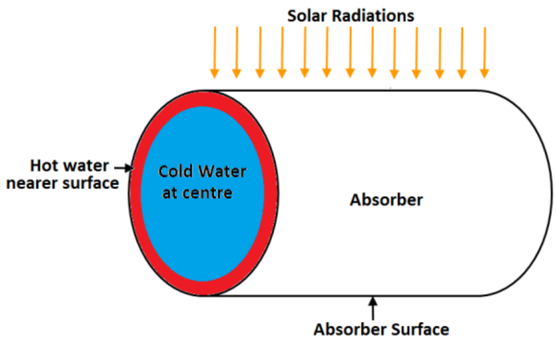


Figure 1. Heat transfer phenomenon in stationary solar collector

The solar radiations are falling on the surface of the absorber. The surface gets heated and its temperature is increased. Now, the heat is transferred to the water adjacent to the surface and water becomes hot.As density of hot water is less, it

remains nearer to the surface of absorber due to natural convection whereas the cold water remains at the center as shown in figure 1.
It is not desirable situation as temperature difference between surface and hot water is less and requires more time and solar energy to heat the water.

2. When the Absorber of Solar Collector is Rotating (i.e. In Rotating Solar Boiler)
The surface of the absorber gets heated due to solar radiation and its temperature is increased. This energy is given to the water nearer to the surface. When the absorber is rotated with certain speed then it produces the centrifugal force in the water. It is shown in figure 2. Now, the cold water at the center of the absorber is heavier than the hot water. Thus cold water starts flowing towards the outward direction under the action of the centrifugal force while hot water is accumulated at the center of the absorber as shown in figure 3.

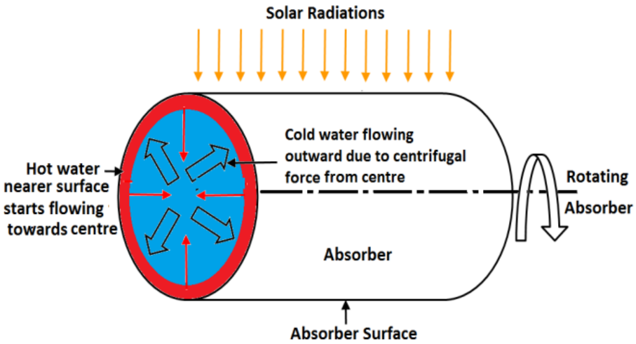


Figure 2. Effect of centrifugal force on the cold and hot water in the rotating absorber

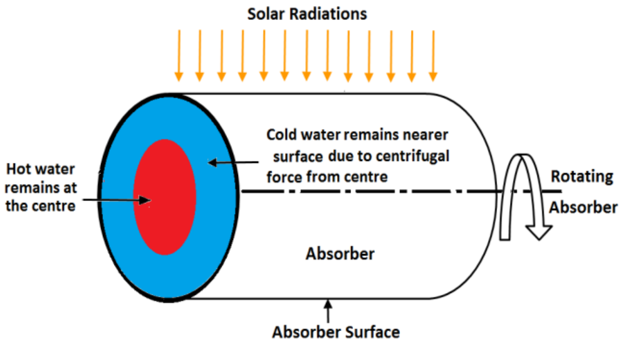


Figure 3. Location of the cold and hot water in the rotating absorber

Thus the cold water remains continuously in contact with the surface of absorber. It develops maximum possible temperature difference nearer the surface between absorber and water. Thus water receives maximum amount of the solar energy and get heated in less time period. It will improve the efficiency of the collector and also reduces the space required for the collector. This working principle is used in design of the new concept of solar collector known as Rotating Solar Boiler.

V. CONSTRUCTION OF ROTATING SOLAR BOILER

It consists of the copper absorber, plastic cover, parabolic reflector, shaft, gear box and electric DC motor. The water is stored in the absorber which receives the solar energy from the sun. The absorber is made up of copper with selective coating to increase absorptivity and to reduce the emissivity of material. The absorber is surrounded by plastic cover to reduce the heat loss from top of the surface due to convection. It is also useful to trap the maximum solar energy in between the cover and absorber due to greenhouse effect. Ends of the absorber and cover are closed by the dish ends as shown in figure 4. This assembly is mounted on the shaft which is driven by the electric motor. The shaft is placed in the ball bearing support for smooth rotation. Generally DC electric motor of capacity 1 HP with the voltage 12 volt is used to rotate absorber with certain speed to enhance thermal performance of solar boiler. Gear box is provided to get required torque and to get the speed variation of the shaft.
The properly designed reflector is used to collect the solar radiation and focus on the absorber. The radiation is focused and collected at the focal point of the parabolic reflector. Hence absorber is mounted at focal point to receive the maximum radiation. Generally, separate inlet and outlet ports are provided to fill and remove the water/ steam from absorber. But sometime the hollow shaft are used for same purpose.

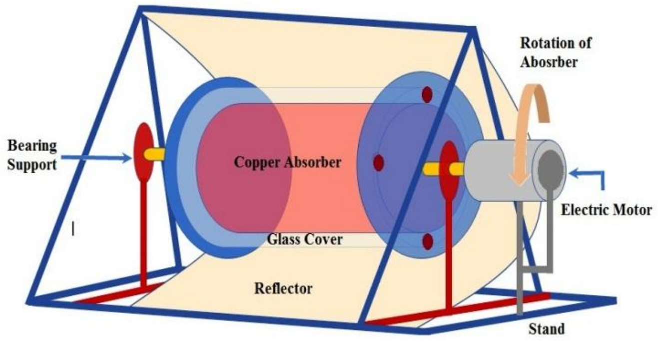


Figure 4.Construction of Solar Rotating Boiler

VI. THERMAL ANALYSIS OF ROTATING SOLAR BOILER

The rotating solar boiler is nothing but the modified parabolic trough solar collector in which the absorber is larger in size and rotating with certain speed. Hence the thermal analysis of rotating solar boiler is done by using same methodology which is used for the parabolic trough with small changes. This section deals with the procedure and formulae used for thermal analysis of rotating solar boiler.

6.1 Basic Terms Used in Thermal Analysis

1) H_b is the beam radiation intensity on horizontal surface in W/m^2
2) H_r is the beam radiation intensity on reflector aperture in W/m^2
3) $R_r = \frac{H_r}{H_b}$, It is ratio of beam radiation intensity on the horizontal surface to beam radiation on reflector aperture. It is less than 1.
4) ρ is specular reflectivity or reflectance of the reflector surface (Generally its value is 0.85)
5) γ is intercept factor. It is defined as fraction of the secularly reflected radiation that is intercepted by the absorber.
6) $\tau\alpha$ is transmittance absorptance product for the cover material
7) C_R is concentration ratio. It is defined as ratio of effective area of the aperture (A_R) to area of the absorber tube (A_a). It is given by

$$C_R = \frac{A_R}{A_a} = \frac{(W - d_a)L_a}{\pi d_a L_a} = \frac{(W - d_a)}{\pi d_a}$$

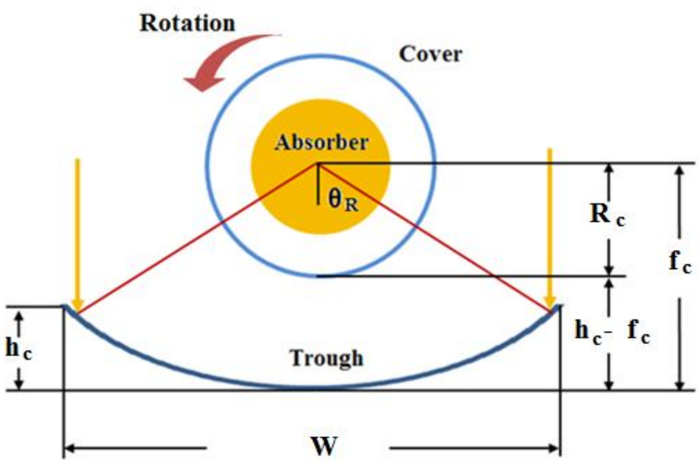


Figure 5 Thermal analysis of the RotatingSolar Boiler

6.2 Solar Energy Available on Surface of Absorber

It is given by the formula

$$Q_{absorber} = H_b R_b \rho \gamma (\tau\alpha)_c A_a \quad \text{... in W}$$

6.3 Loss of Energy from Absorber to Surrounding

It is calculated by equation

$$Q_{loss} = Q_{top} + Q_{edge} \quad \text{... in W}$$

Where,

Q_{top} Heat loss from top surface of cover of boiler in W/m^{2}K
Q_{edge} Heat loss from dish ends of absorber in W/m^{2}K

6.4 Useful Energy Gain by the Absorber

The useful gain of solar energy in calculated by the energy balance equation given below

$$Q_{useful} = Q_{absorber} - Q_{loss}$$

$$Q_{useful} = H_b R_b \rho\gamma(\tau\alpha)_c A_a - Q_{loss} \text{... in W}$$

6.5 Heat Loss from Top and Dish Ends

a) The heat loss from surface of absorber takes place due to both modes of heat transfer i.e. radiation and conduction through layer of air between cover and absorber. The heat loss due to radiation is to be considered by h_{r-a-c}

$$h_{r-a-c} = \frac{\sigma(T_a - T_c)(T_a^2 - T_c^2)}{\frac{1}{\varepsilon_a} + \frac{1}{\varepsilon_c} - 1} \text{... in W/m}^2\text{K}$$

Where

σ is Stefan Boltzmann Constant = 5.67 x10^{-8} W/m^{2}K^4
T_c is average temperature of absorber in K
T_a is average temperature of cover in K
ε_a is emissivity of absorber
ε_c is emissivity of cover

b) When absorber is rotated, the heat is transferred due to conduction only through the air present in gap between absorber and cover. It is calculated by equation of h_{cond}

$$h_{cond} = \frac{K_{air}}{r_a} \frac{1}{ln\left(\frac{r_c}{r_a}\right)} \text{... in W/m}^2\text{K}$$

Where,

r_c is radius of cover in m
r_a is radius of absorber in m
L_a is length of absorber in m
K_{air} is thermal conductivity of the air at temperature T_a

c) When absorber is in stationary condition, the heat is transferred due to natural convention dominantly than conduction through the air present in gap. The natural convective heat transfer coefficient, h_{conv} is calculated by correlation

$$Nu = 0.424\,(GrPr)^{0.25}$$

Where,

Nu is Nusselt's dimensionless Number $= \frac{h_{conv}\, d_a}{K_{air}}$

Gr is Grashoff's dimensionless Number $= \frac{g\beta\,\Delta T L^3 \rho^2}{\mu^2}$

Pr is Prandlt's dimensionless Number $= \frac{\mu Cp}{K}$

Therefore

$$h_{conv} = \frac{Nu\ x\ K_{air}}{d_a} \quad \text{... in W/m}^2\text{K}$$

d) Thermal resistance offered to heat transfer in between absorber and cover is

$$\frac{1}{R_1} = h_{r-a-c} + h_{cond} \quad \text{........ When absorber is rotating with some speed}$$

$$\frac{1}{R_1} = h_{r-a-c} + h_{conv} + h_{cond} \quad \ldots\ldots\ldots \text{ When absorber is in stationary condition}$$

e) The loss of heat from the top of cover takes place due to flow of surrounding air. It is calculated by considering film coefficient due to wind, h $_{wind}$

$$h_{wind} = 5.7 + 3.8\,V \qquad \ldots \text{ in W/m}^2\text{K}$$

Where,

V is velocity of wind or tangential velocity of cover $(R_a.\omega)$

f) The loss of heat from the cover also takes place due to radiation. It is occurred on references of cover temperature and sky temperature. It is calculated by considering radiation heat transfer coefficient, h $_{r-c-s}$

$$h_{r-c-s} = \frac{\sigma\varepsilon_c(T_c+T_s)(T_c-T_s)(T_c^2+T_s^2)}{(T_c-T_{atm})} \qquad \ldots \text{ in W/m}^2\text{K}$$

Where,

h_r is radiation heat transfer coefficient in W/m^{2}K
σ is Stefan Boltzmann's constant = 5.67 x 10^{-8} W/m^{2}K^4
ε_c is emissivity of the cover
T_c is average temperature of cover in K
T_{atm} Atmospheric temperature in K
T_s is sky temperature for radiation in K which is given by
$T_s = T_{atm} - 6$

g) Thermal resistance for radiation and conduction modes of heat transfer between absorber and cover is R_2

$$\frac{1}{R_2} = h_{wind} + h_{r-c-s}$$

h) Overall heat loss coefficient from the top (U_{top}) is given by

$$\frac{1}{U_{top}} = R_1 + R_2 = R_{top}$$

i) Rate of heat loss from top of the absorber is given by

$$Q_{top} = U_{top}A_a(T_a - T_{atm}) \qquad \ldots \text{ in W}$$

Where,

A_a is surface area of absorber in m^2

j) Rate of heat loss from dish ends of absorber due to conduction is calculated by

$$Q_{edge} = \frac{K_{insu}\;A_{end}\,(T_w - T_a)}{b} \qquad \ldots \text{ in W}$$

Where,

b is thickness of dish ends of absorber
K is thermal conductivity of insulation material used in the side cover
$A_{end} = \frac{\pi}{4}d_c^2$, is area of dish ends perpendicular to heat transfer in m^2
d_c is diameter of cover in m

k) Total heat loss from the top and side (Q_L) is given by

$$Q_{loss} = Q_{top} + Q_{edge}$$

$$Q_{loss} = U_{top}A_a(T_a - T_{atm}) + \frac{K_{insu}\;A_{end}\,(T_w - T_a)}{b} \qquad \ldots \text{ in W}$$

6.6 Total Solar Energy Input

Total solar energy input to the rotating solar boiler is given by

$$Q_{in} = H_b R_b A_r \qquad \ldots\text{in W}$$

Where,

A_r is effective area of aperture in m^2 = $(W - d_a)L_a$

6.7 Efficiency of Solar Rotating Boiler

It is given by

$$\eta = \frac{Useful\ energy\ gain\ by\ absorber}{Total\ Solar\ Energy\ Input}$$

$$\eta = \frac{Q_{useful}}{Q_{in}}$$

$$\eta = \frac{H_b R_b \rho\gamma(\tau\alpha)_c A_a \ - \left[U_{top}\, A_a (T_a - T_{atm}) + \frac{K_{insu}\ A_{end}\,(T_w - T_a)}{b}\right]}{H_b R_b A_r}$$

VII. EXPERIMENTAL INVESTIGATION TO DETERMINE EFFICIENCY OF THE ROTATING SOLAR BOILER

The rotating solar boiler is designed to claim the advantage of centrifugal force acting on water due to rotation of absorber. It is only possible, when centrifugal force is more than gravitational and buoyancy forces. For this, device should fulfil following condition [1].

$$\frac{v_a^2}{R_a} > g$$

The selected speeds for the absorber during this study are given in the table 1

Table .1 Different Speeds considered for experimental work

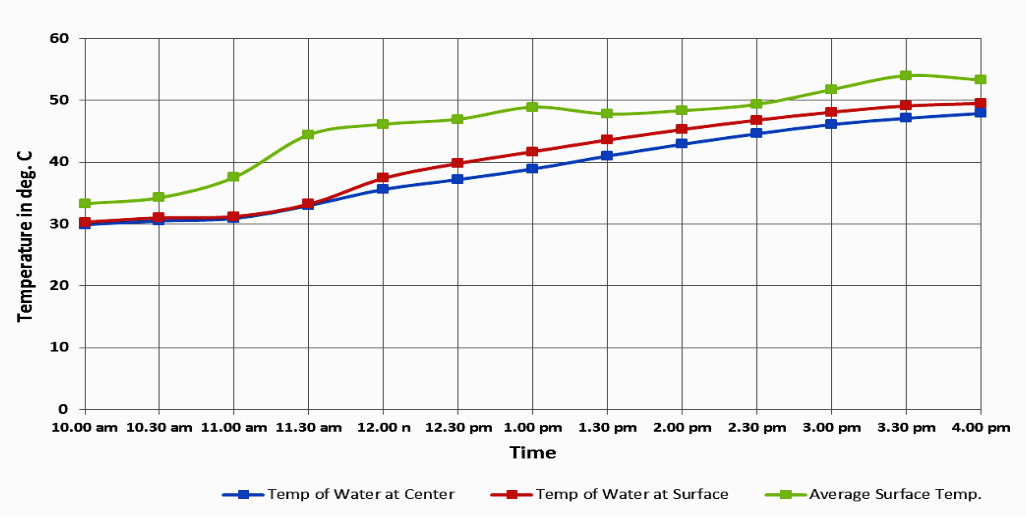
Sr. No.	Speed of Rotation in rpm	Tangential Velocity	$\frac{v_a^2}{R_a}$	Remark
1	Stationary	0	0	Not satisfied
2	40	0.628	2.62	Not satisfied
3	60	0.942	5.9157	Not satisfied
4	80	1.256	10.51	Satisfied
5	100	1.57	16.43	Satisfied

Figure 6 Photograph during experimental work

As mentioned earlier, we conducted experiments on rotating solar boiler working under stationary, 0, 40, 60, 80 and 100 rpm conditions. The manufactured Rotating Solar Boiler has 30cm absorber diameter, 40 cm cover diameter with 85 cm length. The absorber sheet has thickness of 2 mm. All experiments were performed by following standard testing procedure of solar collector. The summary of these observations along with detail calculations are done and represented in form of graphs. These all results are considered to make the interpretation about thermal performance of rotating solar boiler.

VIII. RESULT DISCUSSION

8.1 Effect on Rise in Temperature of Water for Stationary Absorber



As discussed earlier, in conventional parabolic collector, cold water remains at center and hot water is nearer to surface of absorber throughout its working period. Thus it provides lower temperature difference nearer the surface. Thus rate of heat transfer is less in system. Figure 7 represent variation of temperatures of water at center of absorber, nearer to surface of absorber and surface temperature of absorber over period of time. It indicates that temperature of water at center is less than that of temperature nearer to surface of absorber. In stationary condition, water does not attend the maximum temperature of surface of collector over entire period of a day. The maximum surface temperature of absorber is 53.3 ^{o}C at the end of day and higher temperature of water at surface is 49.5 ^{o}C.

It also shows that surface temperature of absorber is increasing with time and having higher value. It is responsible to increase the heat loss from the top of cover. This is because heat loss due to radiation and conduction from absorber depend upon the surface temperature of absorber. As these are given by following equations

$$h_{r-a-c} = \frac{\sigma(T_a - T_c)(T_a^2 - T_c^2)}{\frac{1}{\varepsilon_a} + \frac{1}{\varepsilon_c} - 1}$$

$$Q_{top} = U_{top} A_a (T_a - T_{atm})$$

8.2 Effect on Instantaneous Efficiency for Stationary Absorber

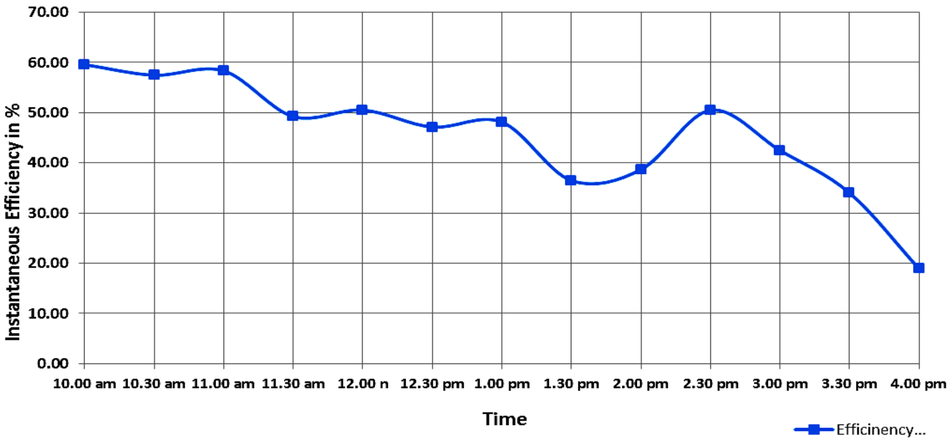


Figure 8 Effect on instantaneous efficiency at stationary condition

Figure 8 represents effect on instantaneous efficiency at stationary condition. It shows that efficiency is also higher at morning session and decreases with time. It highlights that rate of decrease of efficiency is very high. It varies from 59 % to 18 %. The efficiency curve is showing large irregular nature as losses are more. From results of stationary conditions, we come to know that average useful heat energy received by water is 186.08 W and temperature of water at end of day is 49.5 ^{o}C.

8.3 Effect on Rise in Temperature of Water (80 rpm Speed of Absorber)

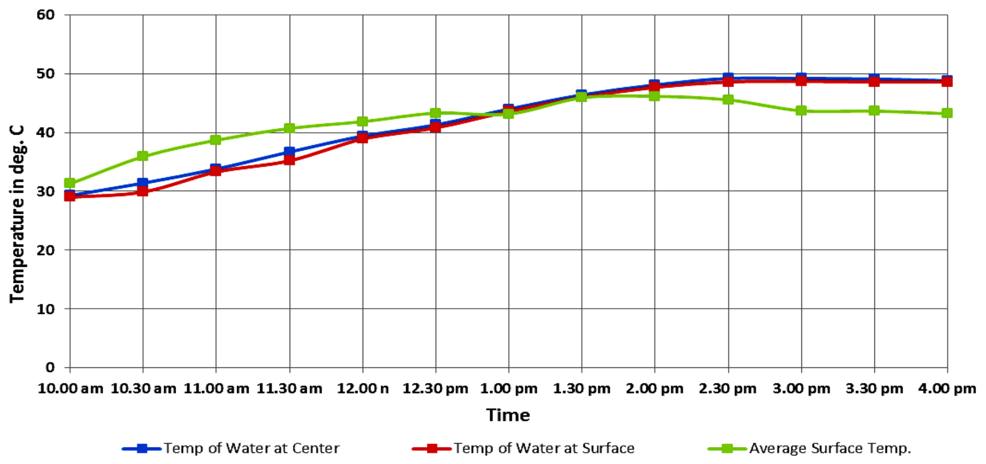


Figure 9 Effect on rise in temperature of water at 80 rpm

In rotating solar boiler, centrifugal force is acting on water due to rotation of absorber. This force helps to enhance the heat transfer in absorber. It is only possible, when centrifugal force is more than gravitational and buoyancy forces. It takes cold water nearer to surface of absorber and provides maximum temperature difference. For this, device should fulfil following condition

$$\frac{v_a^2}{R_a} > g$$

For 80 rpm speed, this condition is fulfilled as it gives $\frac{v_a^2}{R_a} = 10.51$.

Figure 9shows that, hot water is accumulated at centre as it has higher temperature than the temperature of water at surface of absorber. Similarly average temperature of absorber is comparatively less which results in lower heat loss from collector. Same time, water achieves the maximum temperature of absorber within less time period i.e. approximately in three hours. It indicates that the rate of heat transfer is more at 80rpm than that of previous cases.

8.4 Effect on Instantaneous Efficiency (80 Rpm Speed of Absorber)

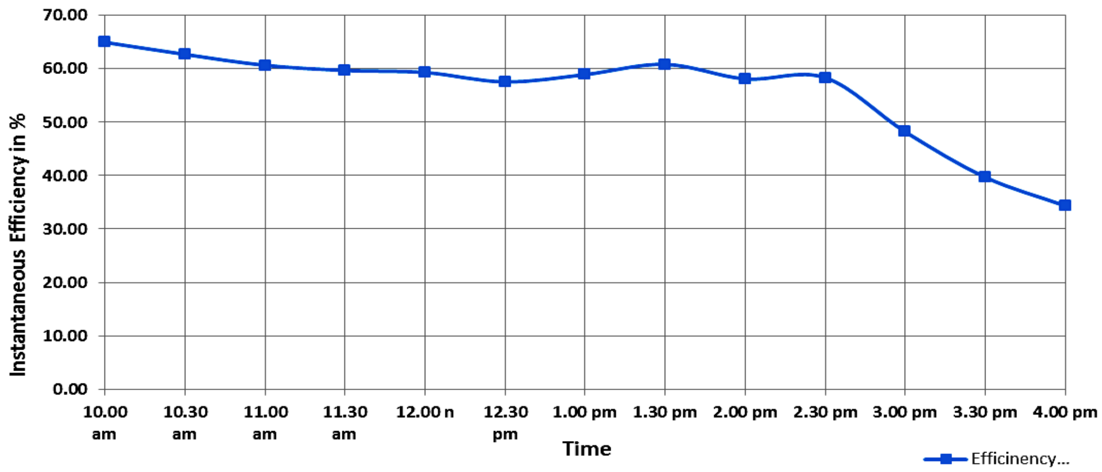


Figure 10 Effect on instantaneous efficiency at 80 rpm

Effect on instantaneous efficiency at 80 rpm is given in Figure 10. The maximum efficiency is recorded with this speed of rotation. It is also important that efficiency remains constant for longer period and showing higher values at all observations compare to previous all cases. Instantaneous efficiency has range of 35 to 66 %. Hence it is concluded that this speed of rotation is more optimum or desirable speed for effective working of Rotating Solar Boiler.

IX. CONCLUSIONS

Present study has suggested new design for solar collector named as Rotating Solar Boiler. This innovative design of solar collector is studied systematically. This rotating solar boiler may be contributed in the future of solar energy application considerably. Because, it shows number of positive results

1. The average temperature of absorber is more with stationary absorber which causes for higher heat loss. But due to rotation of absorber at different speeds, temperature of absorber is less hence losses from top are reduced. In stationary condition, absorber temperature varies between 33 to 53 ^oC. On the other hand, it varies from 31 to 46 ^oC with 80 rpm.

2. Rotation of absorber takes the cold water at the surface of absorber due to centrifugal force action and hot water at centre; it increases heat transfer between the water inside the absorber and absorber surface due to higher temperature difference.

3. Similarly centrifugal force is acting on air layer between cover and absorber of device. It prevents the convective heat transfer in the air layer and contributes to reduce in heat loss from top of cover. At 80 rpm, heat loss is well below which varies from 15 - 64 W whereas for stationary absorber, heat loss varies from 37 to 143 W.

4. These two effects are more effective and dominant with 80 rpm, hence maximum efficiency is observed at this speed. Instantaneous efficiency has range of 35 to 65 % at this speed. It is 9 to 15 % greater than stationary absorber and other cases of rotations.

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