Computational fluid dynamic simulation of a solar enclosure with radiative flux and different metallic nano-particles

Kuharat, S, Beg, OA, Kadir, A and Babaie, M

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<td>Type</td>
<td>Conference or Workshop Item</td>
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<td>USIR URL</td>
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<td>Published Date</td>
<td>2018</td>
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 Nano fluids are currently being explored extensively in solar energy engineering to achieve improved performance in direct thermal absorber systems [1]. Nano fluids achieve significant enhancement in the heat transfer performance i.e. thermal efficiency. Motivated by these developments in nano-technology, in this paper we present recent simulations of steady-state nano fluid solar collectors in a solar collector enclosure [2]. Two-dimensional, steady-state, incompressible laminar Newtonian viscous convection-radiation heat transfer in a rectangular solar collector enclosure geometry is modelled using ANSYS Fluent finite volume code (version 18.1). The enclosure has two adiabatic walls, one hot (solar receiving) and one colder wall. The Tiwari-Das volume fraction nano fluid model [3] is used and three different nanoparticles are studied (Copper (Cu), Silver (Ag) and Titanium Oxide (TiO2)) and water base fluid. The solar radiation heat transfer is simulated in the ANSYS workbench, with the elegant P1 flux model and the Rosseland model. The influence of geometrical aspect ratio (AR) and solid volume fraction for nano fluids is also studied and a wide range is considered than in other studies. These constitute novel contributions in the area of solar nanofluid collectors since these aspects are considered collectively. Mesh-independence tests are conducted. Validation with published studies from the literature is included for the copper-water nano fluid case. The P1 model is shown to more accurately predict the actual influence of solar radiation on thermal fluid behaviour compared with Rosseland radiative model. With increasing Rayleigh number (under base relative to height of the solar collector geometry) there is a greater thermal convection pattern around the whole geometry, higher temperatures and the elimination of the cold upper zone associated with lower aspect ratio. Titanium Oxide nanoparticles achieve higher temperatures and a greater local heat flux at the hot wall. Thermal performance can be optimized with careful selection of aspect ratio and nano fluids and this is very beneficial to solar collector designers. The modelling approach can be extended in future to consider fully three-dimensional simulations and unsteady effects.

MATHEMATICAL MODEL

Laminar, steady-state, incompressible flow is considered for forced convection heat transfer. The nano fluid is the absorber fluid considered a Tiwari-Das nano-particle volume fraction model is deployed [3]. The fundamental equations take the following form: 

\[ \nabla \cdot \mathbf{u} = 0 \]

\[ -\nabla p + \nabla \cdot \left( \mu \nabla \mathbf{u} \right) = \rho_s \mathbf{g} \]

\[ \rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nabla \cdot \left( \mu \nabla \mathbf{u} \right) + \rho \mathbf{g} + \mathbf{F} \]

Here \( \rho \) = fluid density, \( \mu \) = dynamic viscosity of fluid (mPa.s), \( \rho_s \) = density of solid (kg/m³). \( \mathbf{g} \) = gravity vector (m/s²). \( \mathbf{F} \) = body forces (m/s²). \( \rho \mathbf{u} \cdot \nabla \mathbf{u} \) is viscous dissipation. \n
ANSYS Fluent Boundary condition and radiation model

- Heat transfer: \& Heat flux boundaries.
- Right wall: Constant temperature, \( T = 290 \) K.
- Top and bottom walls: Adiabatic.
- Radiative heat transfer is also incorporated using the ANSYS P1 model and Rosseland radiative models.

VALIDATION

To validate the results obtained from the ANSYS Model for natural convection inside a 2-O enclosure filled with copper-water nano fluid, with a Rayleigh number of 106, a comparison is conducted with the earlier study of Abu-Haba and Ofir [4] for an aspect ratio of 1 (opaque enclosure) as shown in Fig. 3 and 4. The CFD simulation, using ANSYS Fluent1 achieves close correlation with the results in [4] as testified by very close similarity in stream line and isotherm pattern contours. Other test cases were also conducted to further confirm confidence in the ANSYS Fluent model. Once confidence was established in the simulations it is possible to progress with complexity in the geometry, buoyancy nano fluid type and radiative effects.

RESULTS

• Results of selected simulations have been presented in Figs. 3-6. Simulations show that the Rosseland model predicts a temperature field (Fig.4) very different from that obtained without radiation. For the low optical thickness in this problem, the temperature field predicted by the Rosseland model is not physically realistic. The P1-differential radiative model produces a more homogeneous thermal effect adjacent to the hot wall and enables radiation field to penetrate more evenly through the nano fluid enclosure, whereas the Rosseland model predicts a biased temperature enhancement only in the top left corner.

• The P1 model yields the complexity profiles since the radiation source in the energy equation, which is proportional to the absorption coefficient, is small. The Rosseland model uses an effective conductivity to account for radiation, while for the correct temperature field, which is in turn results in an erroneous velocity field. 

• Deviations in the velocity profiles for the three cases of the Rosseland model, P1 model and no-radiation model. The P1 velocity profile accurately simulates the presence of a momentum boundary layer along the hot and cold walls. These conclusions are in agreement with other studies in the literature [5].

• Higher Rayleigh numbers (Fig. 6) are achieved for the Titanium Oxide water nano fluid compared with Silver water profiles are much closer to those obtained from nanofluid which is attributable to the higher thermal conductivity of the former.

• With increasing aspect ratio (AR = ratio of height of enclosure to width of enclosure) there is a significant increase in the thermal dual zone at the upper and lower zone of the enclosure. A large aspect ratio number (AR = 30) achieves more homogeneous temperature distribution is achieved at lower aspect ratio.

• At Rayleigh numbers, Re = 106 the structure of streamlines suggest that the flow pattern is characterized by single cell circulation for all three aspect ratio considered (AR = 4, 10, 30). For AR = 15, the circulation is stronger than with the other aspect ratios. However higher aspect ratios, the streamlines distributions are more symmetrical than at the lower AR value where asymmetric is observed and a streamlines emerges in the circulation which is biased towards the left hot wall of the solar enclosure. Vortex structure is therefore closely influenced by aspect ratio.

• Overall the isotherms are compressed towards the hot wall and the cold ceiling and most of the enclosure is occupied by water fluid that is colder. Due to this effect, the single cell is expanded in both vertical and horizontal directions at higher aspect ratio with lesser distortion in the flow. This expansion results in boundary layer formation.

• Nusselt number at the left hot wall is maintained at low aspect ratio (AR =0.5) and enhanced at high aspect ratio (AR =10) indicating that shorter and wider solar enclosures achieve significantly better heat transfer rates than taller and narrower enclosures.

• The present simulations provide a good benchmark for experimental studies and may also be generalized for other metallic nano fluids (gold, silver etc) and extended to the unrealistic case. These aspects are currently under consideration [7, 8].

REFERENCES

2. S. Kumar, An Investigation of Solar Nanofluid Collectors with Different Geometries using CFD Simulation, Year 1 PhD Interim Assessment Report, Aeronautical and Mechanical Engineering Department, University of Salford, Manchester, UK (November, 2018).