# Investigation of Mathematical Modelling to Assess the Performance of Solar Flat Plate Collector

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**Abstract-** A study was under taken to assess the performance of solar flat plate water heater. A customized test rig was used to know the performance. Heat transfer phenomena in the collector system were calculated by using theoretical model. Study revealed that the following results have effects on the performance of the solar collector system. To improve the thermal efficiency of the solar collector system, inlet water temperature should be as low as possible. The efficiency increases more or less linearly with ambient temperature. Increasing the thickness of insulation beyond 5 cm is worthless. Efficiency of the solar collector system will decreases with increase of wind speed. Transmission ratio of glass cover should be more than 0.95 in order to obtain higher thermal efficiency of the collector. If ambient temperature increases there will be higher efficiency of solar collector system because of less heat loss to the surroundings.

**Keywords-** Solar flat plate collector, Mathematical model, Thermal efficiency of solar collector, Useful heat gain, Solar water heating.

## 1. Introduction

There are 0.7 million solar water heater user households, in the residential sector in India. About 65% of which is concentrated in Karnataka and Maharashtra according to Greentech Knowledge solutions [1]. S. P. Sukhatme and J.K. nayak [2] studied the performance of solar flat plate collectors and found out that collector could be used to heat the water up to 100$^{o}$C. Solar energy is the prominent energy of the future as the fossil fuels diminishes day by day. The sun generates its energy by nuclear fusion of hydrogen nuclei to helium. The sun's total energy output is $3.8x10^{20}$ MW, which is equal to 63 MW/M$^2$ of the Sun's surface according to Soteris A. kalogiro [3]. Solar energy radiates outwards in all the directions. The earth receives only small fraction of the total radiation, it is estimated that 84 min of solar radiation falling on earth is equal to the world energy demand for one year [3]. This solar energy can be directly converted into heat by using various solar thermal systems. Flat plate solar collector is one of such collector systems. The advantages of flat plate collectors are as follows which are inexpensive to manufacture, collect both beam and diffuse radiation, and are permanently fixed, so no tracking of the sun is required. Effect of tubular spacing in the flat plate collector was studied by considered two identical collector of spacing of 11cm and 20 cm. The collector with 20 cm spacing of tubes performed better than 11 cm spacing according to Fatigun et al. [4]. In order to reduce the construction cost and maintenance, an integrated collector-storage system with a parabolic reflector was fabricated by A. Teyeb et al. [5], from locally available materials in the Tunisian market. For classical Tunisian climatic conditions, the model, based on the optical and thermal properties of the collector showed that the efficiency of the system varies by 30% for the ambient temperature, 40% for cold water temperature and 9% for the wind velocity according to A. Teyeb et al. [5]. Performance of fixed flat plate collector was compared with solar collector with tracking. P. Rhushi

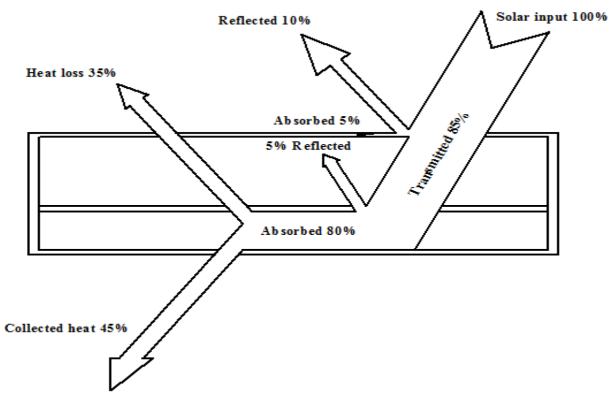
Prasad et al. [6] found from the study, efficiency of flat plate collector with tracking was more than 21% of fixed flat plate collector. Top loss coefficient of the flat plate collector with single glass cover was evaluated by both theoretically and experimentally by Y. Raja Sekhar [7] in laboratory conditions. Efficiency of the collector increases with increase of ambient temperature due to reduction of heat loss from the system.

A sandwich type of collector made by 1mm GI sheets with integrated canals, coated with silica based black paint was fabricated to compare the performance of collector system with conventional collector .Raj thundil karuppa et al. [8] found that there was little difference in the performance of collector between conventional flat plate collector and collector made of GI sheets. As GI sheets are much cheaper than copper and there is no need of bracing the plate and tube, hence GI sheets can be used as absorber materials for low operating temperature. Mobile integrated collector storage system was built to study the performance of collector under Southern Africa. According to M. N. Nieuwoundt and E.H. Mathews [9] water could be heated up to 60°C by mid-afternoon.

This paper presents the effect of various parameters like cold water inlet temperature, ambient temperature, insulation thickness, wind speed, transmission coefficient of the glass cover, on the performance of the solar collector system for Bangalore (13° N, 77.56° E) climatic conditions. A well-known "Hottel-Whiller-Bliss equations were used to assess the performance of solar collector system

### *1.1. Problem Statement*

Figure 1 shows a schematic drawing of the heat flow through a collector. The question is how to measure the thermal efficiency of the collector system, i.e. Instantaneous efficiency of the system.




(Source: www.lth.se/fileadmin/ht/Kurser/MVK160/Project_08/Fabio.pdf)

**Fig.1.** Heat flow through a flat plate collecctor

Thus it is necessary to define step by step, the singular heat flow equations in order to find the governing equations of the collector system.

If ($I$) is the solar irradiation, in w/m², incident on the aperture plane area ($A$) of the collector m2, then amount of solar radiation received by the collector is:

$$Q_i = A\,I \tag{1}$$

However, as it shown in Figure1, a part of this solar radiation is reflected back to the sky, a part of it is absorbed by the covering glass and the remained is transmitted through the absorber plate in turn transmitted to the working fluid. Therefore, the conversion factor indicates the percentage of the solar rays penetrating the transparent cover of the collector and the percentage being absorbed.

Basically, it is the product of the rate of transmission of the cover and the absorption rate of the absorber.

$$\text{Thus, } Q_i = A\,I\,(\tau\,\alpha) \tag{2}$$

As temperature increases in the absorber plate due to incident radiation, part of its heat loss to the surroundings in the form of convection and re-radiation. The rate of heat loss ($Q_o$) is depends upon the temperature of collector and overall heat transfer coefficient ($U_L$).

$$Q_o = U_L\,A(T_c - T_a) \tag{3}$$

Where $T_c$ is an average temperature of the collector and $T_a$ is an ambient temperature in degree centigrade.

Thus, the rate of useful heat gained by the collector under steady state condition is less than heat loss to the surrounding by the collector.

This is expressed as follows,

$$Q_u = Q_o - Q_i = U_L A(T_c - T_a) - A\,I\,(\tau\,\alpha) \tag{4}$$

Also amount of heat gained by working fluid is measures the rate of heat absorbed by the collector, that is:

$$Q_u = mc_p(T_o - T_i) \tag{5}$$

In equation (4) somewhat challenging to measure the average temperature of the plate. It is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful heat gain if the whole collector surface were at the inlet fluid inlet temperature. This quantity is known as "the collector heat removal factor ($F_R$)" and is expressed as:

$$F_R = \frac{mc_p(T_o - T_i)}{[I\tau\alpha - U_L(T_i - T_a)]} \tag{6}$$

When whole collector is at the inlet fluid temperature then the maximum possible useful energy gain in a collector is occurs. The actual useful energy gain is obtained by multiplying the maximum possible useful energy gain by the collector heat removal factor ($F_R$). Then equation (4) can be rewrite as follows:

$$Q_u = F_R A[I\tau\alpha - U_L(T_i - T_a)] \tag{7}$$

Equation (7) is known as the "Hottel – Whiller – Bliss equation" is the widely used expression to measure collector energy gain.

Instantaneous collector efficiency is defined as the ratio of useful heat gain to the radiation incident on the collector is

$$\eta = \frac{Q_u}{AI} = \frac{F_R A[I\tau\alpha - U_L(T_i - T_a)]}{AI} = F_R\tau\alpha - F_R U_L\left[\frac{(T_i - T_a)}{I}\right]$$

For the given collector and flow rate, if it is assumed that $F_R$, τ, α and $U_L$ are constants, then the efficiency is a linear function of the three parameters defining the operating condition i.e. Solar radiation ($I$), Fluid inlet temperature ($T_i$) and Ambient temperature ($T_a$).

## 2. Material and Methods

The absorber plate radiates small amount of heat from back side because of higher temperature. This loss mechanism is due to the function of emittance of the surface for low temperature and long wavelength radiation. Special coatings on the absorber surface increase the absorption of sunlight. One or two transparent cover plates are used to reduce heat loss due to convection, conduction and re-radiation from the top surface. But complete prevention of convective losses is not possible, because convection currents exist between plates and cover sheet.

The collector performance is function of temperature difference between inlet and ambient temperature to solar. Collector performance is calculated by using inlet fluid temperature, but not the average fluid temperature. Every correlation using fluid inlet temperature must specify the fluid flow rate at which measurements are made. The recommended test flow rate for liquid flat plate collector is 0.02 kg/s [3]. Radiation on the aperture area is the total radiation on collector should be considered to calculate thermal performance of the system. This reduces cosine loss of the beam component as collector is tilted from the horizontal.

**Table 1**. Material selection and Design of the collector

| PROPERTY | VALUE |
|---|---|
| Length of the collector | 2 m |
| Width of the collector | 1 m |
| Length of the absorber plate | 1.95 m |
| Width of the absorber plate | 0.95 m |
| Material of the absorber plate | Copper |
| Thermal conductivity of the plate material | 386 W/m k |
| Density of the plate material | 8954 kg/ $m^3$ |
| Plate thickness | 34 gauge |
| Diameter of the tube | 6.35 mm |
| Tube centre to centre distance | 100 mm |
| Number of tube | 9 |
| Glass cover absorptivity/emissivity | 9.3 |
| Diameter of the header tube | 12.7 mm |
| Insulating material used | Glass – Wool |
| Thermal conductivity of insulating material | 0.032 W/m k |
| Density of insulating material | 200 kg/$m^3$ |

Experimental setup for the above said task is carried out by using customized solar flat plate collector system as shown in Figure 2. It consists of water container, flat plate collector, pyranometer and flow meter. Provisions are made to measure inlet, outlet temperature of the working fluid, temperatures of the absorber plate and flow rate. Water from the storage tank enters the flat plate collector and gets heated up as it flows through the riser tube and then hot water enters the storage tank due to density difference. At the same time cold water is replaced from the storage tank. Thermo syphon an effect is sets up within the system. Flat plate collector is tilted at an angle of 25° to the horizontal and facing due south. Experimental set up was placed at latitude of 13° N and longitude 77.56° E, on the top floor of the Mechanical department, Dayananda sagar college of engineering, Bangalore. Experiments were conducted on clear sunny days in the month of April 2013 in order to minimize uncertainty errors in the measurements. Test procedure was followed according to ANSI/ASHRAE [10] to study the thermal performance of solar flat plate collector.

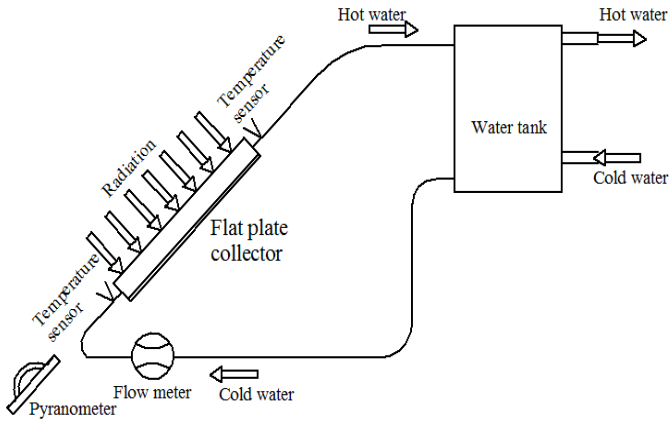



**Fig. 2.** Experimental setup

## 3. Results and Discussion

*Effect of parameters on the efficiency of solar collector system:*

*3.1. Effect of the average cold water inlet temperature:*

Figure 3 shows the effect of cold water inlet temperatures ($T_i$) on thermal efficiency of the collector system. Figure 3 shows inlet temperature has a strong influence on thermal efficiency of the system, as inlet temperature of water is increased, the efficiency of the collector system will be decreased. Teyeb [5] studied the influence of climatic data on collector system, in that study also found similar variation of efficiency versus inlet temperature. In order to improve the thermal efficiency of the solar collector system, inlet water temperature should be as low as possible.

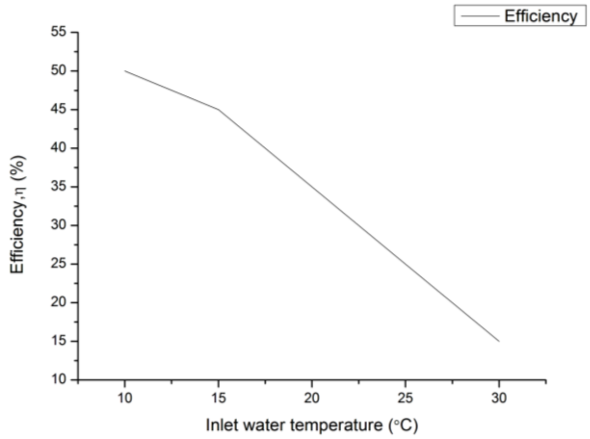



**Fig. 3**. Influence of the inlet water temperature on the system efficiency

*3.2. Effect of the Average Ambient Temperature:*

The effect of the average ambient temperature on the system efficiency is immediately perceptible from the Figure 4. This is also having impact on efficiency of the collector system. The efficiency increases more or less linearly with ambient temperature. Increase in ambient temperature reduces of heat loss by radiation, convection and conduction. So, ambient temperature depends on solar radiation. According to Soteris A. Kalogirou [11] from the basic definition of thermal efficiency of solar flat plate collector, efficiency is increases with increase of ambient temperature. Thermal efficiency intern depends on solar incident radiation.

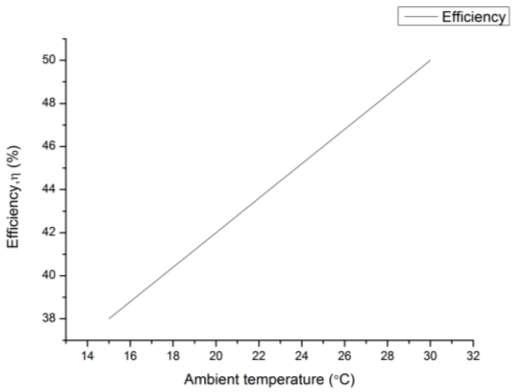



**Fig. 4.** Influence of ambient temperature on the system efficiency

*3.3. Effect of Insulation Thickness on the System Efficiency:*

Effect of insulation thickness: Figure 5 shows variation of efficiency versus insulation thickness. Steady reveals that as it does not have any influence on thermal performance of the system increasing the thickness of insulation beyond 5 cm is worthless. Tomas Matuska et al. [12] used mathematical model and design software tool to evaluate thermal performance of flat-plate collector. The efficiency was poor for the 20 mm insulation and show better efficiency in the range of 50 to 60 mm insulation. So, our experimental results also show similar results.

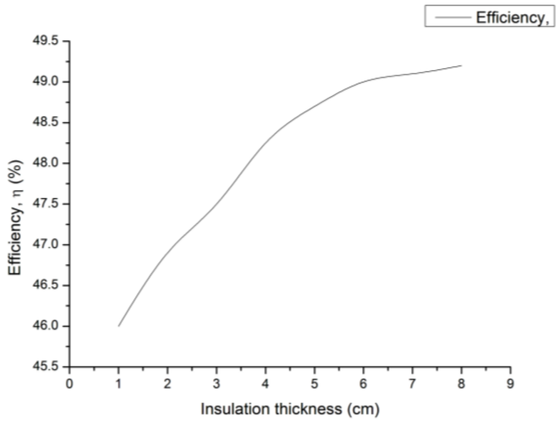



**Fig. 5**. Effect of insulation thickness on the system efficiency

*3.4. Effect of Wind Speed:*

Effect of wind speed on the instantaneous efficiency as shown in Figure 6. As expected efficiency decrease with increase of wind speed. This is due to overall heat loss to the surroundings from the system. Convection heat loss occurs between front side of the collector and ambient media. Effect of wind speed on the efficiency of the system is about 6%. Variation of the efficiency of the collector with respect to wind speed is in accordance with other researchers [5, 13].

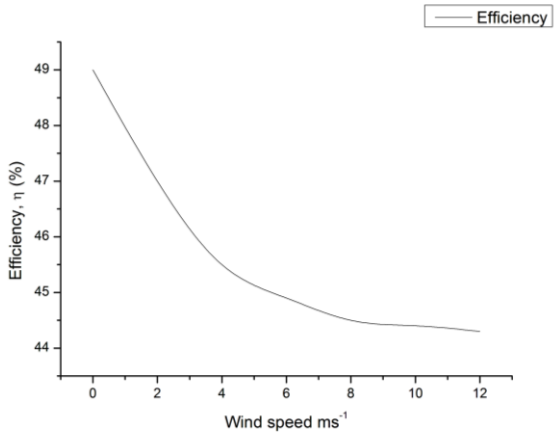



**Fig. 6.** Variation of efficiency with wind speed

*3.5. Effect of Transmission Coefficient of the Glass Cover:*

Optical characteristic of glass cover is one of the important parameters of solar flat plate collector system. Figure 7 shows efficiency of the system is directly proportional to the transmission coefficient of the glass cover. So transmission ratio of glass cover should be more than 0.95 in order to obtain higher thermal efficiency of the collector. Glass cover should have low iron content in it to obtain higher transmission ratio.

Glass cover also reduces convective heat transfer between absorber of the system and the ambient media. The transmission coefficient effects on efficiency of the system in single glass cover system. It will be interesting to investigate its effects on the efficiency with double cover system. Teyeb et al. [5] found similar trends in the variation of efficiency in the study of influence of the climatic data and construction properties on the efficiency of a collector/storage solar water heater.

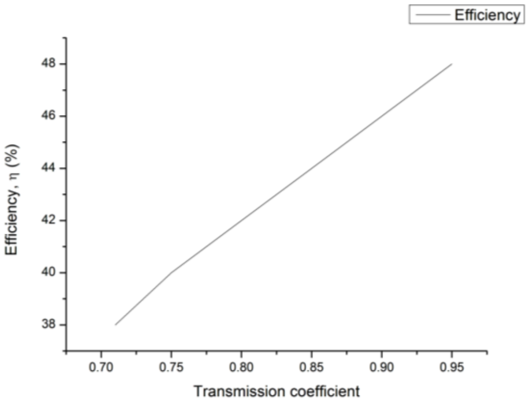



**Fig. 7.** Effect of transmission coefficient of the glass cover .

*3.6. Variation of Instantaneous Efficiency with Time:*

Variation of instantaneous efficiency of solar flat plate collector is shown in Figure 8, as irradiation increases, the efficiency also increases with time. It is seen that efficiency is almost same from 8:00 AM to 9:30 AM, and then increases to maximum efficiency of 51% from 12 noon to 13:00 PM. After 13:00 PM it gradually decreases as irradiation decreases. Variation of efficiency is in accordance of Rhushi Prasad et al. [6].

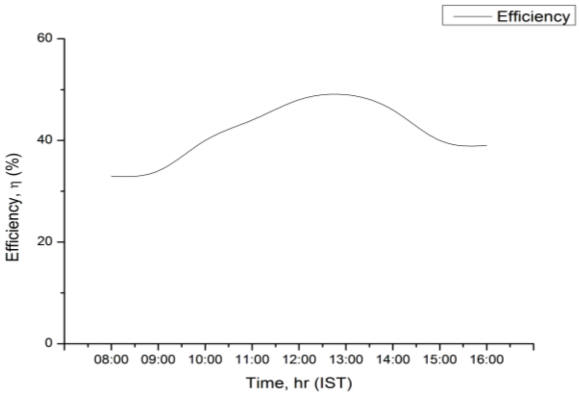



**Fig. 8**. Variation of instantaneous efficiency with time (IST)

3.7 Variation of efficiency according to Klein model: Figure 9 shows the instantaneous efficiency curve was obtained from Klein model versus ratio of temperature difference of ($T_c$ – $T_a$) to the solar radiation rate ($I$) for different values of the average absorber temperatures with wind speed velocity of 1.6ms$^{-1}$. As ambient temperature decreases instantaneous efficiency will also decreases, due to heat loss to the surroundings from the system. If ambient temperature increases there will be higher efficiency of solar collector system because of less heat loss to surroundings. For a collector operating under steady state irradiation and mass flow rate, efficiency versus heat loss parameter is a straight line. A Similar trend was observed by Andoh et al. [14] and Soteris, Kalogirou [11].

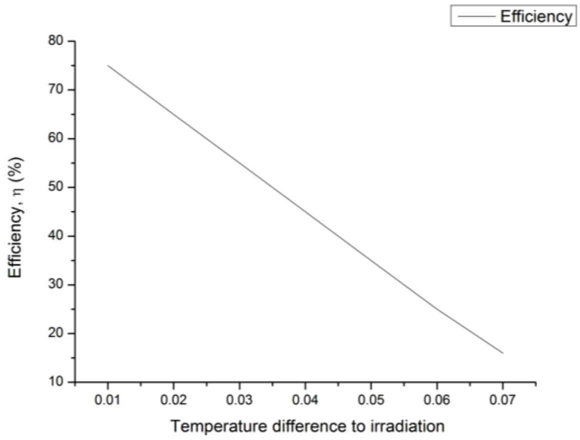



**Fig. 9.** Variation of efficiency with ratio of temperature difference to the solar radiation

## 4. Conclusion

Mathematical models were investigated to study various heat transfer phenomena in solar flat plate collector system. As inlet temperature of water increases, the efficiency of the collector system will decrease. The efficiency increases more or less linearly with ambient temperature. Increase in ambient temperature decreases loss of heat by radiation, convection and conduction to the surroundings. Increasing the thickness of insulation beyond 5cm is worthless as there is no effect on the efficiency of system. Instantaneous efficiency increases to maximum from 12 noon to 13:00 PM. and it also proportional to ambient temperature. Efficiency of the system decreases with the increase of wind speed, due to the heat loss to the surroundings. Transmission coefficient of transparent covers should be more than 0.95 in order to obtain higher efficiency of the collector system. The efficiency could be improved by using good selective coatings.

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