Mathematical modelling and performance analysis of single pass flat plate solar collector

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Abstract. Various type of solar collectors has already been designed and developed. A solar flat plate collector is used to raise the temperature of the passing fluid (air/water) from it. In the present work, a single cover flat plate solar collector was fabricated using the standard methodology proposed by other researches for the construction of conventional solar air heaters. The variation of the solar radiation, the air outlet temperature and the variation of absorber plate temperature throughout the day were recorded. The efficiency, effective optical efficiency, and the effective heat loss coefficient of single cover flat plate solar collector were calculated. The effect of wind velocity on collector’s performance was also studied. The effective optical efficiency of the fabricated collector, effective heat loss coefficient, and the efficiency of the collector was found to be 72.7 %, 8.422 W m⁻² K⁻¹, 36.73 % respectively.

1. Introduction

Solar collectors are devices that transform solar energy into some sort of heat energy using a fluid medium. Solar collectors absorb solar radiation converting it into thermal energy and transfers this energy into a fluid flowing through the solar collector. Now, this heated fluid is used in space conditioning and many other application fields. The solar collector is also equipped with storage tanks so that it can be used when solar radiation is not present. Solar collectors are used in thermo-syphon, space heating and cooling, desalination, solar furnaces, refrigeration and heat generation.

Many researchers have reviewed various types of flat plate solar collectors with various applications [1]–[4]. The basic types of the solar collector are: concentrating and non-concentrating. For the non-concentrating collector, intercepting and absorbing radiation area are same, whereas a concentrating solar collector uses the concave surface to intercept and focus the radiation beam to a smaller receiving area which increases radiation flux. These two types of collectors are further divided into large numbers of collectors depending upon their uses and shapes.

Thermal performance of the flat plate solar collector depends upon the transmittance, absorption and conduction of solar energy and working fluid conductivity. The absorber plate is an important component of solar air heater to decide its performance. In designing the solar collector plate, efficiency factor and heat removal factor are important parameters. Sekha et al. [5] worked on the solar collector and reduced empiricism associated in the design of solar collector. Many researchers have analyzed the maximum energy conversion by the use of coatings applied to the absorber plate [6]–[9].
It has been found that the thermal conductivity of the collector’s absorber plate depends upon fin efficiency factor and heat removal factor and cost factor is the most critical factor in designing a collector [10], [11].

As can be seen from the aforementioned arguments, solar energy systems can be used for a wide range of applications and provide significant benefits, therefore, they should be used whenever possible. Flat plate solar collectors are characterizing with the shape of the solar collector and thermal reflectivity of plate and absorptivity of the plate. The more dominant parameters are reflectivity and absorbing coefficient. The time for which solar energy is incident on the plate and tilt angles of the plate is also dependent parameters for performance analysis of flat plate solar collector. Choudhury et al. [12] proposed construction curves for conventional air heaters for economical designing of flat plate solar collector.

In the present work, a single cover flat plate solar collector is fabricated using the methodology used in the construction of conventional solar air heaters [13]–[15]. The variation of the solar radiation, the air outlet temperature and the variation of absorber plate temperature throughout the day were recorded. The efficiency, effective optical efficiency, and the effective heat loss coefficient of single cover flat plate solar collector are calculated and the effect of wind velocity on collector’s performance is also studied.

2. Proposed methodology

For the construction of the collectors, the methodology proposed by Choudhury et al. [12] was selected. They proposed construction curves for the conventional solar air heater. In these curves, they proposed different curves for construction for three types of solar air heaters. In this work, a single cover flat plate solar collector using the curve data provide by Choudhury et al. [16].

In this methodology, for the construction of the collector’s acceptable values following parameters as inputs have to be predetermined like length of the absorber (decided on the basis of the floor space available), pressure drop (decided by the capacity of the air blower), the mass flow rate of air (decided by the flow of heat energy required for the job to be done by the collector), the air temperature increment for unit incident flux (decided by the metrological data of the place where this collector was being used).

With the help of the design curves, the absorber’s area, absorbers width and depth of the duct were calculated with the following steps:

1. First, select the length of the collector.
2. Then, select the pressure drop and the mass flow rate of air on the basis of where the collector is going to be used.
3. Collect meteorological data of the place where the collector is going to be used.
4. Then, calculate the temperature increment of the air per unit incident flux.
5. Now, with the use of graph between temperature increment of the air per unit incident flux and length for various fixed values of mass flow rate per unit area, find the mass flow rate per unit area.
6. Then, calculate the required air flow from the collector.
7. With the use of required air flow from the collector and mass flow rate per unit area, calculate the area of the collector.
8. Now, with the use of graph between length and duct depth for various fixed values of the mass flow rate per unit area, find the duct depth.

The solar flat plate collector fabricated by the above procedure is shown in Figure 1.
2.1. The positioning of Solar Collector

Flat plate solar collector’s efficiency depends upon positioning of the solar collector. In the fabricated solar collector, the tilting mechanism is provided to obtain the maximum efficiency. The period during which 80% of the collectable solar energy falls on the collector is known as a solar window. In general, the time period from 9 am to 3 pm is considered as “solar window”. The sun’s position determines optimal angles and direction of the solar panel of the collector at different times of the year.

In the northern hemisphere of the earth, the sun is highest in the sky summer season and also in the sky for more hours than it is in the winter. The opposite is true for winter. The solar panels are placed at an angle, 15° less than the latitude where they are installed in the summer and 15° more than the latitude of the place where the collector is installed. The collector faces south, towards the sun for maximum flux absorption. The effect of sun position in the northern hemisphere of the globe is also considered. Sun’s radiation is tilted to 23.5° about its mean position which affects the incident energy and conversion energy of solar collector. Beam radiation has unique direction and can be converged by reflection and refraction technique but diffused radiation cannot be concentrated and does not follow the optical principles. The flat plate collector absorbs direct and diffused both types of radiations. Therefore, the flat plate collector does not require sun tracking system and also has a very little maintenance cost. Though, optical efficiency is less due to large surface area heat loss.

The concentrating ratio is defined as the ratio of the area of the aperture to the area of the receiver. The concentrating ratio for the study is found to be 1. The metallic tubes were soldered/welded to absorber plate. Hence, insulation prevented heat loss from the rear surface and sides of the collector. The glass cover permits short wavelengths solar radiations but opaque to larger infrared radiations. For operation from January to December the tilt can be taken as 0.9 times the latitude for Indian conditions.

2.2. Designing and Fabrication

As stated in the previous sections, some parameter’s values were predetermined in this designing methodology. The length $(L)$ was taken as 150 cm and pressure drop was taken as 30 Pa. From the
metrological data in the month of March, April and May, the average ambient temperature \( T_a \) was found to be 35 °C and the average solar radiation \( I \) was found to be 875 Wm\(^{-2}\). The solar collector was used for drying Chilies. Hence, air outlet temperature \( T_o \) should not be more than 65 °C. From above data temperature increment per solar radiation, \( \frac{T_o-T_i}{I} = 0.034 \). For the experiments, 6 kg of chillies were taken for drying. The chillies water content before \( m_i \) and after drying \( m_f \) was found as 80 % and 10 % respectively. From the aforementioned data, the mass of water to be evaporated was calculated as 5 Kg. The required flow rate of the air was calculated as 50 Kg h\(^{-1}\) m\(^{-2}\), the width of the collector was calculated as 65 cm and depth of duct was calculated as 10 mm with the help of construction curve between length and temperature increment per solar radiation.

3. Mathematical Modelling

In the present design, the transparent cover is placed directly above the absorber plate and there is a layer of air between cover and absorber. The fluid to be heated runs between the layer of insulation and the inner surface of the absorber. Energy flow in this design was studied from [7], [12], [17]–[21]. The theoretical and analytical results were compared from the benchmark results directly above the rear plate of the collector. Following equations can be obtained as the steady-state energy balance equations. The heat transfers that take place in single cover solar air heater are shown in Figure 2.

For the absorber plate:

\[
\alpha_p r_g S = h_{cpf}(T_p - T_f) + h_{cpb}(T_p - T_g) + h_{rpb}(T_p - T_b) + h_{rpg}(T_p - T_g)
\]

For the flowing air:

\[
h_{cpf}(T_p - T_f) = h_{cbf}(T_f - T_b) + \frac{mc_f dT_f}{W dx}
\]

Bottom plate:

\[
h_{cpf}(T_f - T_b) + h_{rpb}(T_p - T_b) = U_b(T_b - T_a)
\]

For cover:

\[
\alpha_g S + h_{rpg}(T_p - T_g) + h_{cpb}(T_p - T_g) = (h_w + h_{rs})(T_g - T_a)
\]

The boundary conditions for the above sets of equations:

\[
T_f(x = 0) = T_{f_i}, T_f(x = L) = T_{f_0}
\]

![Figure 2. Schematic showing heat transfer in single cover solar air heater [12]](image)

In the mathematical model of the flat plate solar collector proposed by Ong [13], there is no heat transfer in between the system and the top cover and there is negligible heat transfer between the cover and stagnant air cavity. Only free convection takes place in an inclined wall cavity. Hence the balance equations obtained for this design of solar collector are the same as proposed by Choudhury and Garg [12] instead of the equation for the flow of air which was replaced by the following equation:

\[
h_{cpf}(T_p - T_f) = h_{cbf}(T_f - T_b) + \frac{2mc_f}{W L}(T_f - T_{f_i})
\]

The equation for the flow of the air is replaced by

\[
\frac{mc_f dT_f}{W dx} = h_{pf}(T_p - T_f) + h_{bf}(T_b - T_f)
\]
4. Performance of the solar collector

The performance of the collector is determined by the distribution of incident solar energy into useful energy and various thermal as well as leakage losses. To measure collector performance, it was exposed to solar radiation and we measure the fluid inlet $T_i$ and outlet $T_o$ temperatures and the flow rate of the fluid. The useful gain is calculated as

$$Q = m.C_p(T_o - T_i)$$

(8)

Under steady state condition, the useful heat delivered by the solar collector is equal to the energy absorbed in the metal surface minus the heat losses from the surface to the ambient environment. The useful heat output of the flat plate collector is given by

$$Q_c = A[I_c(\alpha_a) - U_c(T_{in} - T_{out})]$$

(9)

Introducing the heat removal factor (FR) in the above equation,

$$Q_c = A[I_cFR(\alpha_a) - FRU_c(T_{in} - T_a)]$$

(10)

The efficiency of a general solar collector is stated as the ratio of the useful heat energy output of the collector to the solar energy flux incident on the collector.

$$Efficiency = \frac{\text{useful heat output of the collector}}{\text{solar energy flux incident on the collector}}$$

$$\eta = Qc/AIc$$

(12)

$$\eta = FR(\alpha_a) - FR*U_c(T_{in} - T_a)/I_c$$

(13)

$T_a$ is replaced by $T_p$ in case of air heaters.

$FR(\alpha_a)$ (can be calculated by determining the $y$-axis intercept of the efficiency line equation) is known as the effective optical efficiency and $FRU$ (this can be calculated by determining the slope of the efficiency line equation) is known as effective heat loss coefficient. The outlet temperature of the collector heat transfer fluid is given by

$$T_{out} = T_{in} + Qc/(m*C_p)$$

(14)

The stagnation temperature $T_s$ of the collector, is defined as the temperature of the absorber which is achieved when there is no flow of heat transfer fluid in the collector and therefore, its useful heat output and efficiency both are equal to zero.

$$T_s = T_{in} - T_a + I_c \times (FR(\alpha_a) - FR Uc)/(FRU_c)$$

(15)

5. Results and discussion

A single cover flat plate solar collector/air heater was constructed with the help of construction curve for conventional air heaters. Pyranometer was used for the measurement of the solar radiation, K-type thermocouples were used for measuring collector’s absorber plate temperature, digital thermometer was used in measuring air outlet temperature and Anemometer was used in measuring the velocity of air and wind. The collector was mounted on the stand and the collector was made to face south in the sunshine. Three thermocouples were attached to the absorber plate at 15 cm, 75 cm, and 135 cm across the length of the collector. The observations from the flat plate collector were recorded at the regular interval of 30 minute from 9:00 hours to 16:00 hours and tabulated in Table 1. It can be seen that absorber plate temperature and air temperature at outlet increases as solar radiation increases but wind velocity plays important role in deciding the final value of these temperatures. With the increase in wind velocity both the temperature decreases but the extent by which outlet temperature decreases is more than the absorber plate temperature. The outlet temperature reaches its maximum value 66.9 °C at 1:30 pm and absorber plate temperature reaches its maximum value 82.1 °C at 2:00 pm.
Table 1. Experimental data obtained from the solar collector

| Time (hh:mm) | $V_a$ (m s\(^{-1}\)) | $I$ (W/m\(^2\)) | $T_i$ (°C) | $T_o$ (°C) | $T_p - T_i$ | $\eta$ (%) |
|--------------|------------------------|------------------|------------|------------|-------------|------------|
| 09:00        | 0.1                    | 340              | 28         | 37.9       | 40.6        | 0.037      | 42.07     |
| 09:30        | 0.3                    | 380              | 30         | 39.1       | 46.7        | 0.044      | 34.60     |
| 10:00        | 0.3                    | 560              | 32         | 45.7       | 57          | 0.0446     | 35.35     |
| 10:30        | 0.2                    | 620              | 43         | 58.5       | 69.7        | 0.0431     | 36.13     |
| 11:00        | 0.3                    | 640              | 42.8       | 58.6       | 70.9        | 0.0439     | 35.68     |
| 11:30        | 0.5                    | 660              | 47.9       | 62.9       | 77.6        | 0.0450     | 32.84     |
| 12:00        | 0.1                    | 680              | 48         | 66.3       | 75.8        | 0.0410     | 38.89     |
| 12:30        | 0.5                    | 680              | 48         | 64.1       | 79.8        | 0.0468     | 34.21     |
| 13:00        | 0.5                    | 680              | 47.8       | 64.2       | 78.8        | 0.0456     | 34.85     |
| 13:30        | 0.5                    | 660              | 47.8       | 66.9       | 72.9        | 0.038      | 41.82     |
| 14:00        | 1.5                    | 660              | 47.8       | 61.7       | 82.12       | 0.052      | 30.43     |
| 14:30        | 0.8                    | 620              | 47.5       | 63.5       | 74          | 0.0428     | 37.29     |
| 15:00        | 0.8                    | 620              | 42         | 60.9       | 64.3        | 0.036      | 44.05     |
| 15:30        | 1.8                    | 580              | 40.8       | 55.6       | 64          | 0.040      | 36.88     |
| 16:00        | 0.8                    | 540              | 40.5       | 53.9       | 63.2        | 0.042      | 35.86     |

To calculate the effective optical efficiency and the effective heat loss coefficient, a linear straight line was fitted as shown in Figure 3. The efficiency of the collector was calculated as 36.73 %. The effective optical efficiency was calculated as 72.7 % and the effective heat loss coefficient was calculated as 8.422 W m\(^{-2}\) K\(^{-1}\).

Table 2. Line fitting method for the plot between $(T_b - T_a)/I$ and efficiency

| $x$ $(T_b - T_a)/I$ | $y$ (\(\eta\)) | $x \times y$ | $x^2$ |
|---------------------|-----------------|--------------|-------|
| 0.037               | 42.07           | 0.0156       | 0.001369 |
| 0.044               | 34.60           | 0.0152       | 0.001936 |
| 0.0446              | 35.35           | 0.0158       | 0.001989 |
| 0.0431              | 36.13           | 0.0156       | 0.001858 |
| 0.0439              | 35.68           | 0.0157       | 0.001927 |
| 0.0450              | 32.84           | 0.0148       | 0.002025 |
| 0.0410              | 38.89           | 0.0159       | 0.001681 |
| 0.0468              | 34.21           | 0.0160       | 0.002190 |
| 0.0456              | 34.84           | 0.0159       | 0.002079 |
| 0.038               | 41.82           | 0.0159       | 0.001444 |
| 0.052               | 30.43           | 0.0158       | 0.002704 |
| 0.0428              | 37.29           | 0.0158       | 0.001832 |
| 0.036               | 44.05           | 0.0158       | 0.001296 |
| 0.040               | 36.88           | 0.0148       | 0.001600 |
| 0.0402              | 35.86           | 0.0151       | 0.001764 |

\(\Sigma x = 0.6418\) \(\Sigma y = 550.95\) \(\Sigma xy = 0.2337\) \(\Sigma x^2 = 0.0277\)
Figure 3. Plot of efficiency with $\frac{T_p-T_i}{I}$ for the designed solar collector

The variation of mean solar radiation on absorber plate throughout the day (dated 8/4/2016) (from 9:00 hours to 16:00 hours) is plotted in Figure 4. From the figure, it can be seen that the maximum solar radiation increased till noon and then decreased till 16:00 hours.

Figure 4. Plot showing variation of solar radiation with time

The temperature profile of the flat plate collector throughout the day (dated 8/4/2016) (from 9:00 hours to 16:00 hours) is plotted in Figure 5. From the figure, it can be seen that the temperature of the collector plate increases as the sun’s radiation increases.
Figure 5. Plot showing variation of mean absorber plate temperature with time

The variation of the temperature of the outlet air throughout the day (dated 8/4/2016) (from 9:00 hours. to 16:00 hours) is plotted in Figure 6. From the figure, it can be seen that the outlet air temperature increases as the mean solar radiation on the flat plate collector increases.

Figure 6. Plot showing variation of outlet temperature with time

Figure 7 shows the variation in wind velocity, mean temperature and thermal efficiency of flat plate collector. The thermal efficiency and flat plate temperature are not only affected by the intensity of
solar radiation but this parameter widely affected wind velocity because high wind velocity may extract heat from flat plate collector by means of convection. From Figure 8, it may be concluded that the efficiency of the collector at low solar radiation and low wind speed is higher than as compared to the condition of higher radiation and high wind speed. Hence, it can be concluded that the wind velocity plays important role in the performance of collector. With the increase in wind velocity efficiency of the collector reduces this may be due to the reason that, with the increase in wind velocity the convective heat loss to environment increases.

Figure 7. Plot showing variation of efficiency with wind velocity

6. Conclusions

In the present work, a single cover flat plate solar collector is fabricated and the efficiency, effective optical efficiency, and the effective heat loss coefficient of single cover flat plate solar collector are calculated and the effect of wind velocity on collector’s performance is also studied. A linear straight line was fitted to calculate the effective optical efficiency and the effective heat loss coefficient. Following conclusions were drawn from the study:

1. The efficiency of the collector was calculated as 36.73 %. The effective optical efficiency was calculated as 72.7 % and the effective heat loss coefficient was calculated as 8.422 W m\(^{-2}\) K\(^{-1}\).
2. The maximum solar radiation increased till noon and then decreased till 16:00 hours and the temperature of the collector plate increases as the sun’s radiation increases.
3. The thermal efficiency and flat plate temperature are not only affected by the intensity of solar radiation but this parameter widely affected wind velocity because high wind velocity may extract heat from flat plate collector by means of convection.
4. The efficiency of the collector at low solar radiation and low wind speed is higher than as compared to the condition of higher radiation and high wind speed. Hence, it can be concluded that the wind velocity plays important role in the performance of collector.
5. With the increase in wind velocity efficiency of the collector reduces this may be due to the reason that, with the increase in wind velocity the convective heat loss to environment increases.
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