Solar collector performance analysis with flat and V grooved absorber using java simulation and validation by experiment

Selvanayagi Nevitha*, P Sudhakar², and G Balaji³

M Tech Student, SRM Institute of Science and Technology, Chennai
Asst Professor(SG), SRM Institute of Science and Technology, Chennai
Asst Professor(SG), SRM Institute of Science and Technology, Chennai

*Corresponding author: sachu374@gmail.com

Abstract. The evolving technologies and the diminishing energy resources focuses on utilisation of solar energy. The paper throws a light on the performance analysis of solar collector with flat and v grooved absorber plate utilising simulation (mathematical modelling through JAVA based application) and experimental values. JAVA coding is included to identify the mean outlet temperature of the collector through iteration. The experiment was conducted with varying time of flat and v grooved absorber plate and compared with the values simulated through JAVA application. The simulated results have less than 5% deviation with experimental values. The results figure out that there is an increase in collector efficiency by 5% of solar flat plate absorber plate.

1. Introduction

The ever-growing demand of electricity and diminishing energy resources forces the world to turn to solar and wind energy. Solar energy for just 90 minutes is suffice to cater the annual energy consumption globally. The Potential of Solar energy focuses the world for effective utilisation of solar energy with minimum cost. Solar Collector is used removal of moisture content, heating the space etc depending upon the requirement with either fluid or air as heating medium. To have quality dried products economically at a faster rate, solar energy is harnessed effectively. Several researches were going on to improve the solar collector efficiency. Mathematical modelling and simulation based on JAVA application will help the analysts to check the performance of the solar collector economically.

Mathematical modeling and computation of thermal performance of a single pass solar air collector was presented by Ammari (2003) [1] and found that there is better performance while modifying heater with slat when compared to plain heater. Fabio Struckmann J (2008) [2] analysed the solar flat plate collector and found that overall heat loss coefficient, heat removal factors are not constants but variables.

Different solar air collector’s performance analysis was postulated by Karim et al (2016) show that v groove double pass collector has higher efficiency. [9] More summarises the area to be focused for improving the heat transfer enhancements such as collector plate design, coating of pipes, flow rates, insertion of twisted tubes etc. [5] Rintu Kumar et al (2017) in their simulation has informed that
better drying rate could be obtained for forced circulation than natural circulation due to increased fan velocity. [6] Bashria Abdrub et al (2006) analysed the influence of mass flow rate, flow channel depth and collector length variables on the performance of v groove absorber with single and double flow mode and found that double flow is found to be 4-5% more efficient than single flow mode. [7] Ekadewi A et al (2013) in their paper had optimized the tilt angle of a solar collector for better performance and found the influencing parameters as latitude, time, day, and surface orientation. In this discussion, the influence of increased collector surface area on performance is analysed by incorporating v grooved absorber surface.

2. Set up for Experiment

2.1 Assumptions Made
Underlying assumptions are made for the analysis of the solar collector:
1. Mass flow rate in the collector tubes are assumed as uniform.
2. Heat transfer through the system layers is One Dimension.
3. The collector edges are insulated and heat transfer from the same is negligible
4. Glass and insulation material properties are independent of temperature.
5. All thermal and physical properties of the air gap, fluid (water or air), and absorber are temperature dependent.
6. Loss through front and back are to the same ambient temperature.

2.2 Physical Properties

Table 1. Material Properties and constants

| Property                           | Value         |
|------------------------------------|---------------|
| Thermal conductivity of bottom insulation, \(K_b\) | 0.04 (W/mK)   |
| Thickness of bottom insulation, \(X_b\)   | 0.025 m       |
| Edge area                           | 0.390 m²      |
| Collector area (flat) \(A_C\)        | 0.320 m²      |
| Collector area (V groove) \(A_C\)    | 0.560 m²      |
| No of glass covers                  | 1             |
| \(T\)                              | 0.85          |
| \(A\)                              | 0.96          |
5.67x10^-8

0.12

0.88

4180 J/Kg k

0.0127 m

0.0115 m

0.10 m

58 W/mK

0.0003 m

390 W/mK

2.3 Mathematical Modelling

In a flat plate collector there two type of losses occur. One is the optical losses and the other is the thermal losses. Thermal losses are further divided into edge losses, bottom losses and top losses.

Radiative heat loss happens at collector top.

Convective heat loss happens from glass cover to atmosphere.

Convective heat loss happens from absorber plate to glass cover.

Heat loss coefficient

The top heat loss coefficient by Klein [10] shown in Eq.(1) is used for calculation.

\[
U_t = \left[ \frac{C}{(T_{pm})^4} \right] + \left[ \frac{1}{h_w} \right]^{-1} + \left[ \frac{\sigma(T_{pm} + T_a)(T_{pm} + T_a)^2}{(C + 0.0059 N h_w) + \left( 2 N + 4 + 0.556 \right) \delta g} \right]^N \]

Where

\[ \sigma = \text{Stephan Boltzmann Constant} \]

\[ F = (1 + 0.089 h_w - 0.1166 h_w) * (1 + 0.786 N) \]

\[ N = \text{number of glass covers} \]

\[ C = 520 \times (1 - 0.000051 \beta^2) \]

0 < \beta < 70, for 70 < \beta < 90 take \beta = 70

\[ e = 0.43 \times (1 - 100 / T_{pm}) \]

Heat loss coefficient from bottom is

\[
U_b = \frac{K_b}{X_b} \]

Where

\[ K_b = \text{Thermal conductivity of bottom insulation in w/m}^0 \]

\[ X_b = \text{Thickness of bottom insulation in m} \]

Heat loss coefficient from Edge is given by

\[
U_e = U_b \left( \frac{A_e}{A_c} \right) \]

Where

\[ U_b = \text{Bottom loss coefficient in W/m}^0 \]

\[ A_e = \text{Area of edge in m}^2 \]

\[ A_c = \text{Area of collector in m}^2 \]

Hence Overall Heat Loss Coefficient \[ U_L = U_t + U_e + U_b \]
Fin Efficiency

\[ f = \frac{\tan m \left( \frac{W - D}{2} \right)}{m \left( \frac{W - D}{2} \right)} \]

(5)

Where \( m = \frac{U_L}{K \delta} \)

\( W = \text{centre distance of the absorber tubes} \)
\( D = \text{diameter of absorber tubes in m} \)

Collector Efficiency factor

\[ F^t = \frac{1}{W^t \left( \frac{1}{U_L} + \frac{1}{F_1} + \frac{1}{2D h_f} \right)} \]

(6)

Where,

\( C_b = \text{Bond resistance in W/m}^0K \)
\( D_i = \text{Inner Diameter of absorber tube in m} \)
\( h_f = \text{Heat transfer coefficient of inner tube surface to water in w/m}^2K \)
\( N_t = \text{Nusseltt Number} \)
\( K_{\text{water}} = \text{Thermal Conductivity of water in w/m}^0K \)
\( D = \text{Diameter of absorber tube in m} \)

Collector Heat Removal Factor \( F_R \) is calculated as

\[ F_R = m^c p \left[ 1 - e^{-\left( \frac{F_1 \Delta U_L - U_L}{m^c p} \right)} \right] \]

(8)

where

\( m = \text{mass flow rate of water in Kg/sec} \)
\( c_p = \text{Specific conductivity of water in J/Kg}^0K \)
\( A_c = \text{Collector area in m}^2 \)
\( U_L = \text{Overall loss coefficient in W/m}^2K \)
\( F^t = \text{Collector efficiency facto} \)

Useful Energy Gained

The \textit{useful Energy Gained} by the system is expressed as

\[ Q_u = A_c \times F_R \left[ (\tau a) - U_L(T_R - T_o) \right] \]

(9)

Total Energy

\[ \text{Total Input Energy} = \text{Total radiation (I)} + \text{pump work} \]

(10)

Energy efficiency

\[ \eta = \frac{\text{Useful heat energy gained by system}}{(\text{solar radiation} \times \text{collector area}) + \text{pump work}} \]

(11)
For constant surface heat flux and fully developed single-phase laminar flow (Re < 2300) in a circular tube, Nusselt (Nu) number is constant and independent from Reynolds (Re) and Prandtl (Pr) numbers.

\[ \text{Nu} = \frac{hD}{k} = 4.36 \]  \hspace{1cm} (12)

For v groove surface heat flux and fully developed single-phase laminar flow where 0.5 < Pr < 2000 and 3.10^3 < Re < 5.10^6 in a circular tube, Nusselt number can be obtained by Gnielinski equation which is a modification of Petukhov correlation [10].

\[ \text{Nu} = 4.82 + 0.0185 \cdot (\text{Re} \cdot \text{Pr})^{0.827} \]  \hspace{1cm} (13)

### 2.4 Procedure for finding fluid outlet temperature

The varying input parameters like plate temperature, fluid outlet temperature and thereupon the calculated values are iterated. Initially, heat loss coefficient is calculated using Eq. (1). According to Eq. (1), U_t calculation is dependent on plate temperature (T_p) and is assumed that T_p is equal to fluid inlet temperature plus five degree for calculation of U_t. With the new U_t, Q_u, useful heat is calculated as shown in Eq. (9). Reynolds number is calculated to determine the fluid flow nature (laminar or turbulent), Nusselt number Nu and finally heat transfer coefficient is obtained as per Eq. (12) and Eq. (13). Viscosity (\( \mu \)), density (q), specific heat (C_p), thermal conductivity (k) and enthalpy (h) are calculated for the corresponding fluid temperatures. The calculated enthalpy and outlet temperature are assigned as inlet condition for next iteration and reiterated until T_p and Tout values in present and previous iteration have a convergence criteria of less than or equal to 0.01°C. As fluid outlet temperature is not known, initial fluid mean temperature is calculated as per Eq. (14).

\[ T_m = \frac{T_p + T_{in}}{2} \]  \hspace{1cm} (14)

Once, the heat gain is calculated, the fluid outlet temperature is determined by

\[ T_{out} = T_{in} + \frac{Q_u}{mc_p} \]  \hspace{1cm} (15)

Using Tout, new mean fluid temperature is determined as below

\[ T_m = \frac{T_{in} + T_{out}}{2} \]  \hspace{1cm} (16)

Using the new mean temperature, new Q_u new T_p are calculated as:

\[ T_p = T_{in} + \frac{Q_u}{A_p} \left( 1 - F_R \right) \]  \hspace{1cm} (17)

Then, the algorithm re-evaluates U_t, Q_u by utilizing the new T_p and new T_m.

### 2.5 Technical Stack

The simulator is developed in java which supports performance prediction based on iteration procedure and performance calculation of experimental values also. The equipments included are SFPC with plain absorber plate and plain heat tubes and V Grooved absorber plate with heat tubes. The software components used are,

- The Spring framework with Maven
- The presentation Layer performed by Primefaces 6 and JSF
The business Layer coded in Java 1.8
The backend Layer is in Sqlite db

Start Iteration

Calculate plate temperature with arbitrary value (Ti + 5)

Calculate Q usefull

Based on the Re calculate Nu

Calculate hfi and k, cp and density correspondingly

Tm=(Tp + Tin)/2

Tout=Tin + (Q/mcp)

Tmnew=(Tout + Tin)/2

Calculate Tpnew

If Tpnew-Tp <=0.01

No

Yes

End Iteration

Figure 3. Iteration flow chart
2.6 Graph

Simulation results were compared with the experimental results and the variation of fluid outlet temperature vs energy efficiency, Day time vs efficiency, Day time vs fluid outlet temperature, are plotted as below.

SFPC with Plain Heat Tube:

![Graph](image1)

**Figure 4.** Efficiency vs Fluid Outlet Temperature

It is observed that increase in fluid outlet temperature decreases the efficiency of the system decreases. The simulator data and the experimental data variation are very close and the simulator data is validated and found to be within acceptable limits. Also the variation in Fluid outlet temperature and efficiency in Day time hrs for both simulator and experiment are plotted as below:

![Graph](image2)

**Figure 5.** Fluid Outlet Temperature vs Time
Radiation level and wind speed are plotted for Day time variations. The change in radiation influences the efficiency and outlet temperature. Also the wind speed is considerable influences the heat losses and thus the efficiency of the system:

SFPC with Plain Heat Tube and v grooved absorber plate:

**Figure 6. Efficiency vs Fluid outlet temperature**

The efficiency of the system decreases with raise in the fluid outlet temperature the simulator and experimental data for v groove absorber plate are very close and within acceptable deviations. The efficiency and fluid outlet temperature, radiation and wind speed variations in Day time hrs are as below.

**Figure 7. Fluid outlet temperature vs Time**

**Figure 8. Efficiency vs Time**
3. Conclusion
The developed mathematical model for solar flat plate collector is used to simulate the collector performance under different operating conditions and geometrical change in absorber plate by grooving with V. The simulated and the experimental results are found to be within the deviation limit of 5%. The variations in system efficiency and fluid outlet temperature are observed for both simulator and experiment and found that the efficiency decreases with raise in fluid outlet temperature.

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