Exergy efficiency analysis of a flat plate solar collector using graphene based nanofluid

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Abstract: The thermal efficiency of a flat plate solar thermal collector is largely affected by the thermal conductivity of the fluid used. In this paper, we theoretically analyzed the heat transfer performance, the entropy generation rate, and the exergy efficiency of the two different graphene based nanofluids (graphene/Acetone and graphene/water). From the analyses, it is revealed that by inserting a small amount of graphene nanoparticles in water, exergy efficiency could be enhanced by 21%, comparing to conventional fluids and entropy generation is decreased by 4 %. However, the graphene/water nanofluid shows a lower entropy generation. This characteristic suggests that graphene/water nanofluid is a better candidate for flat solar thermal application.

1. Introduction

The solar radiation intensity in Malaysia varies due to high humidity and unpredictable weather, especially during the period of monsoon. Othman et al. [1] observed that the immediate solar radiation intensity or insolation can reach a maximum value of 1400 W/m\textsuperscript{2} in Malaysia. Various parts of Malaysia have a short duration of sunshine hours. Therefore, an efficient solar collector system for Malaysian conditions should be considered to absorb the maximum heat at minimum convective losses. Solar insolation differs throughout the day, a minimum in the morning, reaching its peak at 2 p.m. and then reducing after that.

Remarkable consideration has been given to solar energy in the recent years. The use of fossil fuels will be limited due to their shortage in reserve as well as for environmental
concerns. As a result, the circumstances are inspiring researchers to find other potential sources of energy. Heat transfer improvement in solar thermal collectors is one of the key issues of energy saving and compact design. Solar thermal energy is broadly used for numerous applications, such as electricity generation, chemical processing, and thermal heating, due to its renewable and nonpolluting nature [2]. Reports on using nanofluids as heat transfer fluids in solar collectors while continue to emerge are limited in number up to date [3-11]. Aravind et al. [11] investigated graphene and graphene–multiwalled carbon nanotube (MWNT) based nanofluids. They reported an enhancement in thermal conductivity of 9.2% and 10.5% for graphene and graphene–MWNT nanofluids in de-ionized water at room temperature for 0.04% volume fraction. Further, an enhancement in heat-transfer coefficient of 193% at Reynolds number 2000 for 0.02% volume fraction of aqueous graphene–MWNT nanofluids suggested the potential application of the present hybrid material-based nanofluids in cooling circuits. Eswaraih et al. [12] investigated the frictional characteristics (FC), antiwear (AW), and extreme pressure (EP) properties of graphene based engine oil nanofluids. They explained that the improvement in FC, AW, and EP properties of nanofluids was respectively by 80, 33, and 40% compared with base oil.

The present objective of this paper is to numerically investigate the efficiency of flat plate solar collector using graphene based nanofluids as the working fluid compared to the base fluid.

2. Scope and Theoretical Approach

Energy and exergy analysis were carried out to evaluate the system efficiency of the solar collector with graphene based nanofluids. Hence, the purposes of this article are to (i) perform the elaborated exergy, entropy generation analysis, the exergy destruction and the pressure drop analyses of flat plate solar collectors using two different nanofluids as the working medium to assess the thermal and exgetic performance, and (ii) discover the effect of the volume flow rate and nanoparticles volume concentration on exergy efficiency, pressure drop, pumping power and convective heat transfer coefficient under particular operating situation. The two considered nanofluids are based on graphene infused nanoparticles in water and in acetone as the two based fluids.

2.1 Energy Analysis: The possible heat gain ($Q_u$) by the absorbing medium can be inscribed as,

$$Q_u = \dot{m}C_p \left( T_{f,\text{out}} - T_{f,\text{in}} \right) = \dot{m}C_{\text{nf}}(1-\phi) \left( T_{f,\text{out}} - T_{f,\text{in}} \right)$$

(1)

The heat capacity and density of nanofluid are calculated according to the simple mixing law as follows [8, 9]:

$$C_{p,nf} = \phi C_{p,fp} + C_{p,fn}(1-\phi)$$

(2)

$$\rho_{nf} = (1-\phi)\rho_{fp} + \phi\rho_{fn}$$

(3)
The Absorbed irradiation per unit area of solar collector absorber plate (S) is determined by,

\[ S = I_T (\tau \alpha) \quad (4) \]

The instantaneous collector efficiency relates the beneficial energy to the total radiation incident on the collector surface, and is written as:

\[ \eta_{En} = \frac{\dot{Q}_u}{A_p I_T} = \frac{\dot{m} C_p (T_{f,\text{out}} - T_{f,\text{in}})}{I_T} \quad (5) \]

Present analysis was performed by considering the normal incidence condition, hence, the \( F_R(\tau_\alpha) \), heat removal factor (\( F_R \)), and overall loss coefficient of solar collector (\( U_1 \)) were set to be constants within the range of tested temperatures.

**2.2 Exergy analysis:** The irreversibility can then be quantified as the difference in exergy measured at the inlet and outlet sections of the control volume or the deficit. The simplest exergy balance equation per unit interception area of a solar collector in steady state can be expressed as shown below:

\[ \dot{E}_g = \eta_{En} \dot{E}_{\text{sun}} - \dot{E}_{\text{loss}} \quad (6) \]

The exergy collection rate in steady state is exergy gained by heat transfer fluid while the fluid temperature increases from \( T_{f,\text{in}} \) at the inlet to \( T_{f,\text{out}} \) at the outlet. The expression of the exergy collection rate, assuming that the fluid is incompressible, can be obtained by use of the following equation [13], without considering the mechanical exergy,

\[ \dot{E}_g = \dot{m} C_p \left( T_{f,\text{out}} - T_{f,\text{in}} - T_a \ln \frac{T_{f,\text{out}}}{T_{f,\text{in}}} \right) \quad (7) \]

The exergy flux from the sun is defined here as:

\[ \dot{E}_{\text{sun}} = I_T \left( \frac{T_a}{T_s} \right) \quad (8) \]

The exergetic efficiency (\( \eta_{Ex} \)) is defined here and is expressed as follows:

\[ \eta_{Ex} = \frac{\dot{E}_g}{\dot{E}_{\text{sun}}} \]

, and after rearranging the equations, it is reduced to:

\[ \dot{m} C_p \left( T_{f,\text{in}} - T_a \right) \left( \exp \left( \frac{-U_1 A_p F}{\dot{m} C_p} - 1 \right) \right) - \dot{m} C_p \left[ \frac{T_a}{T_{f,\text{in}}} \left( \frac{\exp \left( \frac{-U_1 A_p F}{\dot{m} C_p} - 1 \right)}{T_{f,\text{in}}} \right) \left( \frac{T_{f,\text{in}} - T_a - S}{U_1} \right) + 1 \right] \]

\[ \eta_{Ex} = \frac{\dot{E}_g}{A_p I_T} \left[ \frac{T_a}{T_{f,\text{in}}} \right] \quad (9) \]
where, $T_a$ is the ambient temperature (K), $\dot{m}$ is the mass flow rate (kg/s), $A_p$ is the collector area (m$^2$) and $C_p$ is the specific heat (J/kg·K). The required system data including the thermophysical properties are given in Table 1 below.

Table 1. Environmental and analysis conditions for the flat plate solar collector

| Physical Properties | Molecular Formula | Density, at 20°C (kg/m$^3$) | Viscosity, at 25°C (N·s/m$^2$) | Thermal Conductivity, at 25°C (W/m·K) | Specific Heat Capacity at 25°C (J/kg·ºC) |
|---------------------|-------------------|-----------------------------|---------------------------------|--------------------------------------|--------------------------------------|
| Acetone             | (CH$_3$)$_2$CO    | 0.791E$^3$                  | 3.075E$^{-4}$                  | 0.16                                 | 2.160 E$^3$                          |
| Water               | H$_2$O            | 1E$^3$                      | 7.8E$^{-4}$                    | 0.58                                 | 4.182 E$^3$                          |
| Graphene            | [14,15]           | 2.25E$^3$                   | 3E$^{-5}$-5E$^{-4}$[16]        | 6.50 E$^3$[14]                      |

3. Results and Discussion

Results of the exergy efficiency with respect to nanoparticle loading and volume flow rate are depicted in Fig. 1 & Fig. 2. Increasing the volume flow rates resulted in enhanced collector efficiency. Efficiency was calculated using Eq. (5) and data of Table 1. This behaviour may be described by the longer residence times of nanofluid with the hot surfaces inside the collector and is in agreement with Benli’s work [17]. Insignificant difference is observed with the increase in volume concentration of nanoparticles in the base fluid. On the other hand, it is observed that the exergy efficiency increases substantially with the increase in the volume flow rate. The analysis demonstrates that the lowest efficiency belonged to the collector, operated by Graphene/acetone while the maximum was for Graphene/water.
Fig. 1. Effect of nanofluid volume fraction on the exergy efficiency.

Fig. 2. Effect of the flow rate on the exergy efficiency.

Results of the variations of entropy generation with volume flow rate and nanoparticles volume fraction are shown in Fig. 3(a) and Fig. 3(b). It is observed that the entropy generation drops fast with the increase of the volume fraction of nanoparticles and less obvious with respect to volume flow rate. This reduction takes place due to increase of the heat flux on the absorber plate; the irreversibility turns out to be dominant. As a result, rising the volume fraction results in enhanced thermal conductivity of the nanofluids, which happens to improve the thermal conductance. As a result of heat transfer, the irreversibility has developed an effect which is more pronounced than that of the viscous influence to the entropy generation. With increasing the volume fraction of nanoparticles, the functional viscosity of the nanofluids grows and subsequently the nanofluid friction contributes to the entropy generation. However as a whole, the entropy generation (the summation of fluid friction contributions and the heat) reduces in the gap. Graphene/water mixture shows lower entropy generation rate compared to Graphene/acetone mixture.

The analysis presented here is based on Bejan’s work [18, 19]. The analysis, however, is adapted to flat plate collectors because entropy generation minimization is more important for high temperature systems. The minimization of the entropy generation rate implies the maximization of the power output.

In order to quantify the exergy of a system, we must specify both the system and the surroundings. The exergy reference environment is used to standardize the quantification of exergy. The exergy reference environment or simply the environment is assumed to be a large, simple compressible system. In addition, it is assumed that any process does not significantly change the intensive properties of the environment. Some energy and exergy values are dependent on the intensive properties of the dead state. Dead state definitions of
exergy analysis have been studied by Krakow [20]. He reported that an exergy analysis was an implicit comparison of the performance of real thermal systems with the performance of ideal, reversible thermal systems. Gogus et al. [21] studied the influence of the variation of environmental condition in the process. In their study, the general exergy balance of a system was given based on the variation of the temperature of the surroundings. Fig. 4 demonstrates the dead state temperature.

In this paper, the conducted theoretical studies to investigate how varying dead-state temperatures (ranging from 0 to 25 °C) would affect the second law efficiency of the flat plate solar collector. Many authors used a deadstate temperature of 20 or 25 °C as a single value. The deadstate is normally selected to simulate the accessible/actual natural. Fig. 4 shows the variation of the second law efficiencies of various dead state temperatures with the fixed volume fraction and the volume flow rate. It was calculated using Eq. (9) and input data tables. The study proposed that, when the reference deadstate temperature is increased, the second law efficiency value is decreased. This means it increases the value of exergy destruction. Exhaust exergy rates changed at different deadstate temperatures. Exergy loss rates increased with the increase in the deadstate temperatures.

Fig. 3(a) Effect of flow rate on entropy generation

Fig. 3(b) Effect of volume fraction on entropy generation.
4. Conclusion

A comprehensive theoretical study was carried out to evaluate the thermal performance of flat plate solar collector using altered nanofluid as absorbing medium. The assumptions can be drawn that the efficiency of the collector advances with growing nanoparticles volume concentration due to an improved heat transfer to the nanofluid flow. The exergy loss of the system reduces subject to the increase of the collector efficiency. With increasing nanoparticles volume concentration, exergy can be enhanced with reducing exergy loss. From the analyses, it is revealed that by inserting a small amount of graphene nanoparticles in water, exergy efficiency could be enhanced by 21%, comparing to conventional fluids the entropy generation, however, is decreased by 4%.

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