Internal energy analysis with nanofluids in header and riser tube of flat plate solar collector by CFD modelling

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Abstract. In this study, Computational Fluid Dynamics (CFD) modelling of internal energy with different nanofluids (TiO$_2$ and crystal nano cellulose) studied. The modelling was three dimensional under Viscous Laminar model. The base fluid for nanoparticles was 60% water+40% ethylene glycol along with individual water and ethylene glycol fluids. Volume fraction of nanofluids was 0.5% and single-phase model used. The diameter of inlet and outlet was fixed of individual model and three kinds of designing model used here. The diameter of both header and riser tubes varied whereas the number of tubes varied only for riser. The results revealed that diameter and number of tubes (riser) do not affect on the internal energy. Since internal energy only depends on different properties of the inside fluids.

1. Introduction

Solar energy is the most promising renewable energy due to its extensibility and abundant in nature. Negative impact and depletion of fossil fuels enslaved forcefully to realize alternative sources of energy [1, 2]. Green technology revolution has being trying to minimize these burning issues by implementing renewable energies in place of fossil energies. Academic and industrial enterprises participated to build the strongest foundation of renewable energies as well. As consequences, computational numerical simulation has been exposed as a vital tool for improving the industrial process performance and process optimization [3] such as Computational Fluid Dynamics (CFD) is the analysis of systems involving fluid flow, heat transfer and associated phenomena with chemical reactions [4]. By creating virtual design in CFD and the simulation of design should be done easily without practical design model [5].

Many engineering problems [6] as well as various numerical simulations have been performed on solar energy in order to replace the fossil energy successfully [7]. In solar collector, working fluid is flowing through header and riser tubes and the tubes are fixed together in harp-shaped. Generally, water and oil used as working fluids [8]; meanwhile this working fluids has already been changed by several number of researchers to improve the performance of solar collector [9, 10]. Moreover considerable numbers of journals have been published on CFD simulations in case of flat plate solar collectors [11]. Gunjo, Mahanta and Robi [12] validated experimental values of outlet water and absorber plate temperature with numerical values using CFD software of a solar flat plate collector with straight riser and header arrangement. Different operating parameters such as solar insolatio, ambient temperature, inlet water temperature and mass flow rate used and found developed model could predict outlet water
and absorber plate temperature of heating system with reasonable accuracy. Selmi, Al-Khawaja and Marafia [13] studied the problem of water flow in flat plate solar collector simulating with CFD software. CFD modelling has been done of solar irradiation and the modes of mixed convection and radiation heat transfer. They revealed a good agreement between experimental and simulated results. Notwithstanding the novelty of nanoparticles is unparalleled, it also create some negative impact on to the environment as nano toxicity. Nano toxicity is a catastrophic substance and can deface human being and plants [14-17]. As consequences recently the researchers are concentrating more on biodegradable and eco-friendly nanoparticles. Therefore, crystal nanocellulose attracts more attention due to its biodegradability, plentiful in nature, clear, lower density good, mechanical properties and especially green attributes to the environment [18-20].

The purpose of this research is to investigate the effect of diameter and number of tubes (riser) on internal energy with different fluids (water, TiO$_2$ ethylene glycol, 60% water+40% ethylene glycol, crystal nanocellulose) flowing through inside the tubes with constant temperature boundary condition. As different researchers used individual dimension of header and riser tube in experiment and numerical analysis study, therefore to select a distinct dimension is very ambitious. Here three types of design models are prepared with various diameters and numbers of riser tubes using “SOLIDWORKS” software for CFD simulations. The ANSYS workbench with Fluent Flow software used for this numerical simulation and the model was Viscous Laminar.

2. Nanofluids Physical Properties

Density of nanofluid defined as [21],

$$\rho_{nf} = \phi \rho_p + (1-\phi) \rho_f$$  \hspace{1cm} (1)

Thermal equilibrium define the specific heat of nanofluids [22] as Eq. 2,

$$c_{p,nf} = \frac{\phi (\rho c_{p})_p + (1-\phi) (\rho c_{p})_f}{\rho_{nf}}$$  \hspace{1cm} (2)

Thermal conductivity of nanofluids [23] calculated by the following equation,

$$k_{nf} = \frac{k_p + 2k + 2\phi(k_p - k_{bf})}{k_p + 2k - \phi(k_p - k)}$$  \hspace{1cm} (3)

According to literature review, Einstein model of viscosity determine increasing nanoparticles volume concentration linearly increases the viscosity of the suspension [24],

$$\mu_{nf} = (1 + 2.5\phi)\mu_{bf}$$  \hspace{1cm} (4)

Calculative values of density, specific heat, thermal conductivity and viscosity of different nanofluids have been executed using the above equations (1 to 4). Table 1 illustrates the calculative physical properties of different fluids and nanofluids. Reynolds number and flow behaviour has been identified empirically by the (Eq.(5)) Reynolds [25];

$$Re = \frac{\rho D v}{\mu}$$  \hspace{1cm} (5)
Table 1. Physical properties of required fluids and nanofluids

| Physical properties | Water | Ethylene Glycol | 60% Water+40% EG | TiO₂ | Crystal nanocellulose |
|---------------------|-------|-----------------|------------------|------|----------------------|
| Density (kg/m³)     | 998.2 | 1111.4          | 1050             | 2640 | 1050                 |
| Specific heat (J/kg.K) | 4182 | 2415            | 3600.648         | 1270.424 | 2450.324 |
| Thermal conductivity (W/m.K) | 0.6  | 0.252           | 0.260            | 0.91  | 0.31                 |
| Viscosity (kg/m.s)  | 0.001003 | 0.0157        | 0.0022           | 0.00495 | 0.00495             |

3. CFD governing equations
For the computational simulations of required flow geometries and boundary conditions; CFD approach usages the numerical calculation to solve the governing equations. In this study the flow pattern with constant temperature through a combined structure of two circular tubes are simulated using the FLUENT software ANSYS R15.0. Here only single-phase model is set for simulations and simulations done in steady state conditions by solving mass, momentum and energy conservation equations as [26],

Continuity Equation:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0
\]  
(6)

Momentum equation:
\[
\frac{\partial}{\partial t} (\rho \mathbf{U}) + \nabla \cdot (\rho \mathbf{U} \mathbf{U}) = -\nabla P + \nabla \tau + \rho \mathbf{g}
\]  
(7)

Energy Equation:
\[
\frac{\partial}{\partial t} (\rho h) + \nabla \cdot (\rho U_c T) = \nabla \cdot (k \nabla T)
\]  
(8)

4. Methodology
4.1 Designing of Geometry
The models are designed and developed in Solidworks (version 2016). The diameters and of header and riser tube are varied in this study. Table 2 illustrates the parameters of header and riser tube of solar collector. In addition, the number of header tubes is fixed but it varied for riser tubes. Minitab software used to make design statistical approach of geometries showed in Table 3. Three dimensional geometry of header and riser tube is generated here. Figure 1 shows the general view of combined header and riser tube of flat plate solar collector. All models have equal number (two) of header tubes but number of riser tubes varied such as eight, twelve and sixteen accordingly.

4.2 Modelling Procedure
The geometries have been imported to design modeler in ANSYS R15.0 for computational simulation. Automatically Tetrahedrons and CutCell meshing has been done in the three-dimensional computational domain. Figure 2 exhibits 3D meshed model of header and riser tube. Table 4 presents
the common mesh sizing parameters for all models. In addition, mesh independence test studied by changing mesh sizing Relevance Center such as coarse, medium and fine. Pressure-based, Absolute-velocity and Time-steady solver used in this study. Energy equation and Viscous-Laminar model used [27, 28]. In case of Boundary Condition, mass flow rate 0.0083 kg/s and temperature 307k was fixed [29, 30].

Table 2. Parameters of header and riser tubes for three-dimensional modelling.

| Parameters       | Dimension  | Header tube | Riser tube |
|------------------|------------|-------------|------------|
| Diameter (mm)    | 22, 23 and 24 | 10, 11 and 12 |
| Thickness (mm)   | 0.6        | 0.45        |
| Length (mm)      | 1000       | 1714        |
| Number of tubes  | 2          | 8, 12 and 16 |

![Figure 1. Schematic view of basic design model of header and riser tubes](image)

Table 3. Statistical presentation of designing for geometry.

| Number of Riser Tube | Header Diameter (mm) | Riser Diameter (mm) |
|----------------------|----------------------|---------------------|
| 8                    | 23                   | 10                  |
Table 4. Parameters of Mesh Sizing.

| Sizing Setting | Setting | Advance Size Function | Curvature |
|----------------|---------|------------------------|-----------|
| Relevance Centre | Coarse |
| Initial Size Seed | Active Assembly |
| Smoothing | Medium |
| Transition | Slow |
| Span Angle Center | Fine |
| Curvature Normal Angle | Default (18.0°) |
| Growth Rate | Default (1.20) |

Solution calculation is performed based on Pressure-velocity coupling with Simple Scheme and Spatial Discretization. The Solution Control parameters (Under-Relaxation Factors) for the computational simulation are presented in Table 5. Figure 3 presents the converged solution of the simulation and it is relatively similar for all of models.

Table 5. Solution Control Parameters.

| Parameters       | Setting Values |
|------------------|----------------|
| Pressure         | 0.3            |
| Density          | 1              |
| Body Forces      | 1              |
| Momentum         | 0.7            |
| Energy           | 1              |

![Graph showing residuals over iterations](image)
5. Result and Discussion

The results of computational simulations can be analysed in numerical data as in Table 6 or graphical view as in Figure 4. Numerical values of internal energy represent that diameter and number of tubes has no effect on it. All designs show some differences in minimum values of internal energy whereas maximum values are unchanged. Although mesh or grid independence test has been conducted but the results are consistent for all designs. Therefore, internal energy of header and riser tubes depends on the internal fluid characteristics rather than diameter and the number of tubes. Different fluid exhibits individual energy range according to their properties as shown in Table 6. Besides, outlet (Figure 4e) showed fully development of solution. However, some designs are not compatible with all kinds of fluid flow as Figure 5 represents the interrupted trend of energy equation.

![Figure 3. Converge solution](image)

![Figure 4a. Contours of Internal Energy (kpg)](image)

![Figure 4b. Contours of Internal Energy (kpg)](image)
Figure 4. Contours of internal energy (a) model X, (b) model Y, (c) model Z, (d) inlet and (e) outlet.

Table 6. Numerical values of internal energy of fluids and nanofluids.

| Design  | Parameters                      | Internal Energy |
|---------|---------------------------------|-----------------|
|         |                                 | Min(j/kg)       | Max(j/kg) |
| 8-22-11 | Water                           | 7555.765        | 36909.2  |
|         | Ethylene Glycol                 | 4359.228        | 21281.57 |
|         | 60% Water+40% Ethylene Glycol   | N/A             | N/A      |
|         | TiO$_2$                         | 2288.478        | 11204.88 |
|         | Crystal nanocellulose           | 4414.128        | 21588.86 |
| 8-23-10 | Water                           | 7519.131        | 36909.19 |
|         | Ethylene Glycol                 | 4343.408        | 21281.56 |
|         | 60% Water+40% Ethylene Glycol   | N/A             | N/A      |
|         | TiO$_2$                         | 2288.026        | 11204.88 |
|         | Crystal nanocellulose           | 4375.052        | 21588.86 |
| 8-23-12 | Water                           | 7602.524        | 36909.19 |
|         | Ethylene Glycol                 | 4365.053        | 21281.57 |
|         | 60% Water+40% Ethylene Glycol   | 6543.348        | 31769.23 |
|         | TiO$_2$                         | 2311.612        | 11204.88 |
|         | Crystal nanocellulose           | 4421.486        | 21588.86 |
| 8-24-11 | Water                           | 7328.505        | 36909.19 |
| Time | Water | Ethylene Glycol | 60% Water + 40% Ethylene Glycol | TiO₂ | Crystal nanocellulose |
|------|-------|----------------|---------------------------------|------|----------------------|
| 12-22-10 | 7584.952 | 4286.926 | 21281.54 | 6381.715 | 31769.23 |
| 12-22-12 | 7584.952 | 4286.926 | 21281.54 | 6381.715 | 31769.23 |
| 12-23-11 | 7496.358 | 4286.926 | 21281.54 | 6381.715 | 31769.23 |
| 12-24-10 | 7496.358 | 4286.926 | 21281.54 | 6381.715 | 31769.23 |
| 12-24-12 | 7615.049 | 4286.926 | 21281.54 | 6381.715 | 31769.23 |
| 16-22-11 | 7601 | 4286.926 | 21281.54 | 6381.715 | 31769.23 |
| 16-23-10 | 7375.112 | 4286.926 | 21281.54 | 6381.715 | 31769.23 |
| 16-23-12 | 7375.112 | 4286.926 | 21281.54 | 6381.715 | 31769.23 |
| 16-24-11 | 7600.43 | 4286.926 | 21281.54 | 6381.715 | 31769.23 |
Figure 5. Discontinuation of energy equation converge solution.

6. Conclusion
In this numerical simulation, the effect of number and diameter of tubes (header and riser), on internal energy with different fluids flowing through the tubes has been studied using ANSYS R15.0. The simulation results showed that diameter and number of tubes of flat plate solar collector do not affect on the internal energy significantly. Internal energy primarily depends on the physical properties of inside fluids. Besides, some designs are not convenient with some fluids flowing through inside the design model.

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