Numerical Investigation to Assess and Optimize Performance of Flat Plate Solar Collector by Using Different Working Fluid

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ABSTRACT

Sustainable energy becomes an optimal alternative to overcome environmental pollution economical cost of fossil fuel. One of the most effective means to invest solar radiation is flat plate solar collectors. A study carried out to optimize and assess the performance of flat plate solar collector (FPSC) for domestic and industrial applications in the Iraq climate. A 3D numerical model of FPSC has modeled by ANSYS19, CFD tool has been used to investigate thermal transfer through FPSC based on different working fluid. Water, and nanofluid of water/copper nanomaterials were used as working fluid with three different concentrations levels, 0.011 %, 0.055%, and 0.101 %. The velocity of water was 0.3, and 0.5 m/sec respectively. The result of the numerical model was compared with a literature study to prove the reliability of the current model. The result of the current study indicated that, adding Cu nanoparticle to the working fluid enhanced temperatures outlet of FPSC. Also, maximum temperatures can be achieved by reducing the velocity value.

Keywords:
Flat plate solar collector; CFD; thermal efficiency; solar water heater; nanofluid of Cu/water heater

1. Introduction

Increasing demand for energy produced negative environmental impact as a result of fossil fuel usage. The researchers did great efforts to enhance alternatives’ performance of natural energy devices [1]. Resources of natural energy such as hydropower, solar energy, and wind energy are available for human whole time. Solar energy is used to supply hot water for domestic, and industrial applications [2]. Flat Plate Solar Collectors (FPSCs) is considered a simple device and used widely as space heating, domestic application, and industrial application. It consists of absorber, glass cover, pipes, box, insulator, storage unit. The working principle depends on solar radiation received by the absorber plate, then transfers the thermal heat to the working fluid which passes through the collector tubes. The working fluid is circulation inside pipes hence, its temperature increases due exposure time for sunlight. performance of FPSCs depends on absorber geometry, area, volume, the surrounding temperature, pipe diameter, number of pipes in the box, and tilt angle [3, 4]. It can be classified according to working fluid type that passage in the pipe. Air solar heater when working fluid...
used is air, while the liquid solar heater is used water, and colloidal (nanofluid) as working fluid water is used [5]. The stability of nanofluid along with time is one of most characters that must be investigated to achieve the purpose. It has significant findings to used which certain costs of construction, installation, and maintenance. However, it has benefits associated with the cost such as environmental impact, and saving fuel [6]. In the last few years is widely used suspensions colloidal “nanofluid” as a working fluid instead of liquid to enhance efficiency and performance of solar energy systems such as FPSCs [7-11]. It has better thermal properties than liquid [12, 13]. It is preparing by adding nanoparticular materials that range \(0 < 100\) nm to liquid (water, oil, or ethylene glycol with limited volume fraction values to avoid problem might be happened such as flow blockage, sedimentation, and agglomeration [10, 14, 15]. Synthesis a colloidal suspension is not a simple issue, therefore many studies recommended some important consideration must be taken into account [16]. The stability of nanofluid along with time is one of most characters that must be investigated to achieve the purpose. It is might be enhanced by adding a surfactant, which is an economical and efficient method [17-21]. Numerous studies were conducted to prepared various nanofluid suspension for enhancing thermal properties such as, \(\gamma\)Al2O3, Al2O3/water [8, 22-24], CuO, SiO2/water [25, 26, 27], CuO/ethylene glycol [28], Cu/water [29], Ag/water [29-32], Ag/ethylene glycol, [33] ZnO/water [33], ZnO/ethylene glycol [34, 35], MWCNTs/water [36].

In this study, a Flat Plate Solar Collector is modeled by using DesignModeler19 and analyzed by Fluent CFD tool to observe the performance of FPSC based on different working fluid. The study area is Al-Kut city, Wassit, Iraq, on 1st October during the daily time between 9 Am to 4 Pm. During October month the weather temperature is reduced, therefore performance of solar collector diverged. The study aim is assessment performance of FPSC by using water as working fluid, also, to enhance temperature outlet as well as, the performance by using Cu/H2O nanofluid as working fluid.

2. Method and Theory

2.1 Energy Analysis

FPSCs performance is calculated by an energy balance during steady state operation based on the developed mathematical model conducted ASHRE. Therefore, Calculating of heat gain by the solar collector can be expressed by Eq. (1) [11, 37]

\[
Q_g = \dot{m} \cdot c_p \cdot (T_o - T_i) = [A \cdot H_R \cdot S \cdot (\alpha \tau)] - [A \cdot H_R \cdot Q_L \cdot (T_o - T_a)]
\]

(1)

where \(Q_g\) is heat gain by absorber \(w\), \(\dot{m}\) mass flow rate of fluid, \(Kg/sec\). \(c_p\) is specific heat capacity of fluid \(KJ/Kg \cdot K\). \(T_o, T_i\) are represents fluid temperature inlet, and fluid temperature outlet, \(K\). \(H_R\) is heat removal factor. \(S\) is solar intensity, \(W/m^2\). \(\alpha, \tau\) are absorbance, transmission for plate, and glass cover respectively. \(Q_L\) is overall heat losses coefficient \(W/m^2 \cdot K\).

2.2 Specific Heat of Nanofluid

Specific heat capacity of nanofluid can be calculated by Eq. (2) [38].

\[
C_{p,e} = C_{p,p} \theta + C_{p,b}(1 - \theta)
\]

(2)

where \(C_{p,n}\) is specific heat of suspension colloidal, \(C_{p,p}\) is specific heat of nanoparticular, \(C_{p,b}\) is specific heat of base fluid, \(KJ/Kg \cdot K\), \(\theta\) is dimensionless concentration ratio of nanoparticular.
2.3 Concentrations of Nanofluid

Nanoparticular weight concentration of nanofluid is determined by using the following formula in Eq. (3) [39]

\[ \vartheta = \frac{1}{1 + \left( \frac{1}{w} \frac{\rho_p}{\rho_b} \right) \vartheta} \]  

(3)

where \( w \) is nanoparticular weight concentration, \( \rho_p, \rho_b \) are density of nanoparticular and base fluid respectively, \( \text{Kg/m}^3 \).

2.4 Density of Nanofluid

Density of nanofluid is calculated by suggested formula for theoretical calculation as in Eq. (4) [40]

\[ \rho_n = \rho_b \left( 1 - \vartheta \right) + \rho_p \cdot \vartheta \]  

(4)

2.5 Thermal Conductivity of Nanofluid

Thermal conductivity of nanofluid is influenced by the concentrations ratio of nanofluid and temperatures [41]. Therefore, experimental works were conducted to observed the influenced and suggested correlations. Thermal conductivity of nanofluid for three concentration levels are evaluated by correlations in formula Eq. (5)-(7) [42-48-49]

\[ C_n = 0.4451 + 0.0519 \ln T; \text{ at } \vartheta = 0.011\% \]  

(5)

\[ C_n = 0.4633 + 0.0529 \ln T; \text{ at } \vartheta = 0.055\% \]  

(6)

\[ C_n = 0.5017 + 0.0511 \ln T; \text{ at } \vartheta = 0.101\% \]  

(7)

where \( T \) is temperature range between 20 – 60 °C.

2.6 Viscosity of Nanofluid

Viscosity of nanofluid sensitive to temperature, and concentration value of nanofluid. Viscosity defines as the resistance of fluid against share force, therefore adding solid nanoparticular concentrations enhanced the resistance and increased viscosity. Growing temperature level is lead to decrease viscosity of nanofluid [39-45-50]. Viscosity of nanofluid can be calculated by Eq. (8)

\[ \mu_n = \mu_b (1 + \vartheta) \]  

(8)

2.7 Collector Efficiency

Solar collector efficiency is evaluated by Eq. (9) [43]

\[ \eta = \frac{\text{Actual Useful energy}}{\text{Area of collector} \times \text{Solar incident}} = \frac{Q_g}{A \times S} \]  

(9)
where A is solar collector area, $m^2$.

### 2.8 Numerical Modeling

The physical model is simulated as a 3D model by ANSYS 19.0 as shown in Figure 1. Solar collector dimensions and details are included in Table 1. Simulation is performed in weather location of Al-Kut city, Wasit, Iraq Latitude 32.514 N, and longitude 45.823 E, on 1st October from 9 Am to 4 Pm. Thermophysical properties of materials are presented in Table 2. A modeling and numerical analysis procedures described in Figure 2. The analysis of solar radiation load has been calculated under some important hypothesis and simplifications as following:

- In the solver setting, the effect of gravity was considered.
- Viscosity ($K - \varepsilon$), Energy, and radiation models were activated.
- Rosseland model was selected to implement calculations of the solar load. It has two advantages, faster and needs less memory capacity also it is recommended when optical thick greater than 3. Location, date, time, mesh directions were defined.
- Materials of solar collector modeled as absorber plate and walls were modeled as aluminum, pipes were copper, the cover of solar was glass, while the fluids were water and nanofluid of Cu/H$_2$O.
- All sides were modeled as non-slip surfaces.
- Glass cover modeled as a semi-transparent while, absorber plate considered as opaque.
- Boundary conditions were velocity inlet at the inlet, and the outflow at outlet.
- The data were initialized, and residual calculations were more than $10^{-3}$, as shown in Figure 3.

### Table 1
Dimensions of Flat plate solar collector

| Parameters                  | Dimensions, mm |
|-----------------------------|----------------|
| Box Length                  | 1100           |
| Box Width                   | 1000           |
| Box Height                  | 100            |
| Tube Length                 | 9900           |
| Tube Diameter               | 20             |
| Tube Offset                 | 100            |
| Tube Thickness              | 1              |
| Side Wall Thickness         | 1              |
| Upper Cover Thickness (Glass)| 4              |
| Lower Plate Thickness (Absorber)| 1              |
Fig. 1. A scheme of flat plate solar collector

Fig. 2. A computational fluid dynamic flowchart
Fig. 3. CFD calculations convergences

Table 2
Thermo-physical properties of materials [44]

| Material  | Aluminum | Copper | Water | Glass |
|-----------|----------|--------|-------|-------|
| Density (kg/m³) | 2770 | 8800 | 998.2 | 2500 |
| Specific Heat (J/kg.K) | 875 | 420 | 4182 | 840 |
| Thermal Conductivity (W/m.K) | 177 | 401 | 0.6 | 1.7 |
| Emissivity | 0.9 | 0.9 | - | - |

Table 3
Design of experimental by using CFD tool

| Case No. | Working fluid | Concentration ratio | Velocity m/sec |
|----------|---------------|---------------------|----------------|
| 1        | Water         | --                  | 0.3            |
| 2        | Water         | --                  | 0.5            |
| 3        | Cu/H₂O       | 0.011               | 0.3            |
| 4        | Cu/H₂O       | 0.055               | 0.3            |
| 5        | Cu/H₂O       | 0.101               | 0.3            |
| 6        | Cu/H₂O       | 0.011               | 0.5            |
| 7        | Cu/H₂O       | 0.055               | 0.5            |
| 8        | Cu/H₂O       | 0.101               | 0.5            |

3. Result and Discussion

3.1 Validation

In order to prove the validity of the suggested model under the hypothesis and considerations, the result of the current model compared with a literature study which was calculated based on an experimental study [43, 46, 47]. The present numerical results have been validated with experiments accordingly. Offset values were 5%, and 7% for maximum temperature at volume flow rates 5.1 and 6.31 L/min respectively.

3.2 Results

Solar radiation during 1st October and temperature distribution on the solar collector are presented in Figure 4(a) and (b). It can be noticed from the figure, maximum solar radiation reached 942.580 W/m² in the mid-day at 12:00 O’clock. Also, solar radiation incident in the afternoon decreasing rapidly more than the growth in the morning. The velocity of liquid was 0.3, and 0.5 m/
sec respectively with three nanoparticular concentration values $\theta = 0.011\%, 0.055\%, 0.101\%$. The maximum recorded temperature was 45.8°C at 12:00 O’clock when working fluid water and velocity 0.3 m/sec, while was 44.1 °C when velocity 0.5 m/sec, Figure 5(a) and (b). Adding nanoparticular material of copper enhanced outlet temperature of working fluid as well as solar collector efficiency. Maximum recorded temperature proportional to nanoparticular concentration value and inversely with velocity. Therefore, at concentration value (C1) 0.011 %, and velocity (V1) 0.3 m/sec, it was 46.5 °C while at concentration (C1) and velocity (V2) 0.5 m/sec was 44.4 °C Figure 6(a) and (b).

Fig. 4. (a) Solar radiation incident during 1st October, (b) temperature distribution along the pipe

Fig. 5. Water temperature during exposure daily time at (a) $V_1 = 0.3 \, m/sec$ (b) $V_2 = 0.5 \, m/sec$
A second concentration the working fluid temperature increased slightly, the maximum temperature at concentration value 0.055%, and velocity 0.3 m/sec was 46.7 °C, while was 44.5 °C, as shown in Figure 7(a) and (b).

In the third concentration level (0.101 %) nanoparticulate concentration doubled to observe its effects on temperature, as well as solar collector efficiency. Increasing temperature was clear, therefore the maximum recorded temperature was 47.2, and 44.9 °C at 0.3, and 0.5 m/sec respectively, included in Figure 8(a) and (b).

The maximum observed thermal efficiency of FPSC was 61% when water is used as working fluid with velocity 0.3 m/sec, while it was 54% when velocity 0.5 m/sec, Figure 9(a) and (b).

Maximum thermal efficiency was 64%, 67%, 74% under conditions of 0.011, 0.055, 0.101% nanoparticulate concentrations respectively, and velocity 0.3 m/sec. Whereas, it was 55%, 57%, 59% under conditions of 0.011, 0.055, 0.101% nanoparticulate concentrations respectively, and velocity 0.5 m/sec.
4. Conclusions

A numerical investigation carried out to clarify the ability and efficiency of FPSCs for domestic industrial applications when working fluid be water or nanofluid of Cu/H\textsubscript{2}O in Al-Kut city, Iraq. According to the result of numerical simulation can be concluded that

i. FPSCs can provide domestic application by temperature range about 27 to 45.8, and about 47.2 °C for water and nanofluid respectively.

ii. Increasing nanoparticulate volume concentrations increased absorptances of working fluid for solar radiation which lead to increase temperatures, as well as efficiency of solar collector.

iii. Low velocity allows to increase exposure time of working fluid to solar radiation which result in increased temperature outlet and efficiency.

iv. In the study used a concentration levels to avoid the problem might be happened in real design such as flow blockage, sedimentation, and agglomeration.

v. In applications which required higher temperatures, it can be achieved by increasing pipes length.

vi. Cu nanoparticulate expensive somewhat, therefore adding nanoparticulate must consider its advantage relative to cost.
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Conflict
The authors confirm that the work not submitted to another journal or conflicted from other works.

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