Thermodynamic Analysis of Factors Affecting the Performance of Solar Collectors

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Abstract : Thermodynamic analysis has been carried out to understand the performance of flat plate collector and evacuated tube collector and to compare the same in the present study. Major parameters that affect the performance of solar collector are absorptivity and emissivity of absorber, emissivity of glass cover, temperature of absorber plate, collector tilt angle and number of glass covers. All the affecting factors are analyzed numerically and graphs are plotted. It is analyzed that absorber plate temperature has maximum impact over the heat loss from the solar collector. Absorber plate temperature can be maintained at atmosphere temperature for the minimization of heat loss by increasing the mass flow rate of the flowing fluid or by increasing the specific heat capacity of the fluid using nanoparticles.

Keywords: Solar-thermal energy, solar collector, Evacuated Tube, flat plate collector

1. Introduction

Conventional sources of energy (coal, petroleum etc.) are decreasing day by day and causing global warming [1]. Since last 3 decades, non-conventional sources of energy (Solar Energy, Wind energy, Tidal energy etc.) are being investigated extensively [2-3]. Sun is the only and vast source of solar energy that emits electromagnetic radiation of 0.1-100 µm wavelength at 5800K. Solar-thermal collectors are the devices that absorb the solar irradiation and transfer that heat energy to the fluid for different applications. The main component of a solar collector is absorber having maximum absorptivity i.e. almost equal to unity. Depending upon the type of absorber and thermal losses from the absorber, there are many types of solar collectors (Flat plate collector, evacuated tube collector, concentrating collector etc.) [4].

Absorber plate or tube temperature increases as it absorbs the solar irradiation and some of absorbed heat is radiated back to environment due to emissivity of absorber plate. Radiative heat energy is directly proportional to 4th power of absolute temperature of absorber plate therefore radiosity increases as the temperature of absorber plate or tube increases. Efficiency of
the collector will be maximum when the total absorbed heat energy is transferred to flowing fluid inside the tube withminimum heat losses to atmosphere.

In the present paper, every factor affecting the performance of solar collector is analyzed numerically. The performance of solar collector depends mainly on solar intensity G (W/m^2),

absorptivity of absorber tube (α), emissivity of absorber tube (ε), tilt angle, and mean temperature of absorber tube (T_{pm}) [5].The losses from the solar collector are optical losses and thermal losses. Optical losses are due to optical properties (transmissivity, reflectivity) of glass cover [6]. Thermal losses are convective heat loss and radiation heat loss. Convective heat losses are minimized by using glass cover over the absorber plate or tube and radiation losses can be decreased by the maintaining the mean plate temperature equal to ambient temperature.Evacuation between absorber and glass cover minimizes the thermal convective losses.

2. Mathematical Modelling

Useful heat gain of a solar collector can be calculated as follows [7]: -

$$Q = (\tau\alpha)G - U_L(T_{pm} - T_{ambient})$$

Where Q is useful heat gain, τα is transmittance-absorptance product of absorber, G is solar intensity (W/m^2), and U_L is overall heat loss coefficient for the solar collector.

2.1 Flat plate collector

Overall heat loss coefficient of flat plate collector U_L is calculated as follows [8]:

$$U_L = \left[\frac{N}{\left\{\left(\frac{C}{T_{pm}}\right)\left[\frac{T_{pm}-T_{ambient}}{N+f}\right]^{0.33}\right\}} + h_w{}^{-1}\right]^{-1} + \left[\sigma * \left(T_{pm} + T_{ambient}\right) * \frac{T_{pm}{}^2 + T_{ambient}{}^2}{\left\{\frac{1}{[\varepsilon_p + .005N(1-\varepsilon_p)]} + \frac{[2N+f-1]}{\varepsilon_g} - N\right\}}\right]$$

f=(1- 0.04 h_w+ 0.0005 h_w^2)(1 + 0.091N),
C=365.9(1- 0.00883 β +0.0001298 β^2)
β=Collector Tilt angle (Degree), ε_p=absorber plate emissivity (0.08), ε_g=glass emissivity (0.9), h_w=wind heat transfer coefficient (W/m^2 ^{o}K) =8.55+2.56$V_{wind\ (m/s)}$, T_{pm}=Absorber plate mean temperature (K)

2.2 Evacuated Tube Solar Collector

Total heat loss from an evacuated tube solar collector is due to radiation mainly and heat loss by convection is negligible due to evacuation between tube and glass cover.
Heat loss by radiation between absorber tube and glass cover as follows [9]:-

$$h_r = \frac{\sigma\varepsilon_p}{1 + \frac{\varepsilon_p D(1-\varepsilon_p)}{\varepsilon_g D_g}}(T_p{}^2 + T_g{}^2)(T_p + T_g)$$

Where ε_p= absorber tube emissivity (0.08), ε_g=glass emissivity (0.92), D=Absorber tube outer diameter (37 mm), D_g=Glass cover diameter (47 mm), T_p= tube temperature (Kelvin), T_g= glass temperature (Kelvin)

Useful heat gain of ISO 9459-2 evacuated tube solar collector [10],

$Q_u=a_1+a_2 G+a_3 (T_{wi}-T_a)$

The correlation coefficients for the ISO 9459-2 evacuated tube model are a_1= 0.597, a_2= 1.066, a_3= -0.208 and T_{wi} is Tank Temperature and G is solar irradiation for a day.

Instantaneous efficiency of evacuated tube solar collector is written by [11]:

$$\eta = \eta_o - a\frac{(\bar{T}-T_a)}{G} - b\frac{(\bar{T}-T_a)^2}{G}$$

$\bar{T}$= average of Inlet and outlet temperature in the tube, η_o=optical efficiency, T_a= ambient temperature, a & b= heat loss constant of evacuated tube collector

Maximum amount of absorbed heat energy can be transferred by increasing the mass flow rate (m) of flowing fluid inside the absorber or increasing the specific heat capacity of fluid (c_p) [12].

$Q= mc_p(T_p-T_w)$

Specific heat capacity of the flowing fluid can be increased by using metal nanoparticles or carbon nanoparticles in the flowing fluid [13].

$$c_{p,nf} = \phi c_{p,n} + (1-\phi)c_{p,f}$$

Where nf, n and f refer to nanofluid, nanoparticle and base fluid, respectively. Specific heat of nanofluid will be optimum at optimum volume fraction of nanoparticles. As the specific heat capacity c_p increases, maximum amount of heat can be transferred by the same mass flow rate.

3. Results and Discussion

3.1 Effect of number of glass cover over heat transfer coefficient for FPC

Losses of convective heat energy from a flat plate collector have been minimized by increasing the number of glass cover as shown in figure [1]. By increasing the number of glass cover, solar energy reflected by glass cover is increased. Thus, the useful heat gain by the solar collector decreases.

By increasing number of glass cover, maximum amount of solar energy is reflected by glass cover. Therefore maximum 2 glass cover should be used for optimization of solar energy. More the glass cover, greater will be the reflected energy. After 2 glass covers, there is minute change in heat losses as shown in figure [1] and the heat losses due to convection and radiation are increasing as mean plate temperature increases. Heat losses from the absorber can be decreased by maintaining the absorber temperature almost equal to ambient temperature. In the figure [1], n denotes the number of glass cover.

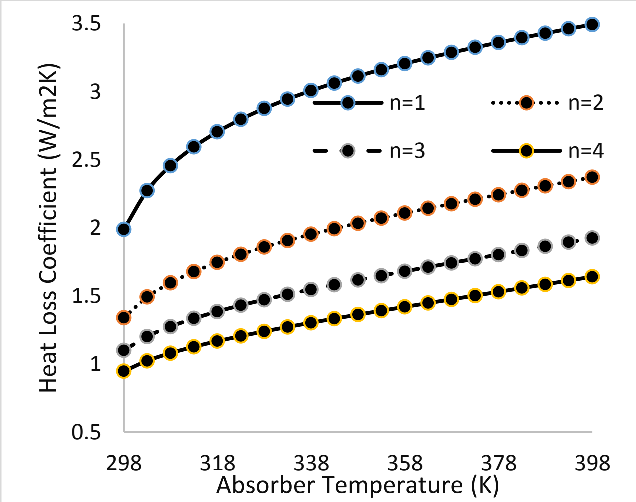

Figure 1. Effect of number of glass cover over heat transfer coefficient for FPC

3.2 Effect of wind speed over overall heat loss of flat plate collector

As the wind speed increases, Reynold's number increases. Therefore, natural convection is turned to forced convection. Heat transfer coefficient for forced convection is greater than that for natural convection. As heat transfer coefficient increases, heat loss from the flat plate collector increases.

Heat loss coefficient of flat plate solar collector increases with increasing wind speed as shown in figure [2]. Flat plate collector having one glass cover is much affected by wind speed and flat plate collector having two glass over, overall heat transfer coefficient is not much affected by increasing the wind speed as shown in figure [2].

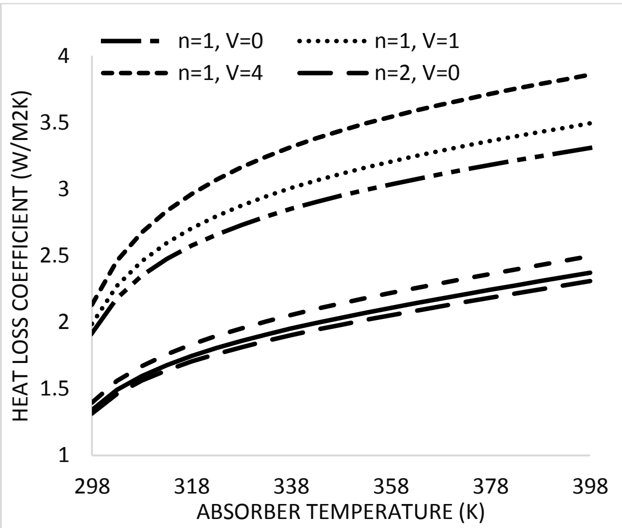

Figure 2. Effect of wind speed over heat transfer coefficient for FPC

3.3 Heat loss by radiation between absorber tube and glass cover of ETC

Evacuated tube solar collector is the best collector among all the collectors due to minimum heat loss to atmosphere. There is radiation heat loss from evacuated tube solar collector and

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heat losses due to convection between absorber tube and glass cover is neglected. As there is vacuum between absorber tube and glass cover, there is no fluid to transport thermal energy from absorber tube. But there will be heat losses too due to convection from glass cover to ambient. Thus overall heat loss confident of evacuated tube solar collector is increased.

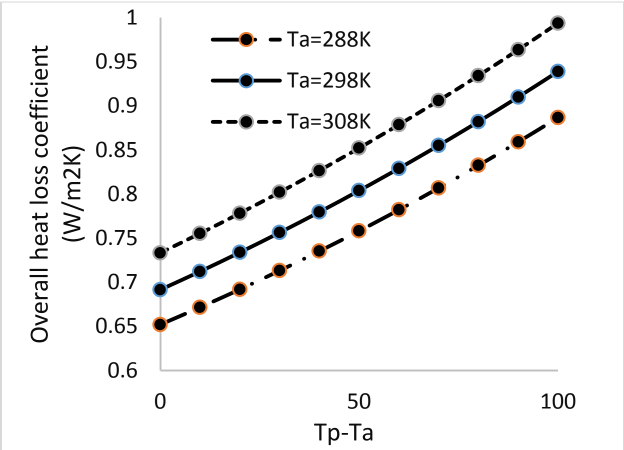

Figure 3. Effect of ambient temperature over heat loss coefficient for ETC

Difference between absorber tube temperature and ambient temperature affects the performance of evacuated tube solar collector. Higher the difference of temperature between absorber tube and ambient, higher will be losses as shown in figure [3]. Heat transfer coefficient due to convection from glass cover to ambient is taken as 12.7 W/m^2 for calculation of overall heat transfer coefficient.

3.4 Effect of absorber tube emissivity over heat transfer coefficient for ETC

There are mainly three component of an evacuated tube solar collector affecting the performance of that evacuated tube solar collector i.e. absorber tube, fluid to transfer the absorbed heat and glass cover. Solar irradiation is absorbed by absorber tube. Absorber tube should have higher absorptivity. Higher the absorptivity, greater will be the absorbed heat. But by Kirchhoff's law, the emissivity of a body which is in thermal equilibrium with its surrounding is equal to its absorptivity of the body. For the higher value of absorptivity, a surface coating is used over the absorber tube.

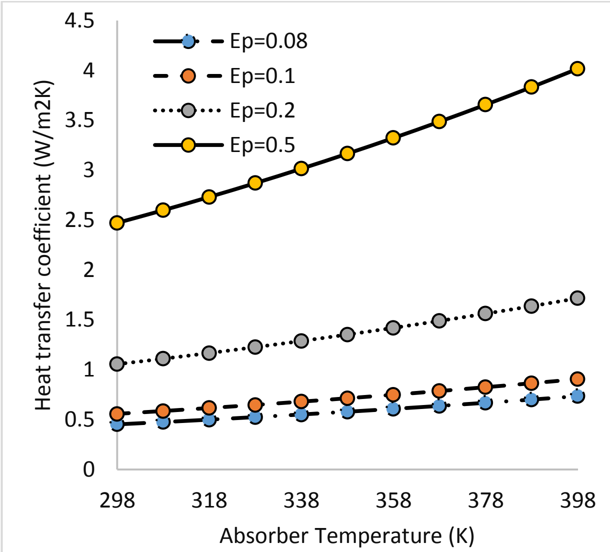

Figure 4. Effect of absorber tube emissivity over heat transfer coefficient

Emissivity of absorber tube affects the performance of evacuated tube solar collector as shown in figure [4]. Higher the value of emissivity, greater the heat loss coefficient is. Absorber tube should have higher the value of absorptivity almost equal to unity, and lower the value of emissivity.

3.5 Heat gain by Evacuated Tube Solar Collector vs Tank Temperature

Evacuated tube solar collector is the best collector due to evacuation between absorber tube and glass cover. There is no fluid transporting thermal energy between absorber tube and glass cover. Hence there will be no heat losses due to convection. There will be only radiation losses from the absorber tube.

Radiative energy from a body is directly proportional to 4th power of absolute temperature of that body. Heat losses due to radiation from absorber tube depends on the absorber tube temperature and emissivity of absorber tube. Radiation losses can be minimized by minimizing the absorber tube temperature equal to ambient temperature by increasing mass flow rate of fluid flowing inside the absorber tube or by increasing the specific heat capacity of the fluid using nanofluid. Lower the tank temperature, Higher will be the useful heat gain by evacuated tube solar collector as shown in [figure 5].

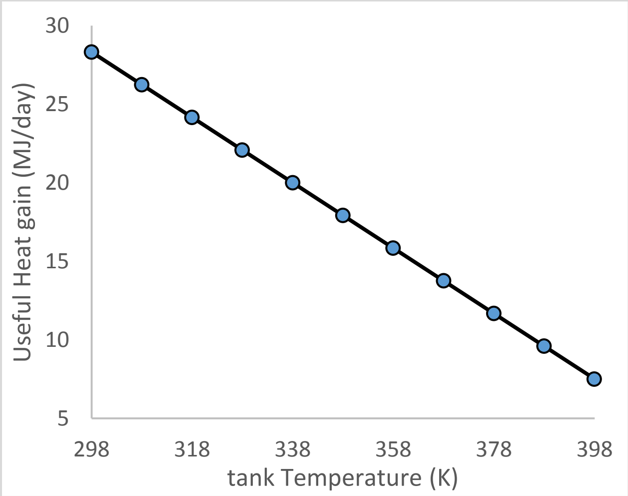

Figure 5. Effect of tank temperature over useful heat gain by ETC

The slope of useful heat gain by evacuated tube solar collector to the tank temperature is negative as shown in figure [5]. Useful heat gain by evacuated tube solar collector is decreasing as tank temperature is increasing. Higher the tank temperature, greater will be the heat losses. Average temperature in the tube should be as low as ambient for maximum heat gain.

Difference between tank temperature and ambient temperature is taken as (dT) in the figure [6]. As the temperature difference between absorber tube and atmosphere increases, useful het gain decreases and losses increases. As the Absorber tube absorbs the solar irradiation, temperature of absorber tube increases. As the temperature of absorber tube increases, loss due to radiation increases as shown in figure [6]. More the difference of temperature between tube and ambient, higher will be the radiation losses and lesser will be useful heat gain.

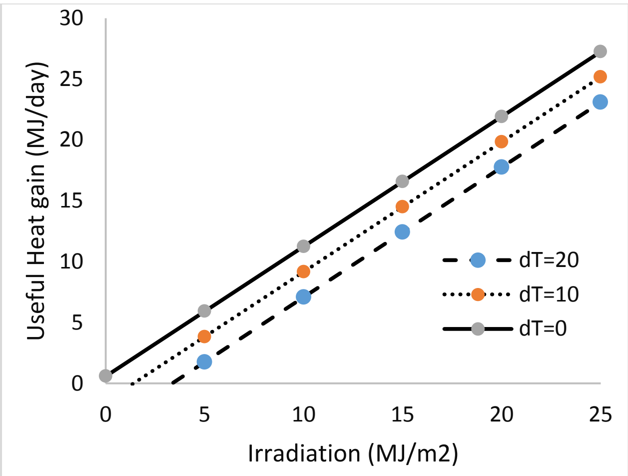

Figure 6. Effect of ambient temperature over Useful heat gain by ETC

3.6 Overall heat loss by ETC and FPC

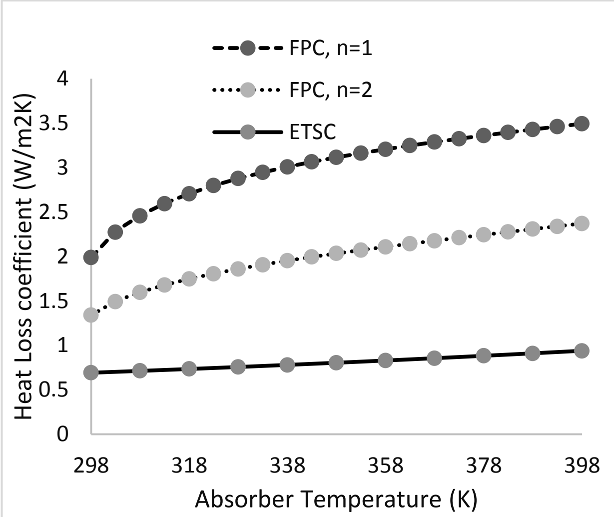

Figure 7. Comparison of Heat loss coefficient for FPC and ETC

Heat loss coefficient for an evacuated tube solar collector and flat plate collector are compared as shown in figure [7]. Heat loss coefficient for flat plate collector is higher than that for evacuated tube solar collector. Therefore, heat loss from flat plate collector is higher than that of evacuated tube solar collector.

Heat loss by flat plate solar collector having (n = 1) glass cover is maximum and heat loss by FPC having two glass cover is less than that of one glass cover and greater than that of ETC. Heat loss by ETC is minimum as there are radiation heat loss only as shown in figure [7].

4. Conclusion

By using selective coating or nano-coating on absorber tube, absorptivity is maximized (=0.92) so maximum amount of irradiation is absorbed and temperature of the tube increases. As the tank temperature increases, heat losses by radiation as well as convection also increases. Heat loss by convection is minimized by using evacuation between absorber tube and glass cover but heat loss by radiation does not need a medium to propagate. Therefore heat loss by radiation is not affected by evacuation. As the temperature of absorber increases, heat loss by radiation also increases. By maintaining the absorber temperature almost equal to atmosphere temperature, heat loss by radiation can also be minimized.Absorber temperature can be maintained almost equal to atmosphere temperature by increasing the mass low rate of the flowing fluid inside the absorber or by increasing the specific heat capacity of flowing fluid using carbon nanoparticles.

Evacuated tube solar collector is the more efficient than flat plate collector having minimum heat losses. For flat plate collector, number of glass cover over absorber plate should be 2 for optimization of absorbed solar energy. More the number of glass covers, higher will be losses due to reflection by glass cover. Heat losses are not affected much by wind speed having 2 glass cover over absorber.

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