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A Comparative Study on the Experimental and Computational Analysis of Solar Flat Plate Collector using an Alternate Working Fluid

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Abstract

Solar liquid collectors are potential candidates for enhanced heat transfer. The enhancement techniques can be applied to thermal solar collectors to produce more compact and efficient energy collection/storage mechanism. Those collectors can be induced for simplest and most direct applications of energy conversion of solar radiation into heat. This work presents a comparative representation of computational simulation and experimental for the processes occurring in liquid flat-plate solar collectors. The working fluid used is propylene glycol and the concentration of propylene glycol (PG) is varied for various mass flow rates. The effect of this variation, on the efficiency of a flat plate solar collector was investigated computationally and experimentally. The experiments were carried out using 4 different mixture concentrations. The designed model is simulated under various flow conditions by varying the mass flow rate and varying the working fluid concentration. In order to verify the designed model and results, an experiment was designed and conducted for several days with variable ambient conditions, flow rates and concentrations. The comparison between the computed and measured results of the fluid temperature at the collector outlet showed a satisfactory convergence. The model is appropriate for the verification of overall efficiency of the system and can be used for any number of working fluids in order to find the outlet temperature.

Keywords:solar flat plate collector; energy conversion; propylene glycol; efficiency of solar collector

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1. Introduction

Solar thermal energy system, converts the energy of the sun directly into heat, which is stored using water, air as a working fluid. The typical solar heating system consists of a collector, a heat transfer circuit that includes the fluid and the means to circulate it, and a storage system including a heat exchanger. Flat-plate collectors have been and may remain the most popular type of solar collectors for general or residential applications. They are simple in design, operate at medium to low temperatures, and have few mechanical parts. In climates where there is a potential for freezing temperatures during part of the year, or in climates where fluids are exposed to high temperatures, anti-freeze/anti-boiling (coolant) is used to protect solar systems against corrosion, freezing temperatures, and overheating. There are many different types of antifreeze like propylene-glycol, ethylene-glycol, triethylene glycol etc. Propylene-glycol has basic properties like: non-toxic, low specific heat capacity, freeze protection, boil-over protection, and anti-corrosion and rust protection. At particular concentration they aid for enhanced heat transfer applications.

Working fluid is primarily responsible for heat transfer; it should possess acceptable heat transfer characteristics. Therefore, as water is an excellent heat conductor, it is added to the solution. Heat transfer enhancement is done by using alternate fluids in solar water heating systems, in which main working fluid mixture is propylene-glycol/water mixtures that are typically subject to deterioration at elevated temperatures. Under these conditions the heat transfer fluid may become corrosive, resulting in accelerated fouling and corrosion of the solar system components. They showed that propylene glycol has extremely low environmental, health, fire and corrosion risk: it may be a good choice if energy use and life cycle costs are not overriding concerns. Propylene glycol is used in air coolers and coaxial heat exchangers and investigated heat transfer characteristics. Many studies have been conducted on the heat transfer performance of engine coolants.

The research in this thesis is concerned with the modelling of the flat-plate solar collector working under various conditions. This is done by designing a solar flat plate collector using designing software, the designed model will be solved using software in an iterative scheme. The proposed solution method solves the designed model considering all the conditions in the collector process, and computes the temperature distributions for any cross-section at the collector. As a verification of the proposed solution method; an experimental work has been done on an active flat-plate solar collector, all the experiments has been performed at the laboratory facilities of the engineering department at LBS College of Engineering, Kasaragod. The experimental results were compared to the results obtained from the analysis.

The theoretical, computational, and the experimental study is carried out in sections 2, 3, 4 respectively. Results obtained in from the various methods, the comparison of results and the discussion on the result is carried out in section 5. The conclusion of this work is discussed in section 6.

2. Theoretical Study

This section describes the flat-plate solar collector system considering the properties of its different zones. In general, the analysed control volume of the flat-plate solar collector contains five regions namely glass cover, air gap, absorber, fluid and the insulation perpendicular to the liquid flow direction.

The energy balance caused by the mass transfer during the circulating of the fluid within the solar collector is included by the definition that the collector's temperature depends on the coordinate in the direction of the fluid flow.

The useful energy can be calculated as follow

$$Q_u = \dot{m} C_p (T_o - T_i) \tag{1}$$

where Q_u is the rate of useful energy gained, $\dot{m}$is the mass flow rate of fluid flow, Ti and To are, respectively, the inlet and outlet fluid temperature of solar collector, and also Cp is the heat capacity of working fluid. The useful energy can also be expressed in terms of the energy absorbed by the absorber and the energy lost from the absorber.

The instantaneous collector efficiency relates the useful energy to the total radiation incident on the collector surface by

$$\eta_i = Q_u/(A_c G_T) \quad (2)$$

$$\eta_i = F_R(\tau\alpha) - [F_R U_L (T_i - T_a)/G_T] \quad (3)$$

$$U_t = \frac{1}{\frac{N}{\frac{C}{T_p}\left(\frac{T_p - T_a}{N+f}\right)^e} + \frac{1}{h_w}} + \frac{\sigma\left(T_p^{\,2} + T_a^{\,2}\right)\left(T_p + T_a\right)}{\frac{1}{\varepsilon_p + 0.00591 N h_w} + \frac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_p} - N} \quad (4)$$

$$F_R = \frac{GC_p}{U_L}\left[1\text{-}e^{-U_L F'/GC_p}\right] \quad (5)$$

$$F_R = \frac{\dot{m}C_p}{A_c U_L}\left[1\text{-}e^{-A_c U_L F'/m^{\circ} C_p}\right] \quad (6)$$

The solar insolation values are obtained from CPCRI, Kasaragod, in terms of (PAR), photo synthetically active radiation .Its unit is μmole/m^2/s.

Observation	Photon	PAR
1	19.6	3555
2	18	3540

Computational Study

The model is used for a flat-plate solar collector with single glass cover working in parallel channel arrangement. All physical dimensions of the collector can be entered as inputs, which make it suitable to any single glass cover flat-plate solar collector without any modifications. All the boundary conditions as the inputs data for analysis are measured:

- Total fluid mass flow rate.
- Total flux of solar radiation.
- Ambient temperature.
- The initial fluid temperature in the storage.

2.1. High Resolution Scheme

For the computational analysis we use various schemes for analysis. Here High Resolution Scheme is used for the analysis. The High Resolution Scheme uses a special nonlinear recipe for at each node, computed to be as close to 1 as possible without introducing new extrema. The advective flux is then evaluated using the values from the upwind node. The recipe for this is based on the boundedness principles used by Barth and Jesperson. This methodology involves first computing at each node using a values involving adjacent nodes (including the node itself). Next, for each integration point around the node, equation is solved for to ensure that it does not undershootor over shoot:

$$\varphi i_p = \varphi u_p + \beta \Delta\varphi . \Delta r \quad (7).$$

3. Experimental Study

Table 1. Dimensions of the flat plate collector.

Component	Specification
Collector	
Area	0.54m^2
Length	0.9m
Width	0.6m
Bottom header	
Material	Copper
Diameter	0.031m
Length	0 .6m
Riser pipes	
Material	Copper
Diameter	0.019 m
Length	0.9 m
Top header	
Material	Copper
Diameter	0.031m
Length	0.6 m
Inclination of flat plate collector	26^O S

Fig.1.Photograph of experimental Setup

All the experimental work that was done to verify the analysis took place in the Mechanical Engineering department of, LBS College of Engineering, Kasaragod using a flat-plate solar collector. The solar collector has one (0.6m×0.9m) single glass cover and flat plate of same dimension. The plate consists of 8 tubes and 2 headers made of Copper with tube spacing of 5 inches and a diameter of 0.75 inches. While the absorber made of Red Copper with a black chrome selective surface, the flat-plate has 2 inches Thermocole insulation, and cased by a frame of Aluminium. The flat-plate solar collector was mounted on an iron frame inclined at 26°S. Reagent grade propylene glycol ($C_3H_8O_2$) was used in the experiments without further purification. Propylene glycol–water mixtures were prepared gravimetrically. Various properties of the mixture is obtained from standard which is given below.

Thermometers were used to measure the fluid temperature in the inlet and outlet of solar collector. The flow rate is controlled with two metering valves, one at the main flow loop. The flow rates are measured by collecting the fluid for a period of time, 60s, helping a precise measuring container and a stop-watch.

4. Result & Discussion

This chapter presents the results obtained from the theoretical and experimental works. The first part gives the discussion ofproposed computational model and various parameters observed. The second part presents a comparison between the numerical obtained temperatures and the experimentally measured data. The experimental results include the performance of the Flat plate solar collector using propylene glycol/water as base fluid at various glycol volume concentrations (0%, 25%, 50%, and75%,) as well as various mass flow rates (0.0167, 0.024, and 0.008 kg/s). The tests of the solar collector are administered for many days with clear sky and moderate wind speed (average wind speed was 2.6 m/s). These tests have performed around solar noon at time 12 pm–2 pm. Figure shown below gives temperature difference between inlet and outlet of the solar collector with various PGconcentrations for different testing conductions, in which the inlet temperature is not controlled. According to the graphs shown below with increasing PG concentration, the temperature difference is in increasing manner.

4.1. CFD Predictions

1) *Various results for 0.008 m^3/s flow rate:*

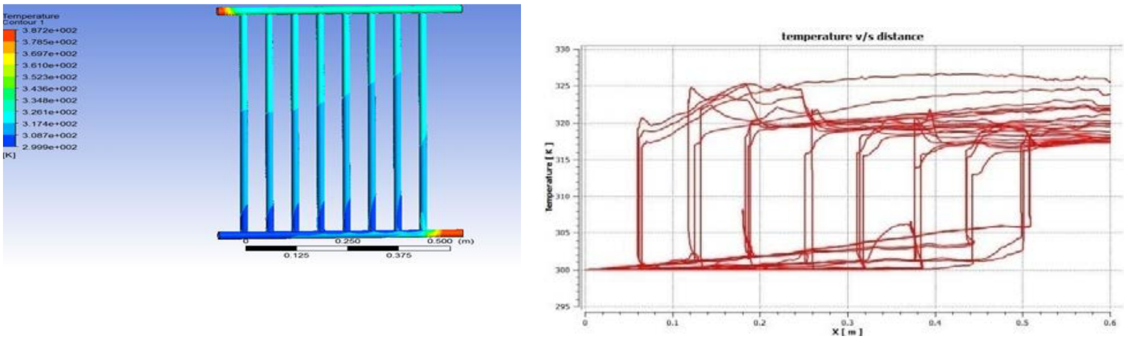

Fig.2. For 0.008m^3/s and 0% PG concentration: (a) Temperature contour (b) Temperature v/s X axis graph

The above figures describes the temperature contour[fig 5 (a)] of the plate and the temperature plot [fig 5 (b)] of the streamlines of the liquid passing through the pipes. The graph plotted gives the temperature of the liquid anywhere in the pipe. From the inlet opening, the fluid enters with a temperature of 300K and as it flows inside the pipes, the temperature increases and then it reaches maximum at the outlet.The temperature contours at ifferent conditions, clearly shows the maximum and minimum temperature of the plate and the variation of plate temperature for different PG concentration and flow rates.

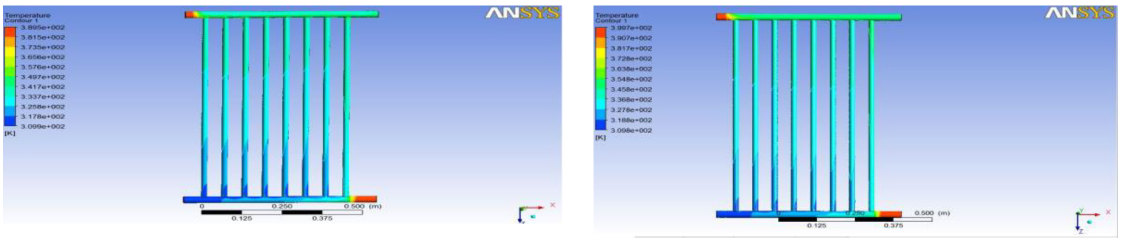

Fig. 3. Temperature contour for 0.008m^3/s (a) 25% PG conc(b) 50% PG conc

The temperature contour shows the plate temperature increases as the PG concentration increases. This shows that the conductivity of the fluid decreases as the PG concentration increases, since there is no effective heat removal.

Table 2.Computationally obtained Outlet temperature, for various flow rates and concentration

Flow rate (m^3/s)	**PG Concentration (%)**	**Inlet temperature (k)**	**Outlet temperature (k)**
0.008	0	300	316
	25	310	326
	50	310	328
	75	310	332
0.016	0	304	315
	25	310	321
	50	310	323
	75	311	326
0.024	0	304	314
	25	309	318
	50	309	321
	75	310	323

2)Comparative graphs for different flow rates and concentration:

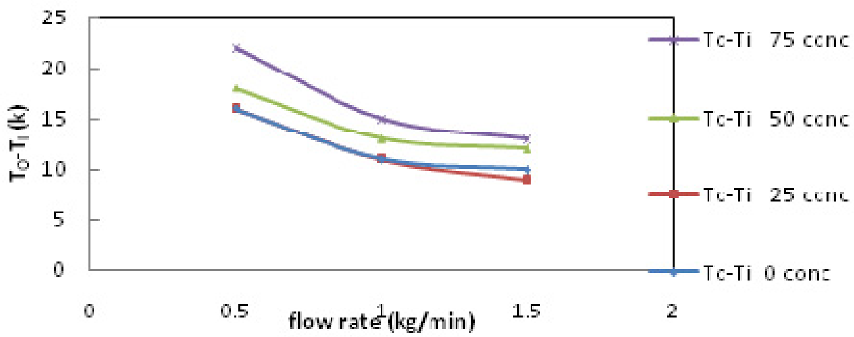

Fig.4.Temperature difference graph for various concentration

The above figure proves that at higher concentration heat transfer between absorber and medium improves and therefore the temperature difference increases (To-Ti), and the residence time of the working fluid within the collector decreases but the useful energy removed increases, thus the overall thermal losses decrease. Also, it can be anticipated that, with increasing mass flow rate the collector efficiency increases due to the decreasing absorber temperature and therefore lower losses for a lower temperature difference with the air temperature.

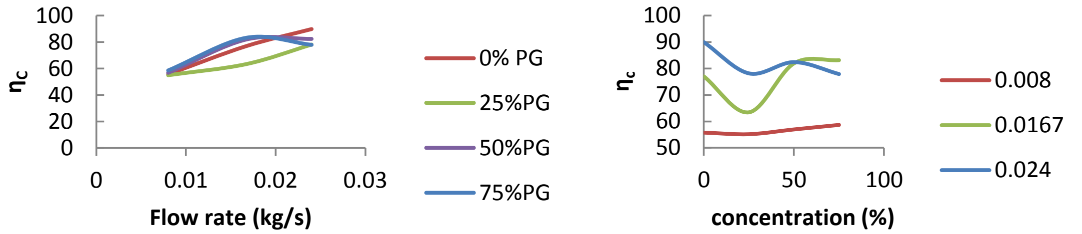

Fig.5.Computational efficiency for: (a) different flow rate (b) different concentration.

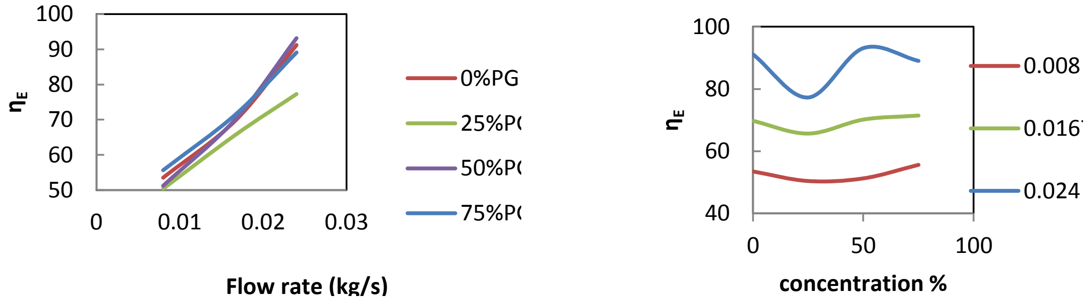

Fig.6. Experimental efficiency for: (a) different flow rate (b) different concentration.

From the graphs it is evident that, with increasing PG concentration, the temperature difference shows an increasing trend. However, since the heat capacity of these PG concentrations are not the same, the same trend cannot be expected while plotting the efficiency curve.

From theoretical study it is seen that, with increasing mass flow rate the $F_R(\alpha\tau)$ value is almost constant in each case. However, the F_RU_L value is of decreasing manner with increasing mass flow rate, which means that the efficiency of solar collector increases with increasing mass flow rate. The thermal conductivity of PG/water is less than that of pure water. Thus, in the case 25% PG with 0.008, 0.0167, and 0.024kg/s mass flow rates the efficiency of the Flat plate solar collector, is about 3.14%, 4.1%, and 13.94% less than that for 0% PG (pure water), respectively.

By increasing volume concentration from 25% to 75% the efficiency of the Flat plate solar collector increases. However, it must be noted that by increasing PG concentration, the leaking problem of fluid will increase. Also, by increase in PG concentration the fluid's viscosity has increased largely which can lead to the higher amount of required pump energy. However, this increase in the electrical power consumption is usually low compared with solar heat gain enhancement.

Numerical analysis was done on the designed model and the result obtained is agreeing reasonably with experimental results. The temperature difference (To-Ti) increases when the Propylene-glycol percentage increases. The theoretical efficiency obtained for water is about 58% and the computational and the experimental efficiency 55.7% and 53.5% respectively. Thus the model is validated. At higher flow rates as the PG concentration reaches above 50%, there is increase in efficiency and the temperature difference decreases.

. While comparing the efficiencies, both the computational and the experimental efficiency is satisfactorily agreeing in the case of 0.0167kg/s (1kg/min) flow rate. Efficiency of the system is enhanced when PG concentration of 50% is used and it is more evident in case of 0.0167kg/s, flow rate. PG concentration of 25% should not be used in any case, since for all the flow rates the efficiency and the temperature difference is also decreasing. At 25% PG concentration the decrease in thermal conductivity is more prominent than the decrease in specific heat capacity. At lower flow rates, the PG concentration of 75% is more efficient when compared to other concentrations.

The computational model can used to find out the efficiency and output temperature in case of 1kg/min flow rate, since the trend shown is very similar to experimental one At higher flow rates the computational and experimental efficiency are not satisfactorily coinciding.

At higher temperature differences, F_RU_L parameter is more dominant in collector efficiency. The F_RU_L value for higher PG concentrations is lower than that for 0% PG (pure water). At lower temperature differences, $F_R(\alpha\tau)$ parameter is more dominant in the collector efficiency The $F_R(\tau\alpha)$ for 0% PG (pure water) is higher than that for other PG concentrations.

From the basics

$$h \ \alpha \ k/\delta t \qquad (8)$$

- heat transfer coefficient (h),
- k -the thermal conductivity of the test fluid
- δt-thickness of thermal boundary layer

From the graph of thermal conductivity-the thermal conductivity enhancement due to the increasing of fluid temperature reduces with increasing PG concentration For higher PG concentrations the amount of thermal boundary layer decrease is higher than that of water compared with the increase of thermal conductivity at lower PG concentrations. At higher PG concentrations (50%PG), according to the heat transfer coefficient approximation ($h = k/\delta t$) the higher decrease in the thermal boundary layer, δt, can compensate the lower increase in the thermal conductivity decrease. When the PG concentration reaches more than 75%, there is a drastic decreases in thermal conductivity, and F_RU_L values also do not show much difference compared to lower concentrations, thus the collector efficiency decreases.

5. Conclusion

The effect of using the propylene glycol–water at various PG concentrations as absorbing medium in a Flat-plate solar water heater at different mass flow rates (0.008, 0.0167, 0.024, kg/s) is investigated. The results show that using propylene glycol–water at 25% PG concentration reduces the maximum efficiency compared to that for 0% PG (pure water) by 5% and 15% experimentally and computationally respectively in mass flow rate of 0.0167 kg/s. By increasing PG volume concentration from 25% to 50%, the efficiency of the Flat-plate solar collector is increased and by increasing volume concentration from 50% to 100% the maximum efficiency of the Flat-plate solar collector decreased by 5% and 14% respectively in mass flow rate of 0.024kg/s. From this study ,it is inferred that the amount of fuel cost that is been saved while using solar pre heated water in industries can be increased by incorporating an alternate working fluid like propylene glycol at a particular concentration for particular flow rate .According to the study, by using pure water, the amount that could be saved is Rs.1100/day, by incorporating 50% PG at 0.0167 kg/s flow rate, the amount that could be saved reaches Rs.1450/day .It is to be noted that, at particular flow rates, specific concentration of propylene glycol-water mixture should be used in order to enhance the efficiency of the total system.

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