1. INTRODUCTION

Nano fluids are increasingly being deployed in numerous energy applications owing to their impressive thermal enhancement properties. Motivated by these developments in the current study we present finite volume numerical simulations of natural convection in an inclined three-dimensional (3D) prismatic direct absorber solar collector (DCS) containing water-nanofluid. Strady-state, incompressible laminar Newtonian viscous flow is assumed. The enclosure has one hot (solar receiving) and one colder wall while all the other walls are adiabatic. ANSYS FLUENT’s computational fluid dynamics software is employed. The Tiwari-Das volume fraction model is utilized to simulate nanofluids and allows a systematic exploration of volume fraction effects. The effects of thermal buoyancy (Rayleigh number), geometrical aspect ratio and enclosure tilt angle on isotherm and temperature contours are presented with extensive visualization in both two and three dimensions. Grid-independence tests are included. Validation with published studies from the literature is also conducted. A significant modification in vortex structure and temperature distribution is computed with volume fraction, Rayleigh number, aspect ratio and tilt angle. Gold nanoparticles even at relatively low volume fractions are observed to achieve substantial improvement in heat transfer characteristics.

MATHEMATICAL MODEL

The 3D models of heat transfer in the solar nanofluid absorber are designed in ANSYS FLUENT [1]. The geometric configuration is illustrated in Fig.1. The fundamental equations for steady viscous, incompressible laminar flow and thermal convection are the three-dimensional, time-independent Navier-Stokes equations and energy equation, which, in a Cartesian coordinate system, take the following form:

\[ D \text{D'Alambert mass conservation} (3-D \text{ continuity}) \]

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \]  

\[ \text{x-direction momentum conservation} \]

\[ \frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u \mathbf{u}) = \nabla \cdot (\tau + p) + \rho g_x \]  

\[ \text{y-direction momentum conservation} \]

\[ \frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho v \mathbf{u}) = \nabla \cdot (\tau + p) + \rho g_y \]  

\[ \text{z-direction momentum conservation} \]

\[ \frac{\partial \rho w}{\partial t} + \nabla \cdot (\rho w \mathbf{u}) = \nabla \cdot (\tau + p) + \rho g_z \]  

\[ \text{Energy equation} \]

\[ \frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho h \mathbf{u}) = \nabla \cdot (\mathbf{q} + \rho h g) \]  

Tiwari-Das model allows different concentrations (volume fraction) and types of metallic nano-particles. Where nanofluids properties can be calculated from follow equation

\[ \phi = \rho_{nf} / \rho_{liq} \rightarrow \rho = \phi \rho_{nf} + (1-\phi) \rho_{liq} \]

\[ c_{nf} = \frac{(1-\phi) c_{liq} + \phi c_{nf}}{\phi} \]

\[ s_{nf} = \frac{(1-\phi) s_{liq} + \phi s_{nf}}{\phi} \]

The key dimensionless parameters which computed are local Rayleigh number (Ra) and the average Nusselt number on the hot wall (TwID)

\[ Ra = \frac{\beta (T_w - T_{in}) L^3}{v \nu} \]

\[ Nu = \frac{h L}{\nu} \]

\[ \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \alpha \nabla^2 T \]

3. GRID STUDY & VALIDATION

An extensive mesh testing procedure was conducted to guarantee a grid-independent solution. The grid independence test has been performed on a cubical enclosure (i.e. aspect ratio =1) with Ra = 10^6, \( \phi = 0.02 \% \) and 3% gold nanoparticles by volume. The results of the mesh variation are shown in Fig. 3. It is evident that the simulations attain mesh-independent convergence with approximately 40,000 tetrahedral elements (Fig. 2). From Fig. 4, it shows that the non-dimensional temperature along the horizontal centroid in the YL=0.5, confirms that the present results are close to the benchmark results. Furthermore, it also confirms that the grid resolution of the simulation is fine enough to obtain the independent results.

4. RESULTS AND DISCUSSION

Fig. 5 shows the evolution in hot wall 3-dimensional temperature contours plots with a progressive increase in tilt angle (x = 0, 10, 30, 45 and 60 degrees) at Rayleigh number of Ra = 10^6. As the enclosure tilt angle is increased this the hotter zones expand steadily to occupy a greater area in the enclosure. The warmer green contours are progressively replaced with hotter yellow contours and the colder blue zone is systematically compressed although it is not eliminated. The red hotter linear zone along the left edge is slightly expanded but does not grow to the full extent of the edge length. The stronger thermal buoyancy present contributes to enhancement in thermal diffusion and also enhances thermal boundary layer thickness at the left wall. This effect has also been computed by Ostrach [2] for Newtonian fluids. Scaling thermal buoyancy contribution via tilting the enclosure is therefore a simple but powerful mechanism for regulating temperature distribution in the solar collector.

5. CONCLUSIONS

(i) Higher aspect ratio leads to improved heat transfer in the regime with deeper penetration of warmer zones in the enclosure.

(ii) Increasing Rayleigh number (which indicates velocity) relative to viscous hydrodynamic force) induces an intensification in heat transfer from the left wall through the enclosure space and much more homogenous temperature distributions are eventually obtained.

(iii) With increasing nano-particle volume fraction, heat penetrates more effectively into the enclosure from the hot wall and temperature magnitudes are enhanced.

(iv) With greater inclination of the enclosure there is a progressive elevation in heat transfer from the left hot face (heated wall) towards the opposite cold wall, and temperatures are elevated mainly in the upper left zone with a more extensive warming in the central zone.

(v) Heat Das is dramatically increased with greater nano-particle volume fraction, and aspect ratio whereas it is suppressed with greater inclination of the enclosure.

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