Exergy analysis of forced convection solar flat plate collector using different working fluids.

T Rajagopal¹, N Prasanna¹, S Ajay¹, A Yazharasu² and K Aranganathan¹

¹Department of Mechanical Engineering, Kongu Engineering College, Perundurai-638060, India.
²Department of Automobile Engineering, Dr. Mahalingam College of Engineering and Technology, Pollachi-642003, India.

*E-mail address: mechrajagopal@gmail.com

Abstract. Solar energy is a widely available energy resource which can be effectively utilized without any effect on the environment. The solar Flat Plate Collector (FPC) is most commonly used collector in many solar thermal applications, but the energy absorption from the solar irradiation and transporting heat to the working fluid is less efficient. The efficiency of the collector can be enhanced by varying different parameters like reducing the air gap between the absorber plate and the glass cover of the collector, optimizing the dimensions of collector components and using high thermal stability working fluids. In these present work experimental investigation and exergy analysis carried out on two selected working fluids water and coolant, are compared. The maximum outlet temperature for coolant and water as working fluid is recorded as 63°C and 59°C during higher solar intensity. The exergy efficiency of water and coolant is obtained as 6.7% and 7% respectively during peak sunshine hours.

Keywords: Solar energy, Working fluids, Solar flat plate collector.

1. Introduction

FPC is the most comprehensivesolar energy source technology that has been commercialized for various thermal applications. The efficiency of exploiting the heat from solar irradiation and transfer heat to the working fluid for any application is limited due to the effects of various design and thermo physical parameters. Numerous researches have been experimented by altering the design parameters like glass cover thickness, glass cover coating, absorber material and its thickness, optimizing the distance between the absorber plate and the glass cover. The efficiency is also enhanced by using reflector to maximize the use of solar radiation on FPC[1]. Various alternate working fluids such as nanofluids, glycolin forced circulation methods are also investigated in order to increase the performance of the system. The use of nanofluids involves certain challenges as low stability, high viscosity, complexity, the weight fraction ratio, which must be considered during the selection process[2].

When nanofluids were used as a working fluid, yielded better exergy and energy efficiencies in the system integrated with carbon nanotubes[3]. A numerical simulation model is developed for determination of four optimal operational parameters including the area of the collector, mass flow...
rate, volume of the heat accumulator and energy efficiency [4]. Exergy analysis helps to identify the optimized configuration of the performance assessment system[5]. Advances exergy analysis on FPC proposed the absorber plate exergy annihilation is inevitable but the glass cover exergy destruction can be minimized [6]. The maximum raise in energy efficiency of FPC was reported at 23.47% by integrating the multiwalled carbon nanotube/water with graphene/water as base fluid[7]. Increase the rate of heat gain of working fluid an energy storage material as paraffin wax positioned on upper and lower pathway of airflow channel which resulted better exergy efficiency [8]. Hybrid nanofluid has provided enhancement in exergy efficiency of 6.9% when compared to 5.7% in the use of nanofluid as alumina- water[9]. Exergy loss has been minimized by increasing the inlet velocity of working fluids, thus substantial reducing the surface temperature of the collector [10]. Exergy and energy efficiency reported for two different sizes of Aluminium oxide- water nanofluid with various mass flow rates[11]. FPC using three different mass flow rates of working fluids has been modelled using an artificial neural network optimization process to examine the optimal fluid flow [12]. Exergy analysis helps to exploits the source of energy loss, improve the identification of economic assessment and optimization activities [13]. In this experimental work FPC [14-16] is designed and fabricated based on optimized design and thermo physical parameters[17]. Recent researches have focused more on nanofluids due to its heat transfer properties but optimum concentration has only yielded better thermal improvements and its stability would be reduced over a period of time [8]. A glycol also tends to increase the characteristics of heat transfer indifferent thermal applications at selected concentrations[18]. Water is a conventional working fluid with freezing temperatures during the winter season while coolant oil (ethylene glycol) is chosen as an alternative working fluid due to its anti-freezing, anti-corrosive properties. Various concentrations of glycol are experimented and reported an improvement in thermal efficiency of between 25% to 50% [18]. Exergy analysis is carried out for conventional working fluid water and coolant oil at 30% concentrations in the developed FPC and compared with each other.

2. System Description
FPC is a non-concentrating solar collector made up of major components such as glass cover, absorber plate, copper tubes and insulation material. A fabricated FPC based on the selected specification as shown in Figure 1.

![Figure 1. Experimental setup of Flat Plate Collector](image-url)
Solar radiation from the sun travel through the transparent glass over and strikes the coated black surface absorber plate have high absorptivity. The design parameters of the glass cover are selected as glass thickness 4mm, length 1000mm and width 780 mm respectively [17, 19]. The absorber plate material is selected as aluminum with specifications of 1mm thickness, 940 mm length, 720 mm width respectively [17, 20, 21]. A solar thermal energy absorbed by the absorber plate that is transferred to the fluid flowing inside the runner tube. The copper tubes are selected to transfer the heat from solar radiation to the working fluid with 8mm riser pipe diameter and header pipe diameter of 22 mm respectively. A thermal insulating material appended at the sides and bottom of the collector absorber plates to reduce the system heat transfer losses. Two working fluids are selected as water and coolant oil based on thermal properties to evaluate the performance of the experimental system. A working fluid is circulated to the system with the help of pump in forced circulation mode.

3. Exergy Analysis

Exergy is described as the maximum amount of work that can be produced by a system or a maximum amount of energy which can be effectively utilized. The exergy analysis will help to identify the maximum availability of useful energy generated by any particular system [22].

The basic form of an exergy equilibrium equation considering without the effects of deviation from potential and kinetic energy as below [23]

\[ E_{in} + E_{s} + E_{out} + E_{L} + E_{d} = 0 \] (1)

The exergy inlet fluid flow is given as

\[ E_{in,f} = \dot{m} \times C_{p} \left[ T_{in} - T'_{a} - T_{a} \ln \left( \frac{T_{in}}{T'_{a}} \right) \right] + \frac{n_{in} \times \Delta P_{in}}{\rho} \] (2)

A revised equation based on considering the sun as unlimited thermal source.

\[ E_{in,Q} = \eta \times \dot{I}_{T} \times A_{P} \left[ 1 - \frac{T_{a}}{T_{r}} \right] \] (3)

At a steady state stored exergy is null, therefore exergy inlet comprises of exergy rate of inlet fluid flow and exergy rate of absorbed solar energy.

\[ E_{in} = E_{in,f} + E_{in,Q} \] (4)

The exchange rate contains just the exergy limit of the fluid outlet movement

\[ E_{out,f} = -\dot{m} \times C_{p} \left[ T_{out} - T_{a} - T_{a} \ln \left( \frac{T_{out}}{T_{a}} \right) \right] - \frac{n_{out} \times \Delta P_{out}}{\rho} \] (5)

The amount of exertion of flow from the absorber to the atmosphere

\[ E_{L} = -UA_{P}(T_{p} - T_{a}) \times \left[ 1 - \frac{T_{a}}{T_{p}} \right] \] (6)

U = Overall heat loss coefficient = optimized value = 4.6797W/m²K

The amount of exergy lost involves three factors; first one temperature gradients between the absorber plate surface and the heat from the solar radiation

\[ E_{d,\Delta T_{a}} = -\eta_{O} \times I_{T} \times A_{P} \times T_{a} \times \left( \frac{1}{T_{p}} - \frac{1}{T_{a}} \right) \] (7)

The second factor is considered as pressure reduction in the ducts

\[ E_{d,\Delta P} = -\frac{n_{\Delta P}}{\rho} \times \frac{T_{a} \times \ln \left( \frac{T_{out}}{T_{in}} \right)}{(T_{out} - T_{in})} \] (8)

The third factor is assumed as variation in temperature between the surface of the absorber plate and the fluid agent.
\[ E_d\Delta T_f = -\dot{m} \times C_p \times T_a \left[ \ln \left( \frac{T_{out}}{T_{in}} \right) - \frac{(T_{out}-T_{in})}{T_p} \right] \] (9)

And the total rate of energy destruction is
\[ E_d = E_d\Delta T_g + E_d\Delta p + E_d\Delta T_f \] (10)

The solar collector exergy efficiency decides the increase in fluid flow exergy by the radiation source upon the primary radiation exergy. Through considering the concept of exergy efficiency, the Solar collector’s second law efficiency equation is obtained:
\[ \eta_{ex} = \frac{\dot{m} \left( T_{out} - T_{in} - T_a \ln \left( \frac{T_{out}}{T_{in}} \right) - \Delta p \right)}{T_a \times A_p \times \left( 1 - \frac{T_a}{T_e} \right)} \] (11)

4. Results and Discussion
The experiment was carried out for five days in a separate week for both the working fluids to determine the performance of the collector. Solar intensity of the particular day at peak sun shine hours indicates the high heat transfer from the absorber plate to the working fluid. In Figure 2 (a), the temperature measured during experiments at various points are plotted using coolant oil as working fluid. During the noon time with maximum solar intensity leads to peak outlet temperature of the fluid and absorber plate temperature are recorded as 351 K and 358K respectively. A high exergy efficiency obtained as 870W/m² corresponding to the peak solar intensity observed at the same time as shown in Figure 2 (b). In the collector all the parameters depend on the solar intensity and are directly proportional to the absorber plate temperature which resulting in a high rate of heat transfer to the working fluid.

![Figure 2. Comparison of coolant oil Inlet, Outlet, Flat Plate temperature in K (a) along with solar irradiation for the corresponding time, (b) corresponding to Exergy efficiency.](image-url)
Figure 3. Comparison of Water Inlet, Outlet, Flat Plate temperature in K (a) along with solar irradiation for the corresponding time, (b) corresponding to Exergy efficiency.

In Figure 3 (a), exhibits the temperature recorded at various points of the system using water as working fluid. A high absorber plate temperature is recorded during noon time at peak sunshine hours which helps to increase the transfer of heat from the plate to the working fluid. The maximum exergy efficiency is achieved as 6.7% during the higher solar intensity leading to increased outlet operating temperatures, as shown in Figure 3 (b).

Figure 4. Comparison of exergy efficiency of both working fluids with (a) outlet temperature (b) time.

In Figure 4 (a), the exergy efficiency is compared with outlet temperature of both the working fluid which reveals higher temperature contributing to better results. When the experiment began in the morning with low sunshine hours representing the performance of the system as shown in Figure 4 (b). The peak sunshine hours at mid noon increases the efficiency of the system due to an increase in solar intensity during the particular period. Then the solar intensity gets decreases with the progress of time, which results in decreasing the exergy efficiency for both the working fluids[22].

The exergy efficiency of the coolant achieved maximum of 7% while compared to hybrid nanofluid alumina-water as working fluid yielded 6.9%[9]. An optimal design requirements of the collectors such as glass cover thickness[24], absorber plate material[25], and the selection of suitable working fluid[18] helps to enhance the efficiency of the developed system. The experimental data is an evident
from the solar intensity imposed as a decisive factor with negligible wind velocity for improving the performance of any solar thermal system. Improving the performance of the thermal system, fluid selection plays a significant role in the use of solar thermal energy for various applications.

5. Conclusion
Exergy analysis gives a comprehensive understanding of the system energy distribution such as potential of conversion into useful energy and amount of heat loss occurring in the system. Exergy efficiency of the system using coolant oil is marginally higher than that of working fluid water. Solar radiation is the cause of the heating of the working fluid and can have a smaller impact on exergy efficiency due to experiments carried out on different weeks with different fluids. When selecting the working fluid for any heat transfer application, the thermo physical parameters must be considered in order to yield an enhanced result of any solar collectors. This experimental system for different working fluids including nano fluids and with thermal energy storage materials, with varying mass flow rates, can provide a better outcome in all aspects.

Nomenclatures

| Symbol | Description | Units |
|--------|-------------|-------|
| T_in  | Inlet temperature |       |
| T_out | Outlet temperature |       |
| T_s   | Sun temperature |       |
| T_a   | Ambient temperature |       |
| T_p   | Plate temperature |       |
| A_p   | Area of the collector |       |
| ρ     | Density of the Working fluid |       |
| m     | Mass flow rate of fluid |       |
| K     | Kelvin |       |
| E_in  | Inlet exergy rate |       |
| E_out | Outlet exergy rate |       |
| E_s   | Stored exergy rate |       |
| E_d   | Destroyed exergy rate |       |
| E_l   | Leakage exergy rate |       |
| C_p   | Specific heat capacity |       |
| η     | Efficiency of Collector |       |
| I_r   | Incident solar energy per unit area |       |
| ΔP_out | Pressure drop at outlet |       |
| U     | Overall heat loss coefficient |       |

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