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<table>
<thead>
<tr>
<th>Title</th>
<th>Simulation of a nanofluid-based annular solar collector</th>
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</thead>
<tbody>
<tr>
<td>Authors</td>
<td>Kuharat, S and Beg, OA</td>
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<td>Type</td>
<td>Conference or Workshop Item</td>
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<tr>
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</tr>
</tbody>
</table>

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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 in this study. 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 nano-particles (copper oxide, aluminium oxide and titanium oxide nanoparticles) is examined. The Tiawi-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 Rosslend radiative models. The ANSYS FLUENT finite volume code (version 18.1) is employed to simulate the thermal 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.

Mathematical Model

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 with forced convective heat transfer. The annular nanofluid is the absorber fluid and the Tiawi-Das nano-particle 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:

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

For the energy conservation equation is:

\[ \frac{\partial E}{\partial t} + \frac{\partial \left( \rho u E \right)}{\partial x} + \frac{\partial \left( \rho v E \right)}{\partial y} + \frac{\partial \left( \rho w E \right)}{\partial z} = \frac{\partial}{\partial x} \left( \mu \frac{\partial E}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial E}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu \frac{\partial E}{\partial z} \right) + \rho f \]

where \( E \) is the total energy, \( \rho \) is the density, \( u, v, w \) are the velocity components in the three directions, \( \mu \) is the dynamic viscosity, \( f \) is the fictitious body force, and \( \rho f \) is the specific heat flow. The Tiawi-Das model allows different concentrations (volume fraction) and types of metallic nano-particles. Where nano fluid properties can be calculated from follow equations:

\[ \rho = \frac{\mu_{f}}{\mu} \]

where \( \rho \) is the density, \( \mu \) is the dynamic viscosity of the pure fluid, \( \mu_{f} \) is the dynamic viscosity of base fluid, \( \rho f \) is the mass density, \( \rho_{f} \) is the mass density of nanofluid, \( C_{p,f} \) is the specific heat, \( \rho_{f} \) is the density of fluid, \( \lambda_{f} \) is the thermal conductivity, and \( k_{n} \) is the nanoparticle thermal conductivity.

For example, the boundary condition and radiation model:

At the inlet: Volume flow rate inlet of 0.002 kg/s.
At the outlet: Zero pressure outlet from one face.

Heat flux: Heat is added as the sun radiation intensity of 877 W/m². In ANSYS FLUENT the natural convection condition is set as 0.93 N/m². The heat transfer is also incorporated using the ANSYS solar load model and Rosslend radiative models. The ANSYS FLUENT finite volume code [2] is employed to simulate the thermo-fluid characteristics.

Results & Discussion

5a, 6a and 7a show a significant modification in temperature distributions as volume fraction is enhanced from 0 to 0.01, to 0.05 and finally 0.1. There is progressive heating from the base annulus of the annular region with increasing volume fraction. The blue zones are progressively eliminated, and green zones (higher temperature) extend further towards the upper annular end. Red (maximum temperature zones) begin to appear at the highest volume fraction (Fig. 7a). The increase in concentration of metallic nanoparticles clearly enhances thermal conductivity of the nanofluid in the annular region and this intensifies thermal diffusion and heat transfer (Figs. 11a, 12b, 13a). The temperature contours were compared at the same volume fraction for aluminum oxide (Figs. 6a, 6b, 10a) but are substantially lower than those obtained for Copper oxide (Figs. 6a, 7a, 8a). This confirms the superior performance of Copper oxide in achieving thermal enhancement in the annular solar collector.

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 aluminum oxide but significantly lower temperatures than Copper oxide.
(iii) Temperature cross-sections exhibit significant enhancement in magnitudes with volume fraction for all three metal nano-particles, although the best performance again is with Copper oxide.
(iv) There is flow acceleration for the Copper oxide case at the highest volume fraction which is confined to the extreme zones of the annular geometry (inlet and outlet).
(v) Velocities are initially increased with volume fraction for the Aluminium oxide case but subsequently reduced with maximum volume fraction they are reduced.
(vi) Pressure drops are also significantly with increasing volume fraction for the Copper oxide case and not altered significantly for either Titanium oxide or Aluminium oxide cases.

References


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