Flat Plate Solar Collector Performance Analysis and Parametric Studies

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Abstract:
This study has looked into and reported on heat transport analyses in flat plate collectors (FPC), a non-concentric type solar thermal system. To get the results using water as the working fluid in the absorber tubes of the collector, theoretical modelling and simulation are used. To determine how much heat is lost from the absorber plate to the surrounding air, a total heat loss coefficient is used. As part of parametric analysis, the effects of mass flow rate, inlet temperature, wind speed, and sun radiation are considered.

Keywords: Flat plate collector; Solar thermal; Modeling and simulation; Overall heat loss coefficient; parametric analysis

1. Introduction

Solar collectors are a crucial component of active solar heating systems. They gather solar energy, transform it into radiation to create heat, and then transfer that heat to a fluid (usually water or air). Solar thermal energy can be used to power solar room heating systems, solar pool heaters, and solar water heating systems. It has been proven that numerous different solar collector designs are functional. One of two major groups of solar collectors encompasses these patterns: The entire collector area used to block the sun's rays and the size of the absorbing surface for flat-plate collectors is similar in size. Vast areas of lenses or mirrors used as collectors concentrate light onto a smaller absorber.

2. Methodology

Any climate can use solar water heaters. The effectiveness of these heaters varies depending on the quantity of solar energy present in the area and, more crucially, how chilly the water entering the system is. The solar water heating system works more effectively when the incoming water is cooler. Numerous studies have looked at how well solar water heating systems function; for examples, see and the references referenced therein. Both active and passive solar water heaters are available. The heated water in the active solar water heating system is moved throughout the system by a pump. On the other hand, a passive solar water heating system does not require pumps to circulate the heated water. This type of system is more dependable and straightforward to maintain than active systems because it has no electric components that could malfunction.

Warm water rising, also known as natural convection, is how a thermosiphon solar water heater circulates water through the solar collector and into the storage water tank. The buoyancy-induced flow of heated water from the water heater determines the temperature in the storage water tank. The storage water tank must be located above the solar collector in this type of design. Water in the solar collector naturally rises into the storage tank above as it gets lighter as it gets hotter.

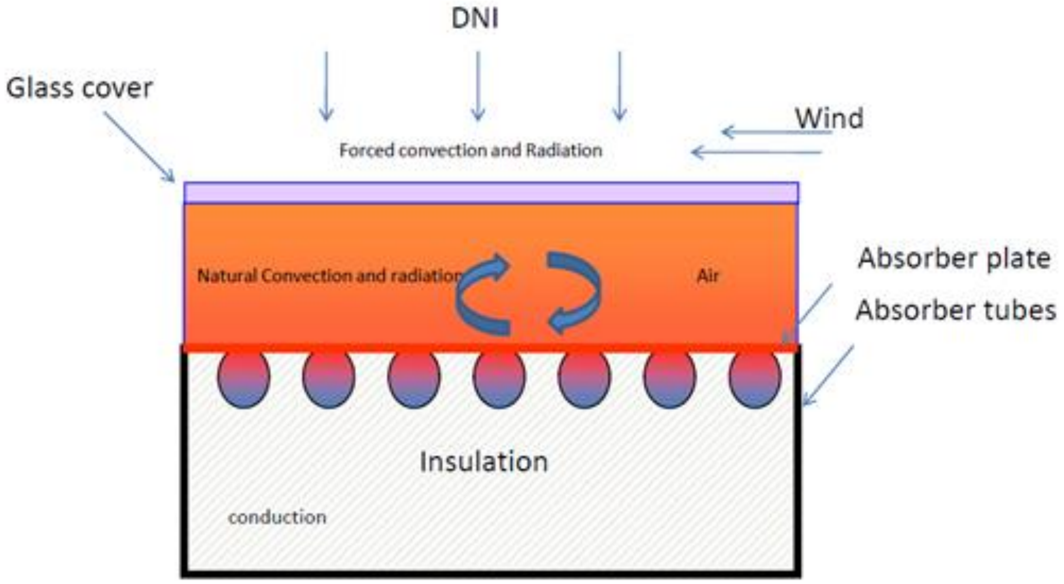

Figure 1: Flat plate collector (FPC)

Collectors are devices used to capture solar heat. In concentrated solar thermal systems, absorber plates or tubes are often employed to absorb heat from reflectors, whereas in non-concentrated systems, sun radiation directly strikes the collectors. For low-temperature heating applications, a Flat Plate Collector (FPSC) is a non-concentrated solar thermal device (Figure 1). After striking a glazing surface, solar energy passes through it and hits an absorber plate. In FPC, low ferrite glass is typically utilized as the cover due to its low reflectivity, low absorptivity, and high transmissivity characteristics. Additionally, convection loss is decreased by using a glass cover. A tiny enclosure separates the absorber plate from the glass cover.

The basic parts that make up a conventional liquid flat-plate collector are i) the absorber plate ii) the tubes fixed to the absorber plate through which the liquid to be heated flows iii) the transparent cover iv) the collector box.

3. Heat Transfer Modeling

An energy balance on the absorber plate yields the following equation for a steady state.

$$q_u = A_p S - q_l \qquad (1)$$

where,
q_u = useful heat gain,i.e.the rate of heat transfer to the working fluid,
S = incident solar flux absorbed in the absorber plate,
A_p = area of the absorber plate, and
Q_L= rate at which heat is lost by convection and re-radiation from the top, and by conduction and convection from the bottom and sides.

The flux incident on the cover of the collector is given by

$$I_T=I_b r_b+I_d r_d+(I_b+I_d)r_r \quad (2)$$

Each of the terms in the above equation is multiplied by a term called the transmissivity – absorptivity product in order to determine the flux S absorbed in thee absorber plate.
In which ,τ = transmissivity of the glass cover system, the ratio of the solar radiation coming through after reflection at the glass air interfaces and absorption in the glass to the radiation incident on the glass cover system,
α= absorptive of the absorber plate
$(\tau\alpha)_b$= transmissivity-absorptivity product for beam radiation falling on the collector, and
$(\tau\alpha)_d$= transmissivity-absorptivity product for diffuse radiation falling on the collector.
Thus, in order to evaluate q_u ,it is necessary to derive expressions to calculate the values of $(\tau\alpha)_b$,$(\tau\alpha)_d$ and q_l.

Thus,the instantaneous collection efficiency is given by

$$\eta_i =\frac{\text{useful heat gain}}{\text{radiation incident on the collector}}= q_u/A_c I_T \quad (3)$$

where A_c is the collector gross area(the area of the top most cover including the frame). A_c is usually 15 to 20% more than A_p.

If the liquid flow rate through the collector is stopped, there is no useful heat gain and the efficiency is 0. In this case, the absorber plate attains a temperature such that $A_pS=q_l$. This temperature is the highest that the absorber plate can attain and is sometimes referred to as the stagnation temperature. It also helps in choosing proper materials for construction of the collector.

Conveniently, from the point of view of analysis to express the heat loss from the collector in terms of an overall loss coefficient is defined by the equation

$$q_l= U_l A_p(T_{pm}-T_a) \quad (4)$$

where U_l = overall loss coefficient,
A_p= area of the absorber plate,
T_{pm} = average temperature of the absorber plate,
and T_a = temperature of the surrounding air (assume to be on all sides of the collector).
Heat loss from the collector is the sum of the heat lost from the top, the bottom and the sides.
Thus ,

$q_l = q_t + q_b + q_s$ (5)

where

q_t = rate at which heat is lost from the top

q_b = rate at which heat is lost from the bottom,

and q_s = rate at which heat is lost from the sides.

Each of these losses is also expressed in terms of coefficients called the top loss coefficient, the bottom loss coefficient and the side loss coefficient and defined by the equations

$q_t = U_t A_p(T_{pm}-T_a)$ (6)

$q_b = U_b A_p(T_{pm}-T_a)$ (7)

$q_s = U_s A_p(T_{pm}-T_a)$ (8)

The definition of each of the coefficients is based on the area A_p and the temperature difference $((T_{pm}-T_a)$. This is done for convenience and helps in giving the symbol additive equation

$U_l = U_t + U_b + U_s$ (9)

The losses can also be pictured in terms of thermal resistances.

The overall loss coefficient is an important parameter since it is a measure of all the losses. Typical values ranges from 2 to 10 w/m^2-k.

The top loss coefficient U_t is evaluated by considering convection and re-radiation losses from the absorber plate in the upward direction.For purposes of calculation it is assumed that the transparent covers and the absorber plate constitute a system of infinite parallel surfaces and that the flow of heat is one dimensional and steady. It is further assumed that the temperature drop across the thickness of the covers is negligible and the interaction between the incoming solar radiation absorbed by the covers and the outgoing loss may be neglected.

Hence,

$$\frac{qt}{Ap} = h_{p\text{-}c1}(T_{pm}-T_{c1})+\frac{\boldsymbol{\sigma}(\mathrm{Tpm4}-\mathrm{Tc14})}{(\frac{1}{\epsilon p}+\frac{1}{\epsilon c}-1)} \quad (10)$$

$$= h_{c1\text{-}c2}(T_{c1}-T_{c2})+\frac{\boldsymbol{\sigma}(\mathrm{Tc1}-\mathrm{Tc2})}{(\frac{1}{\epsilon c}+\frac{1}{\epsilon c}-1)} \quad (11)$$

$$= h_w(T_{c2}-T_a)+\sigma\boldsymbol{\epsilon}_c(T_{c2}^4 - T_{sky}^4) \quad (12)$$

Where,

$h_{p\text{-}c1}$ = convective heat transfer coefficient between the absorber plate and the first cover,

$H_{c1\text{-}c2}$ = convective heat transfer coefficients between the first and second covers,

h_w = convective heat transfer coefficient between the top most cover (in this case second) and the surrounding air ,

T_{c1}, T_{c2} = temperatures attained by the two covers,

T_{sky} = effective temperature of the sky with which the radiative exchange takes place,

$\boldsymbol{\epsilon}_p$ =emissivity of the absorber plate for long wavelength radiation, and

$\boldsymbol{\epsilon}_c$ = emissivity of the covers for long wavelength radiation.

These equations constitute a set of 3nonlinear equations which have to be solved for the unknowns T_{c1}, T_{c2} and q_t. However, before this it is necessary to have some co-relations for calculating the convective heat transfer coefficients h_{p-c1},h_{c1-c2} and h_w and the sky temperature T_{sky}.

The bottom loss coefficient U_b is evaluated by considering convection and conduction losses from the absorber plate in the downward direction through the bottom of the collector. It will be assumed that the flow of heat is one dimensional and steady.

$$U_b=k_i/\delta_b \tag{13}$$

Where k_i= thermal conductivity of the insulation,

δ_b= thickness of the insulation.

As in the case of the bottom loss coefficient, it will be assumed that the conduction resistance dominates and that the flow of heat is one dimensional and steady. The one dimensional approximation can be justified on the grounds that the side loss coefficient is always smaller than then top loss coefficient.

$$q_s=2L_3(L1+L2)k_i\frac{Tpm-Ta}{2\delta s} \tag{14}$$

$$U_s = \frac{(L1+L2)L3ki}{L1L2\delta s}$$

The final one dimensional analysis will be perform along the direction of fluid flow with the objective of determining the variation of fluid temperature.This analysis will help in linking the useful heat gain rate with the fluid inlet temperature.

Thus, the useful heat gain rate for the collector

$$q_u = mC_p(T_{fo}-T_{fi}) \tag{15}$$

$$=\frac{mCp}{Ul}[S-U_l(T_{fi}-T_a)][1-\exp\{-\frac{F\prime UlAp}{mCp}\}]$$

$$q_u = F_RA_p([S-U_l(T_{fi}-T_a)] \tag{16}$$

$$\text{where, } F_R=\frac{mCp}{UlAp}[1-\exp\{-\frac{F\prime UlAp}{mCp}\}] \tag{17}$$

the term F_R is called the *collector heat-removal factor*.It is an important design parameter since it is a measure of the thermal resistance encountered by the absorbed solar radiation in reaching the collector fluid.

4. Results and Discussion

The reduced temperature is directly proportional to the collector mean temperature and inversely proportional to the instantaneous solar radiation.

Mean inlet fluid temperature directly affects the efficiency of solar collectors. The higher is the temperature of the collector inlet fluid, the lower the obtained efficiency (Figure 2).Increase in solar heat flux increases the overall heat flux. The nature of the graph is depicted in Figure 3.With increase in the solar heat flux, the fluid outlet temperature increases and thus nature of the graph is seen as in Figure 4.

The subject of heat flux is of great importance since, with every change in heat flux, there is a very large difference in the efficiency obtained. Therefore, to get the desired efficiency, the incident solar flux absorbed in the absorbed plate should be maximized. Thus, the nature of the graph shown varies linearly (Figure 5). The heat losses from the transparent cover to the ambient air are due to radiative and convective exchanges which are affected by the wind velocity, ground, and surrounding condition and by long wave radiation from the sky.

The wind velocity can contribute to losses in the collector though not as significant as the number of glazing cover. The loss coefficient increases as the wind velocity also increases and this is attributed to the increased convective and radiative losses from the glazing cover to the surrounding (Figure6).

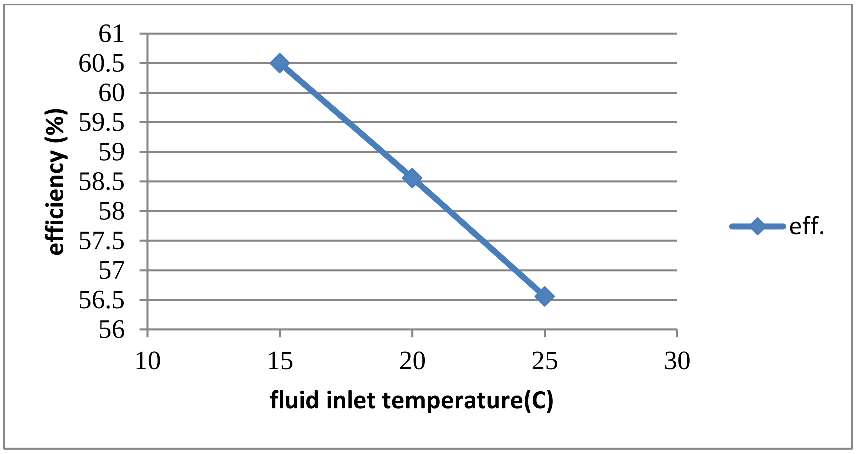

Figure 2: Variation of efficiency of a collector with fluid inlet temperature

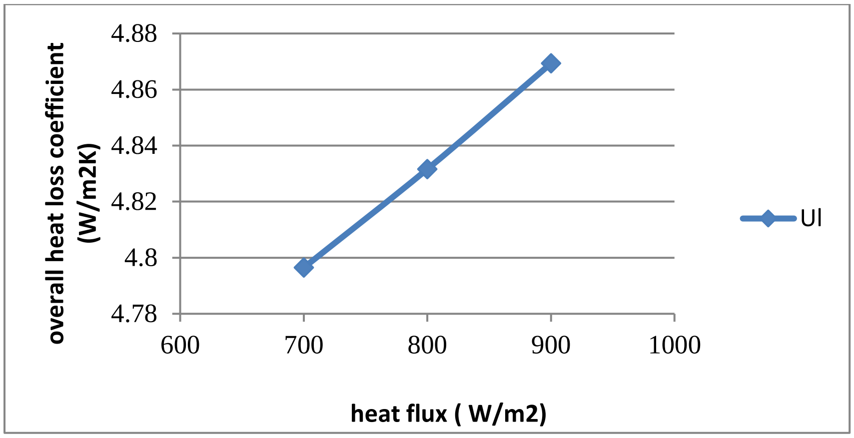

Figure 3: Variation of overall heat loss coefficient with heat flux

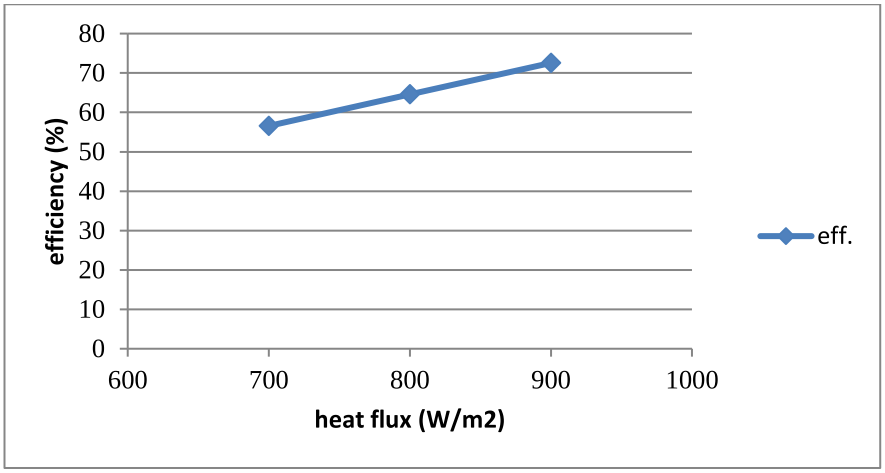

Figure 4: Variation of efficiency of a collector with heat flux

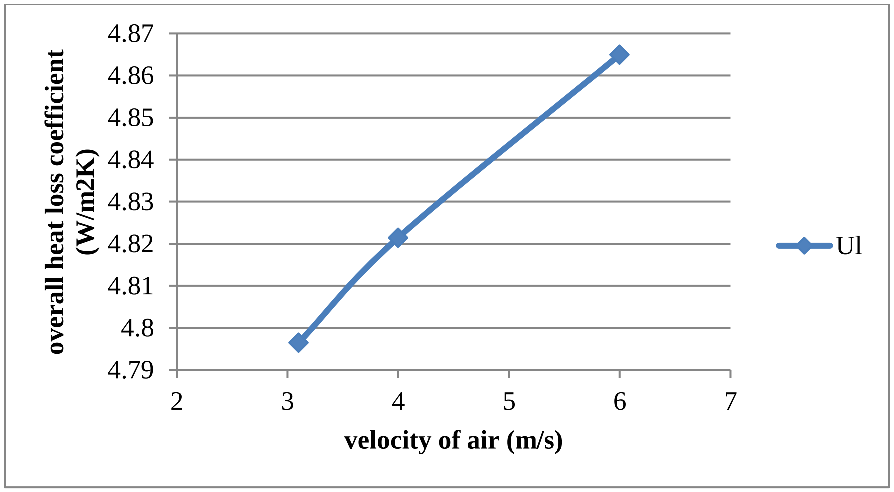

Figure 5: Variation of overall heat loss coefficient with velocity of air

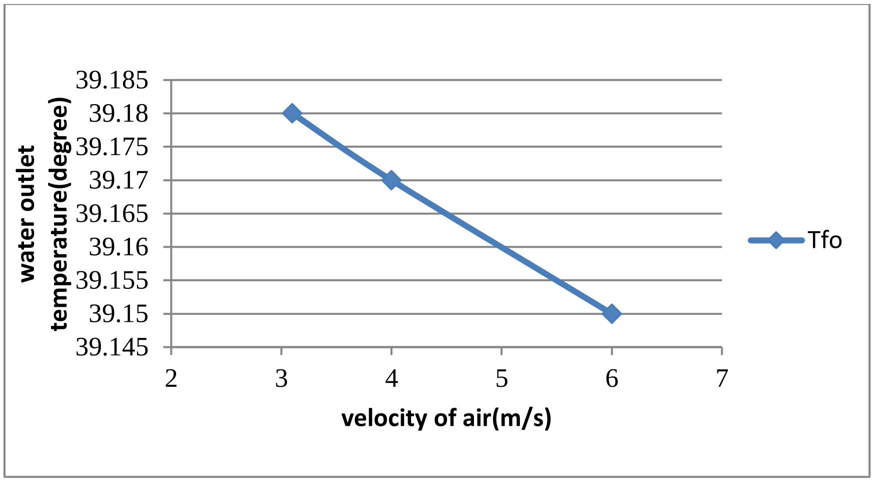

Figure 6: Variation of water outlet temperature with velocity of air

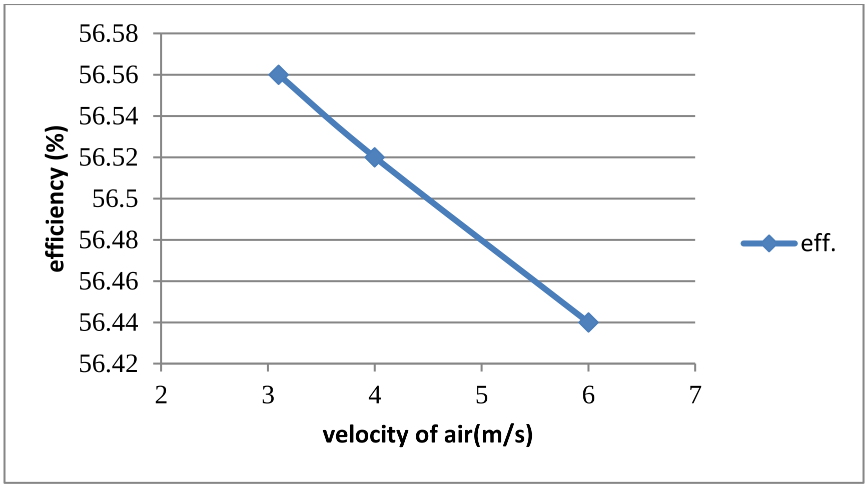

Figure 7: Variation of efficiency of collector with velocity of air

With large increase in velocity of air (Figure 7), there is very small decrease in outlet temperature of fluid. Thus, it does not make a large difference in the efficiency to be obtained. It is the environmental parameter that influences the performance of a solar water heater.Thus, the nature of the graph is a straight line.

5. Conclusions

Solar thermal collectors are used to convert solar energy into renewable energy for heating water. A solar water heating system includes a number of increasingly popular technologies.

Thermodynamics and the theory of heat transfer were used in the theoretical modelling and analysis. Using a variety of input factors, including fluid inlet temperature, heat flux, water mass flow rate, plate to cover spacing, and air velocity, a parametric research of solar water heaters was also conducted.

Using all the input variables, different output variables including the overall heat loss coefficient, fluid outlet temperature, and collector efficiency were produced.

A functional parameter that significantly affects how well a solar collector performs is the fluid inlet temperature. With higher levels of Tfi, the collector's efficiency declines more or less linearly. The quantity of incident flux that the absorber plate is able to capture has a significant impact on the effectiveness of the solar water heater. The overall loss coefficient is a crucial variable since it measures all losses. The total amount of heat lost from the top, bottom, and sides of the collector makes up its heat loss. In order to increase efficiency, it is necessary to reduce heat loss.

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