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SIMULATION OF A NANOFLUID-BASED ANNULAR SOLAR COLLECTOR

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Abstract

A numerical study of convective heat transfer in an annular pipe solar collector system (Fig. 1) is conducted. The inner tube contains pure water and the annular region contains nanofluid. Three-dimensional steady-state incompressible laminar flow comprising water-based nanofluid containing a variety of metallic nanoparticles (copper oxide, aluminium oxide and titanium oxide nanoparticles) is examined. The Tiwari-Das model is deployed for which thermal conductivity, specific heat capacity and viscosity of the nanofluid suspensions is evaluated as a function of solid nanoparticle volume fraction. Radiative heat transfer is also incorporated using the ANSYS solar flux and Rosseland radiative models. The ANSYS Fluent finite volume code (version 18.1) is employed to develop the thermo-fluid characteristics. Mesh independence tests are conducted. The influence of volume fraction on temperature, velocity, pressure contours is computed and visualized. Copper oxide nanofluid is observed to achieve the best temperature enhancement. Temperature contours at cross-sections of the annulus are also computed.

MATERIALS AND METHODS

The three-dimensional models of heat and fluid flow in the solar collector tube are designed in ANSYS Fluent computational fluid dynamics software. Laminar, steady-state, incompressible flow is considered and forced convective heat transfer. The annular nanofluid is the absorber fluid and the Tiwari-Das nanofluid volume fraction model is deployed [1]. The fundamental equations for steady viscous, incompressible laminar flow are the three-dimensional time-independent Navier–Stokes equations, which in a Cartesian coordinate system, take the following form:

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \]

\[ \nabla \cdot (\rho u) = 0 \]

\[ \nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot (\mu \nabla u) + \rho g \]

\[ \nabla \cdot (\rho u T) = \nabla \cdot (k \nabla T) + \dot{q} \]

\[ \frac{\partial T}{\partial t} + \frac{\partial (u T)}{\partial x} = \frac{1}{Pr} \nabla \cdot (k \nabla T) \]

\[ \frac{\partial q}{\partial t} + \frac{\partial (u q)}{\partial x} = \frac{1}{Pr} \nabla \cdot (k \nabla q) \]

where \( \rho \) is the density, \( u, v, w \) are the velocity components in the x, y, z directions, \( p \) is the pressure, \( \mu \) is the dynamic viscosity, \( \rho c_p \) is the specific heat at constant pressure, \( k \) is the thermal conductivity, \( q \) is the heat flux.

Results & Discussion

Fig. 4 shows the grid sensitivity analysis. The largest elements used in case one can be considered as a coarse mesh with 100008 elements. On increasing the number of elements to 200000 (case two), the graph shows a variation indicating that the simulation is not convergent. The next part of the grid independent study covers cases three, four and five. Upon observation of cases four (329501 elements) and five (849636 elements), cases closer to a fine mesh, where the difference between the two values is infinitesimal and hence considered negligible. This shows that the simulation is convergent at case four with 448636 elements. This grid independence study provides on appropriate grid size (coarse four) which is subsequently adapted for all further simulations and is of sufficient quality to guarantee mesh-independent and converged results i.e., the most accurate results possible with the minimum number of elements.

Fig. 4. Grid sensitivity analysis. The largest elements used in case one can be considered as a coarse mesh with 100008 elements. On increasing the number of elements to 200000 (case two), the graph shows a variation indicating that the simulation is not convergent. The next part of the grid independent study covers cases three, four, and five. Upon observation of cases four (329501 elements) and five (849636 elements), cases closer to a fine mesh, where the difference between the two values is infinitesimal and hence considered negligible. This shows that the simulation is convergent at case four with 448636 elements. This grid independence study provides an appropriate grid size (coarse four) which is subsequently adapted for all further simulations and is of sufficient quality to guarantee mesh-independent and converged results i.e., the most accurate results possible with the minimum number of elements.

Fig. 11a, 12b and 13b (temperature cross-section slice views) also show that as the volume fraction of titanium oxide nanoparticles, as we progress from the lower end of the annular region to the upper end. Stronger red oxide cases (high temperature) and yellow cases (low temperature) appear to grow considerably. The magnitudes achieved are larger than those for the aluminium oxide cases (Figs. 4b, 10b and 10b). However, they are still somewhat less than those attained for the Copper oxide cases (Figs. 5b, 6b and 7b). Apparently therefore higher nanoparticle concentrations (volume fractions) of Copper oxide attain the best thermal performance since the best absorption of solar thermal energy is achieved. Intensified thermal convection currents are generated for this case. Titanium oxide is the next best option, whereas Aluminium oxide is the least successful option. These findings are important since they generalise previous studies in which a single metallic nanoparticle was examined e.g. Copper oxide by Moghadam et al. [3] or two metallic nanofluids (silver oxide and aluminium oxide) by Madadh et al. [4].

Figs. 5c, 6c and 7c illustrate the evolution in velocity through the annular space. A less tangible influence is computed with increasing volume fraction. In all cases, high velocity zones arise at the inlet and outlet with slower zones in the intermediate sections. The primary influence on velocity is via the viscosity modification in the Tiwari-Das model. Although there is a slight intensification in velocity i.e. flow acceleration at the highest volume fraction (Fig. 7c), this is only identified in the extreme zones of the annular geometry.

Conclusions

(i) Copper oxide nanofluid is observed to achieve the best temperature enhancement. Temperature contours at cross-sections of the annulus are also computed.

(ii) Titanium oxide achieves higher temperatures than Aluminium oxide but significantly lower temperatures than Copper oxide.

(iii) Temperature cross-sections exhibit significant enhancement in magnitudes with volume fraction for all three metallic nanoparticles, although the best performance again is with Copper oxide.

(iv) There is flow acceleration for the Copper oxide at the highest volume fraction although it is confined to the increasing volume fraction of titanium oxide nanoparticles, as we progress from the lower end of the annular region to the upper end. Stronger red oxide cases (high temperature) and yellow cases (low temperature) appear to grow considerably. The magnitudes achieved are larger than those for the aluminium oxide cases (Figs. 4b, 10b and 10b). However, they are still somewhat less than those attained for the Copper oxide cases (Figs. 5b, 6b and 7b). Apparently therefore higher nanoparticle concentrations (volume fractions) of Copper oxide attain the best thermal performance since the best absorption of solar thermal energy is achieved. Intensified thermal convection currents are generated for this case. Titanium oxide is the next best option, whereas Aluminium oxide is the least successful option. These findings are important since they generalise previous studies in which a single metallic nanoparticle was examined e.g. Copper oxide by Moghadam et al. [3] or two metallic nanofluids (silver oxide and aluminium oxide) by Madadh et al. [4].

(v) Velocities are also increased with somewhat increasing volume fraction for the Copper oxide case and not altered significantly for either Titanium oxide or Aluminium oxide cases.

References


