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Research Article

Thermal Performance Analysis of Water Heating System for a Parabolic Solar Concentrator: An Experimental Model based design

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Abstract

The work presented in this paper deals with the question of how solar energy might most effectively and efficiently be used in supplying energy for water heating. For this an experimental model based performance analysis is carried out between two models. The water temperature is raised from 20°C to 68.7°C with glass-covered ½ copper tube and 20°C to 62.4°C with glass-covered ½ aluminium tube. The thermal performance analysis is carried out through a mathematical modeling of the system for optimize results.

Keywords: *Thermal losses, material selectivity, absorptivity, mass flow rate, operating parameters, thermal efficiency etc.*

1. Introduction

The performance model of the solar collector is focused on a coated absorber pipe enclosed in a glass envelope: the receiver of the parabolic trough solar collector (PTSC). The experimental model is a steady state, single dimensional model and is based on fundamental material and energy balances. Incident solar energy on the solar collector is distributed among useful energy gain, optical losses, and thermal losses. The model deals with the thermal losses resulting from conduction, convection and radiation heat transfer to the surroundings, from the receiver. The parabolic trough solar collector model is based on energy balance relations for the absorber pipe and the glass envelope together with heat transfer correlations for the various the energy streams among them and the surroundings. This model predicts how the efficiency of the PTSC is influenced by different parameters like direct normal solar radiation, the incidence angle, collector dimensions, material properties, the operating temperature, the presence of air in the annular space, the wind speed, the operating flow rate, air temperature and the relative humidity present in air.

2. Fluid mechanics and heat transfer

A. Introduction

In the systems like being described here, the elements therein presents some resistance to the fluid flow, results in pressure drop which modify the flow and influence the operation. If a force is applied uniformly over a certain area A, the pressure over that area P will be given as the ratio between these two quantities:

$$P = dF/dA = (d(\dot{\mathbf{m}}.\mathbf{a}))/d\mathbf{A}$$

The exchange of energy between two bodies of different temperatures is called *heat transfer*. This mechanism or modes of transformation of energy generally occurs via three different ways like radiation, convection and conduction. In solar thermal processes, the way in which the assessment of heat transfer takes place amongst different key elements of solar hot water system essentially requires system design and performance predictions. The radiation heat transfer mode of energy transformation occurs through electromagnetic radiation emission and absorption between bodies of different temperature and is known as thermal radiation. This mode does not require any solid medium to propagate. This mode, mathematically, can be described through Stefan-Boltzmann equation, which describes the energy rate emission:

$$q_r = \sigma.A.T^4 \qquad (1)$$

The emissivity of real surfaces is dependent upon the wavelength, temperature properties, physical properties and geometrical properties of the surface. For analytical calculation, in order to use constant values for emissivity following assumptions are made:

- Radiation properties are independent of wavelength.

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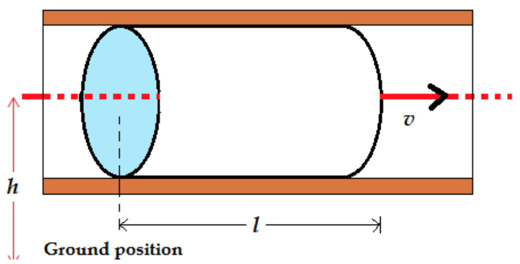
- Surfaces are diffuse equally.
- Surface temperature is uniformly distributed.
- Incident energy is uniformly distributed over the surface.

Thermal energy gained or lost by a body during the process of heat transfer can be expressed in terms of the temperature change undergone by the body itself, the mass of body and the capacity. The variation in energy can be expressed by equation:

$$E = Q = M.C_P.(T_{initial} - T_{Fluid}) \quad (2)$$

B. Pressure loss

For laminar flow, the volume of a liquid flowing through a tube is directly proportional to the pressure difference driving the liquid and proportional to the fourth power of the tube radius.



The above statement is supported by Poisseuille's law, which accurately describes the flow of liquids through pipes as long as laminar flow exists, mathematically:

$$L_F = (\pi.r^4.\Delta P)/(8.\rho.l) \quad (3)$$

Where: r = radius of pipe
ρ = viscosity of water
ΔP = differential pressure
l = length of pipe

If a force is applied uniformly over a certain area A, the pressure over that area P will be given as the ratio between these two quantities:

$$P = dF/dA = d(m.a)/dA \quad (4)$$

For fluid flow in pipes, A is the cross sectional area of the pipe. The volume (V) occupied by a fluid is related to its mass (m) via the mass density (ρ):

$$\rho = dm/dV \quad (5)$$

Where: $dV = d(A.l)$
or $dA.l.\rho = dm$
or $P = \rho.a.l$

While dealing with situations which involves pressures in fluid, the force causing the pressure are the weight of the fluids or the fluid elements, such as the pressure developed at the bottom end of the hot water tank. In this case:

$$P = \rho.g.h \quad (6)$$

3. Planning of prototype system

An accurate design of parabolic trough collector is done by the use of the software called PARABOLIC CALCULATOR 2.0 Version, which is easily available on the internet. Table 1 defines various parameters used for optimize designing of the parabola and figure 1 shows the graph showing the coordinate values of the parabola designed using software GRAPHIMATICA.

Table 1 Different parameters with their design values

Parameter	Design value (in ft)
Linear Diameter	4.59
Volume	6.28
Area	12.57
Depth	1.00
Diameter	4.00
Focal Length	0.25

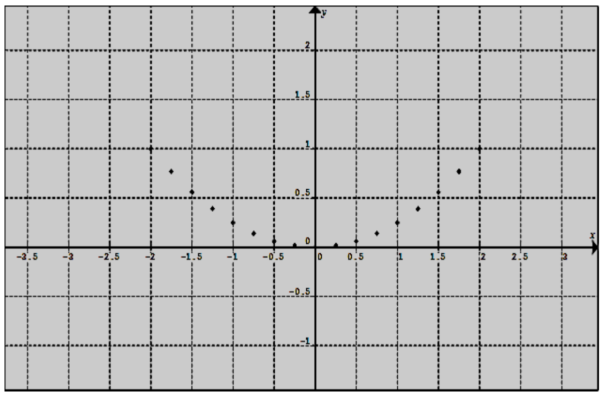


Figure 1: Graph showing the values of x, y calculated with help of software GRAPHMATICA

A. Design & Fabrication

The design of parabolic trough collectors are structurally rather more simpler than other types of concentrated collectors but it requires more accuracy and precision for continuous tracking so as to make sure that concentration of solar radiations is good enough on the absorber tube throughout the day. The precise design and accurate dimensions on x, y directions of a PTSC ensures the better optical efficiency of whole system and hence also improves the overall thermal efficiency.

B. Design parameters

The design parameters of parabolic trough collector can be classified into two categories:

1. Geometric
2. Functional

The geometric parameters of a PTSC systems includes its aperture width and length, rim angle, focal length, diameter of the glass envelope (if required) and the concentration ratio. While the functional parameters includes optical efficiency, instantaneous and overall thermal efficiency and receiver thermal losses.

Main sources of errors are due to the defects in reflector material, support structure, location of receiver w.r.t the focal plane of PTSC and misalignment of the parabolic trough collector:

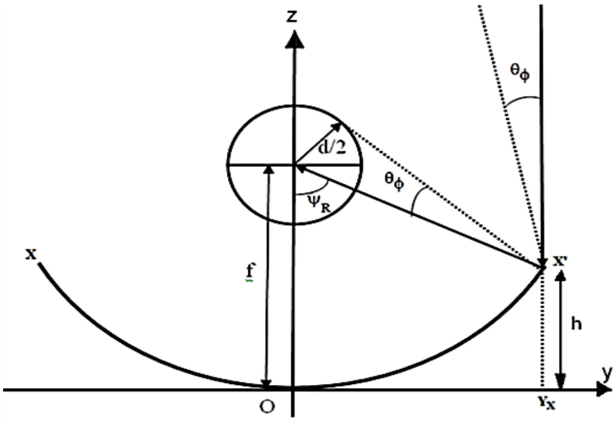


Figure 2: Design parameters of PTSC

The corresponding points are obtained by the use of this software and hence a perfect parabolic shape is made at different values of x and y axes.

Equation of parabola: $Y = 0.041667X^2$

Focal point at (1/4a) is:

¼(0.041667) = 6 above origin

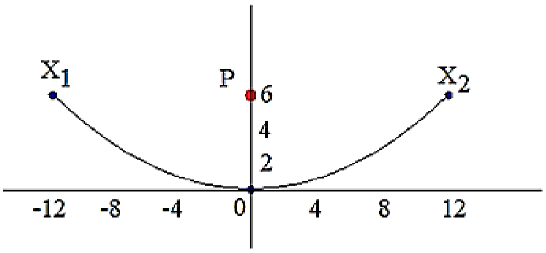


Figure 3: Parabola design using Parabola Calculator

Let length of parabola (or the linear diameter) from point X_1 to X_2 be S and t be twice the focal length:

$$t=2f$$
$$q = \sqrt{(t^2+P^2)}$$

where P is the distance from origin to X

Thus, $S = ([P.q/t] + t.\,ln[(P+q)/t]$ (7)

Where P =12 and t = 2×6 = 12.

Also $q = \sqrt{(12^2+12^2)} = 16.97$ (all units in inches)

On substituting the values of P, t and q in equation (7), we get

S = 27.54 (approx.)

Thus, linear diameter (X_1 to X_2) will be S = 27.55

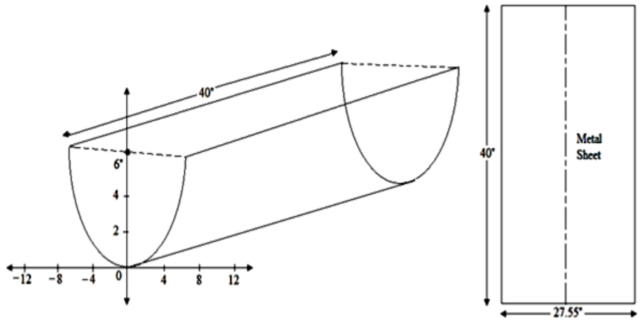
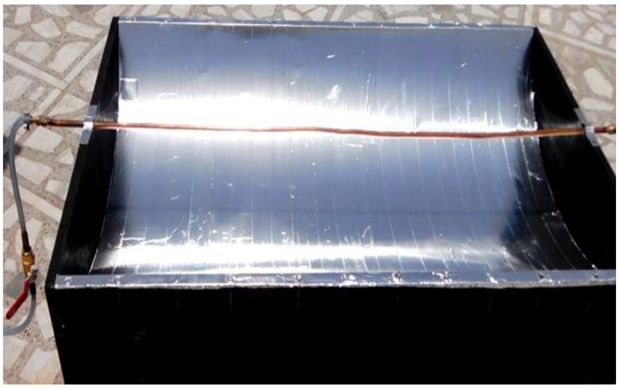


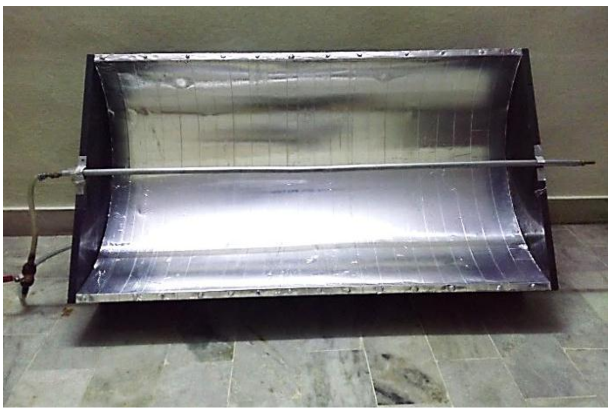
Figure 4: Scale to Collector

C. Fabrication of prototype Parabolic Trough Solar Collector System

After being finalizing the design considerations of the parabolic trough solar collector the main task is to fabricate the PTSC system with the use of different easy available materials and more economic. The main emphasis is on reducing the cost of PTSC system by the use of different alternate materials without compromising on the quality and hence performance of the system. The fabrication of PTSC system is shown in below figures:



(a)



(b)

Figure 5: Parabolic Concentrator with (a) Cu absorber tube (b) Al absorber tube

4. Working experimental model

A. Heat Transportation

The collector performance is a function of the temperature of the fluid entering the collector.

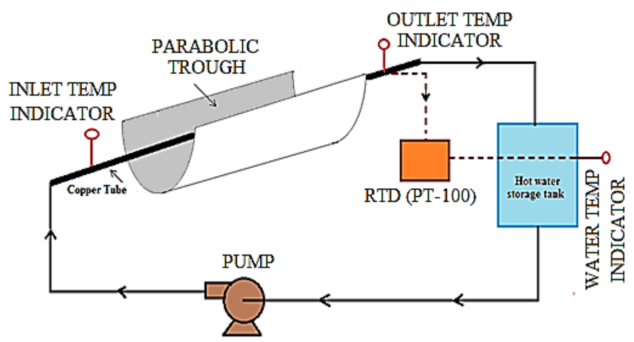


Figure 6: Basic experimental set-up

This temperature is the same as the temperature in the exit portion of the storage unit. On neglecting the heat losses from the connecting pipes, the outlet temperature from the collector becomes the inlet temperature to the storage unit. Following figure shows the basic schematic arrangement for water flow through the receiver copper pipe.

The model for SHWS is composed of six sections:

- Heat collection elements: concentrating collector panel and absorber copper boiler tube (½) array where the heat transportation or phase change takes place.
- Reservoir (approx. 15 liter) that supplies water to the absorber tube.
- Storage tank
- Conveyance system (tubes, valve and pipes)

The HWST used in the experimental set up is of 15 liters capacity filled with water, as a working fluid. Water is circulated to the absorber tube with the help of a water pump which is located inside the storage tank. The mass flow rate of water through the absorber tube is 0.1344kg/sec. During circulation it gains heat in the absorber tube and comes back in the storage tank. The water is then re-circulated again and again through the absorber tube throughout the whole day. A glass cover tube is used over the absorber tube to reduce the conduction, convection, and radiation losses.

B. Working parameters

The fabricated PTSC has different components e.g reflector, absorber tube, support structure, etc. The work is mainly concentrated on the experimental investigation and comparison of different material absorber tube with the use of glass cover and comparative results are obtained. Following are the main components of the experiment carried out:

1. ½ diameter Aluminium with glass tube cover 45mm in diameter
2. ½ diameter Copper tube with convective glass tube 45 mm in diameter

Here the aperture area is $1.4 m^2$.

5. Result & discussion

The performance of the fabricated PTSC hot water generation system is determined by obtaining the values of collector's performance, like:

- Useful heat gain
- System thermal efficiency
- hourly thermal efficiency for different combinations of:
    - Daily solar radiation ($kWh/m^2/day$)
    - Wind speed (m/s)
    - Air temperature (°C) at minimum & maximum levels and average level
    - Relative humidity (%)

All the parameters are measured as a function of time over one hour period under transient and steady state conditions. The ambient temperature, storage tank water temperature and collector outlet water temperature is measured with the help of RTD (Pt-100) digital output indicating instrument.

A. Project location	*Climate data location*
Location: Jaipur, Rajasthan, India	Jaipur/Sanganer
Latitude: 26.84 ˚N	26.82 ˚N
Longitude: 75.78 ˚E	75.80 ˚E
Elevation: 390.00 m	390.00 m Ground

B. Steady state performance analysis test of PTSC

The PTSC test was performed only on clear days when the DNSR (direct normal solar radiance) was greater than $6 KW/m^2$. The following results are obtained with the experimental analysis of the fabricated PTSC system for hot water generation.

The calculations are based on the steady state incompressible energy equation (8) utilizing Darcy-Weisbach friction losses equation (9) as well as minor losses. The calculations computed are flow rate, velocity, pipe diameter.

For the experimental set up in figure,

$$h_P - h_T = h_{OUT} - h_{IN} + h_{Losses} \tag{8}$$

$$h_{IN} = h_{OUT} + h_{Losses}$$

$$\acute{Z}_1 = f \frac{L}{D}\left(\frac{V^2}{2g}\right) + K\left(\frac{V^2}{2g}\right) \tag{9}$$

$$\acute{Z}_1 = f_A \frac{L_A}{D_A}\left(\frac{V^2}{2g}\right) + f_B \frac{L_B}{D_B}\left(\frac{V^2}{2g}\right) + f_C \frac{L_C}{D_C}\left(\frac{V^2}{2g}\right) + K\left(\frac{V^2}{2g}\right)$$

For these factors, the Reynolds's number (Re) at 20oC, on assuming the temperature changes in pipe are neglected on *V*, is given by:

$$Re = \frac{u.D}{\nu} = 1.34 \times 10^4 \quad (10)$$

V = 1.06 m/sec

Assume that f_A = 0.029 and f_B = 0.029 from Moody's Chart. Concentration ratio C = $\frac{A_a}{A_r}$ = 78.2 % (Calculated on average day Solar radiance of 6.79 KW/m2)

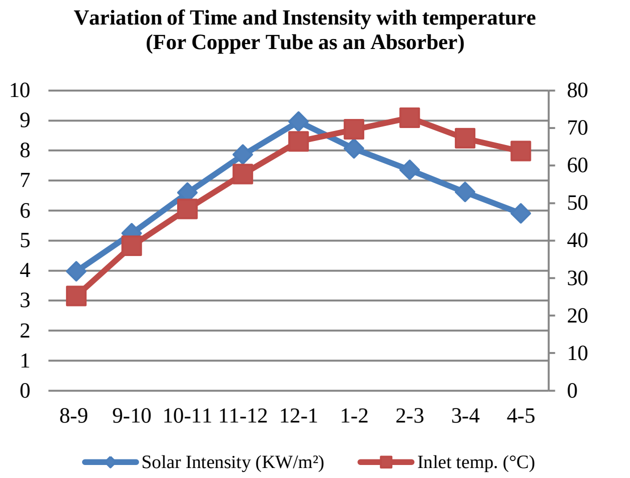
Mass Flow rate ($\dot{m}$) is calculated by:

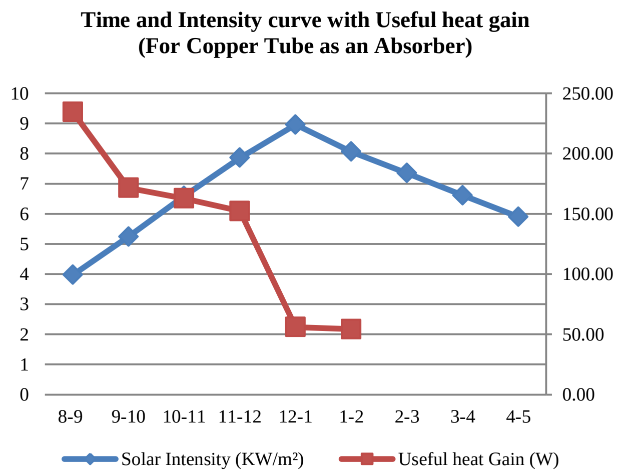
Q =A.V = 3.55 × 10-2 gal/sec

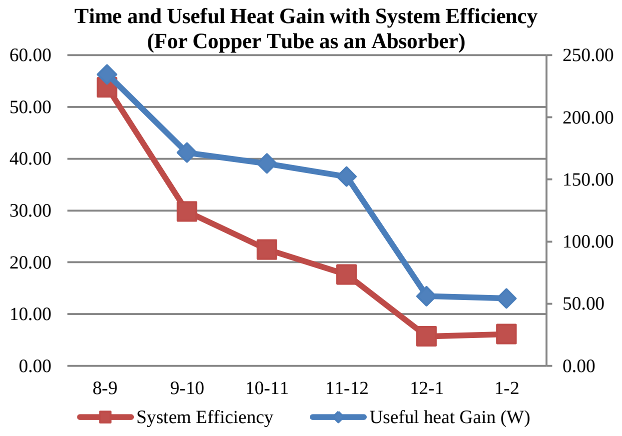
$\dot{m}$ = 0.1344 Kg/Sec

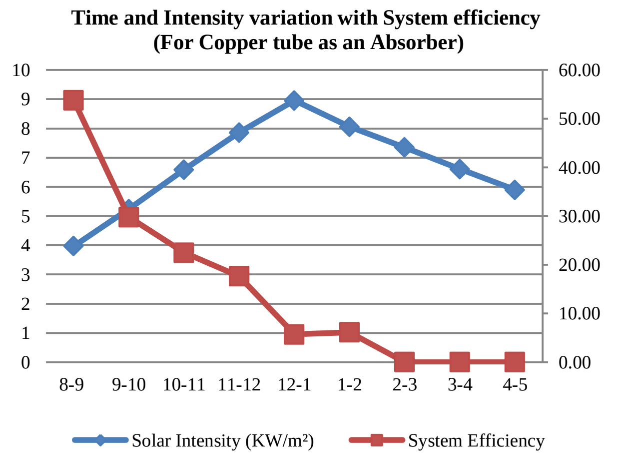
The following graphs show the variation of different quantities for Copper and Aluminium tubes as an absorber four ways:

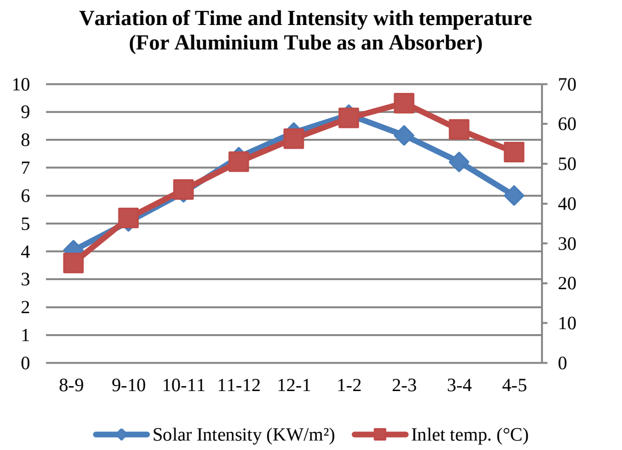
a) Variation of time and intensity with temperature
b) Variation of time and intensity with useful heat gain
d) Variation of time and intensity with thermal efficiency

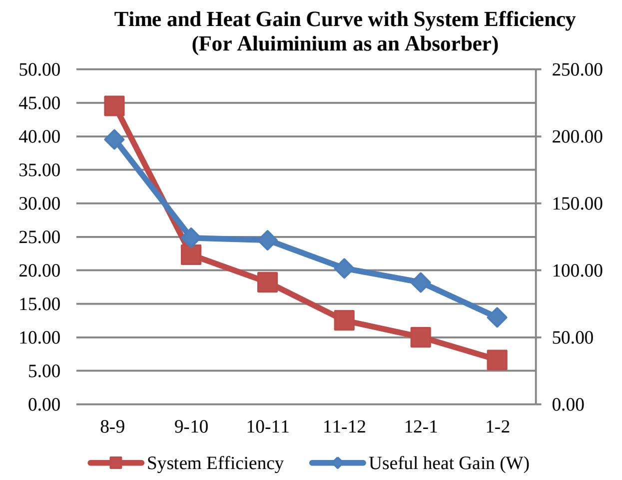


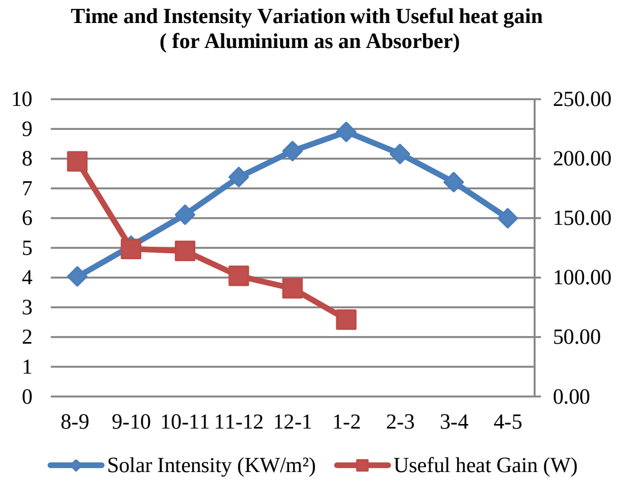


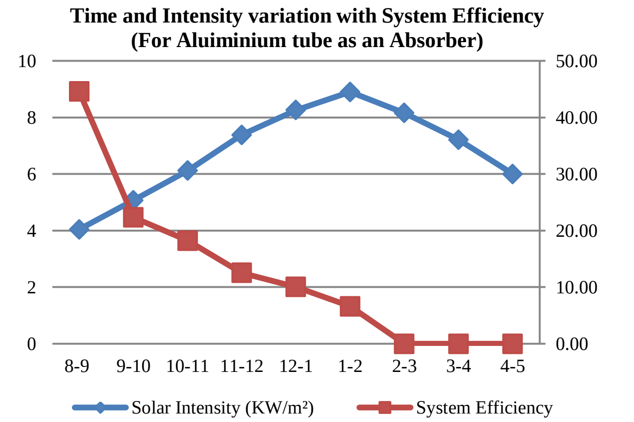












6. Discussion

It is observed from the graphical representations of the both Aluminium and Copper absorber tube that:

a) As the time increases the temperature of the water increases from 25.2ºC at 8:00 A.M to the peak temperature of 65.2 ºC for Aluminium tube and 72.7 ºC for Copper tube at 2:00 P.M.
b) Due to increase in thermal losses the temperature of water decreases after 2:00 P.M and the solar intensity also decreases with the increase in time. The temperature of water decreases more rapidly than the solar intensity.
c) The maximum increase in temperature of water is between 8:00 A.M to 9:00 A.M and the minimum increase is between 1:00 P.M to 2:00 P.M.
d) As the time and solar intensity increases the instantaneous efficiency and thermal efficiency decreases up to the peak temperature.
e) Both the efficiencies are at their maximum values between 8:00 A.M-9:00 A.M.
f) The useful heat gain also decreases with an increase in time.

Conclusion

The above results are compared with that of an Aluminium absorber tube and it is observed that the maximum temperature of water in the storage tank is higher when copper tube is used. The hourly thermal efficiencies and instantaneous efficiency is also higher in case of copper tube. Also the values of the useful heat gain taken hourly are higher in comparison to the Aluminium tube. As the thermal conductivity of copper is higher than Aluminium therefore the peak temperature of the water in the storage tank is attained at 1:00 P.M which is earlier than that in case of Aluminium tube. So the use of copper tube gives the better performance and results than the Aluminium tube and hence it is used further in the experiment with the glass cover tubes of different diameters.

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