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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Computational Fluid Dynamic Simulation of a Solar Enclosure with Radiative Flux and Different Metallic Nano-Particles

ABSTRACT

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 advancements in nano-technology, in this poster we present recent simulations of steady-state nanofluid flow and heat transfer in a rectangular solar collector enclosure geometry modeled with ANSYS FLUENT finite volume code (version 18.1). The enclosure has two adiabatic walls, one hot (solar receiving) and one cold wall. The Tiwari-Das volume fraction model [3] is used and three different nanoparticles are studied (Copper (Cu), Silver (Ag) and Titanium Oxide (TiO2)) and water base fluid. The solar radiative 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 wider range is considered than in other studies. These constitute novel contributions in the area of solar nano fluid 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 nanofluid case. The P1 model is shown to more accurately predict the actual influence of solar radiative flux on thermal fluid behavior compared with Rosseland radiative model. With increasing Rayleigh number, the velocity field changes in buoyancy effect. Significant modification in the thermal flow characteristics is induced with emergence of different vortex regions. With increasing aspect ratio (under base relative to height of the solar collector geometry) there is a greater thermal convection pattern around the wall geometry, higher temperatures and the elimination of the cold upper zone associated with lower aspect ratio. Titanium Oxide nano particles 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 particles 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.

MATHMATICAL MODEL

Laminar, steady-state, incompressible flow is considered with forced convection heat transfer. The nanofluid is the absorbing fluid in a one dimensional problem of a Tiwari-Das nano particle volume fraction model is deployed [3]. The fundamental equations take the following form:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot ( \rho \mathbf{u} ) &= 0 \\
\nabla \cdot \mathbf{u} &= 0 \\
\n\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} &= -\nabla p + \nabla \cdot \left( \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \right) + \mathbf{F} \\
\n\frac{\partial \rho e}{\partial t} + \nabla \cdot ( \rho \mathbf{u} e ) &= \nabla \cdot ( k \nabla T ) + \dot{Q}_v
\end{align*}
\]

Energy conservation:

\[
\frac{\partial \rho e}{\partial t} + \nabla \cdot ( \rho \mathbf{u} e ) = \nabla \cdot ( k \nabla T ) + \dot{Q}_v
\]

\[
\text{Silicon Nano particles volume and } V_f \text{ volume of fluid, } \mu, \rho, k, \text{ dynamic viscosity of nanofluid(solid), density, thermal conductivity of nanofluid(solid), density of base fluid}
\]

Here \( \phi \)-volume fraction, \( \rho \)-nano particles volumetric and \( V_f \)-volume of fluid, \( \mu \text{, } \rho, k \)-dynamic viscosity of base fluid, \( \rho, k \)-the density of fluid, \( \rho, k \text{ nanoparticles density, } \rho, k \text{ nanoparticles specific heat, } \rho, k \text{ thermal conductivity, } \rho, k \text{ fluid thermal conductivity and } k, \rho \text{ thermal conductivity. The key local dimensionless parameters which may be computed in the post-processing in ANSYS FLUENT} \]

Rayleigh number: \( R = \frac{\rho g T_0 (T_m - T_c)}{\mu k} \)

Nusselt number: \( Nu = \frac{h_{cf} D}{k} \)

Here \( g \)-gravity, \( \beta \)-coefficient of thermal expansion, \( u \)-thermal diffusivity, \( L \)-coordinate, \( I \)-injection coefficient, \( D \)-height of the enclosure, \( g \)-gravitational acceleration constant in m/s², \( \mu \text{, } \rho, k \text{ microfluid parameters, } \rho, k \text{ nanofluid parameters, } \rho, k \text{ base fluid parameters, } \rho, k \text{ nanoparticles parameters, } \rho, k \text{ nanoparticles specific heat, } \rho, k \text{ nanoparticles thermal conductivity, } \rho, k \text{ fluid thermal conductivity and } k, \rho \text{ thermal conductivity. The key local dimensionless parameters which may be computed in the post-processing in ANSYS FLUENT} \]

ANSYS FLUENT Boundary condition and radiation model:

\( \text{Right wall: Constant temperature, } T=290 K \).
\( \text{Top and Bottom walls: Adiabatic.} \)
\( \text{Radiative heat transfer is also incorporated using the ANSYS P1 model and Rosseland radiative models.} \)

RESULTS

Validation

To validate the results obtained from the ANSYS Model for natural convection inside a 2-D enclosure filled with copper-water nanofluid, with a Rayleigh number of \( 10^6 \), a comparison is conducted with the earlier study of Aliv-Hatami [4] for an aspect ratio of \( 1 \) (square enclosure) as shown in Fig 3 A-B. The CFD simulation, using ANSYS FLUENT achieves close comparison to the results in [3] as is testified by the 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.

COMPARISON BETWEEN RADIATION FLUX MODELS

Comparision of Aspect ratio effect for Titanium Oxide-Water

COMPARISON OF HEAT TRANSFER RATES FOR DIFFERENT NANO-PARTICLES

COMPARISON OF ASPECT RATIO EFFECT FOR TITANIUM OXIDE-WATER

COMPARISON OF ASPECT RATIO EFFECT FOR TITANIUM OXIDE-WATER

CONCLUSIONS

- 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 model significantly produces a non-homogeneous thermal effect adjacent to the hot wall and enables radiation to penetrate more evenly through the nanofluid enclosure whereas the Rosseland model predicts a biased temperature enhancement only in the top left corner.
- Non-homogeneous temperature field is obtained due to the presence of a non-homogeneous layer on the hot and cold walls. The same characteristics are also found in other studies with the same radiation field.
- Larger Nu numbers (Fig. 5) are obtained for the Titanium Oxide nanofluid compared with Silicon Water profiles are much closer to those obtained from nanofluid which is attributed to the higher thermal conductivity of the former.
- With decreasing aspect ratio (AR = ratio of height of enclosure to width of enclosure) there is a significant non-homogeneity in the thermal dual zone at the upper and lower zones of the enclosure. A non-homogeneous temperature distribution is achieved at lower aspect ratios.
- At Rayleigh number, \( R = 10^6 \), the structure of streamlines suggest that the flow pattern is characterized by single cell circulation for all aspect ratio considered (AR = 4, 3.5, 2, 1.5, 1, 0.5, 0.25). For AR = 0.5 is circulation is stronger than the other aspect ratios. However at higher aspect ratios, the streamline distributions are more symmetrical than at the lower AR value where divisionary is observed and a streamem emerges in the circulation which is biased towards the hot wall of the solar enclosure. Vortex structure is therefore clearly 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 large core of higher temperature the opposite side. 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 reduces in boundary layer formation.
- Nusselt number at the left hot wall is maintained at low aspect ratios (AR =0.5) and increased at high aspect ratio (AR = 0.25) indicating that shorter side is much cooler and nanofluid enclosure significantly achieve 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 particles (gold, zinc etc.) and extended to the unsteady case. These aspects are currently under consideration [7, 8].

REFERENCES