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Abstract: A numerical simulation model for laminar flow of nanofluids in a pipe with constant heat flux on the wall was built to study the effect of the Reynolds number on convective heat transfer and pressure loss. The investigation was performed for hybrid nanofluids consisting of CuO-Cu nanoparticles and compared with CuO and Cu in which the nanoparticles have a spherical shape with size 50, 50, 50nm respectively. The nanofluids were prepared, following which the thermal conductivity and dynamic viscosity were measured for a range of temperatures (10 -60°C). The numerical results obtained were compared with the existing well-established correlation. The prediction of the Nusselt number for nanofluids agrees well with the Shah correlation. The comparison of heat transfer coefficients for CuO, Cu and CuO-Cu presented an increase in thermal conductivity of the nanofluid as the convective heat transfer coefficient increased. It was found that the pressure loss increases with an increase in the Reynolds number, nanoparticle density and particle volume fraction. However, the flow demonstrates enhancement in heat transfer which becomes greater with an increase in the Reynolds number for the nanofluid flow.

Key words: Nanofluid, heat transfer enhancement, oxide nanoparticles, hybrid nanofluid, pressure loss, heat transfer coefficient

1 INTRODUCTION

A nanofluid is the suspension of nanometre sized nanoparticles into a base fluid. The main purpose of the preparation of a nanofluid is to enhance the properties of heat transfer for the base fluid, but this can have a bad effect on the flow properties, where the solid particles, in millimetre and micrometre sizes, behave as a two-phase flow which increases the power needed to force the fluids to move. The preparation of the nanofluids was made through the suspension of nanoparticles in a base fluid¹, which increases the thermal properties of the nanofluid and makes it behave as a one-phase flow.

The liquid-particles are compounds consisting nanoparticles of less than 100 nm suspended in a fluid with less than 4% volume fraction. The determination of the heat transfer coefficients is required to obtain all the thermophysical properties².

The copper material nanoparticles were suspended in an EG (ethylene glycol) base fluid at 0.3 volume fraction and it was found that the thermal conductivity increased by 40%³. It has been reported that the suspension of alumina with a volume fraction of 1-4% in water will increase the thermal conductivity by up to 10-25%. These thermal conductivity enhancements have been explained for temperatures ranging from 21-51°C using theoretical models such as that developed by Hamilton and Crosser⁴, which can be used to predict the thermal conductivity of nanofluids⁵. Research-
ers studied the effect of volume concentration experimentally for 0.5-1.2% copper-water nanofluids and the enhancement of the heat transfer coefficients was found to be 1.05 to 1.14% in a circular tube for constant heat flux at the wall of the tube at the constant velocity inlet\(^5\). Also, Xuan and Li\(^6\) investigated experimentally the flow and convective heat transfer of nanoparticles of Cu suspended in deionized water through straight horizontal brass pipes with constant heat flux, where the concentrations of Cu in the water was in the range of 0.3 -2%. The Nusselt equation was derived for a laminar and turbulent range, i.e. 800-25,000, where in this range; the classical Dittus and Boelter\(^7\) correlation is not applicable for nanofluids. The enhancement of heat transfer was 60% for a 2% concentration compared with water.

An experimental system was built to study the heat transfer enhancement at the entrance region using a nanofluid consisting of Al\(_2\)O\(_3\)- water with a laminar flow, and the system included the nanofluid flowing through the pipe with heat flux supplied on the wall for different concentrations of nanoparticles\(^8\). The Nusselt equation was calculated for the nanofluids and the temperature profile along the test pipe, and the results showed that the Reynolds number and volume concentration were the primary effects in the heat transfer coefficient. An experimental study was presented to determine the heat transfer enhancement in a horizontal tube heat exchanger with a nanofluid in the laminar flow. The graphite nanoparticles were a disc shape with an aspect ratio of 0.02 and were used to enhance heat transfer with the side effect of highly increasing the viscosity of the nanofluid. The researchers investigated two types of nanofluids with different base fluids and different flow rates of 62-507 cm/min, different Reynolds numbers 5-110 and fluid temperatures of 50-70°C. The experimental results indicated that the heat transfer increased with an increase in the particle volume fraction and Reynolds number, while the heat transfer coefficient of the nanofluids moderately increased compared with the base fluid and its temperature\(^9\).

Sundar et al.\(^10\) reported an experimental investigation studying the Peclet and Nusselt number for different volume fractions of alumina-water flowing in a circular tube at a constant wall temperature. An experimental rig was used to study the effect of twisted tape inserted in a circular tube on the heat transfer of nanofluids with different volume concentrations. A further enhancement in heat transfer with twisted tape was achieved when compared with a smooth tube under the same conditions\(^11\), where the convective heat transfer coefficient and pressure drop of Al\(_2\)O\(_3\)- water flowing through a constant heat flux circular tube in a fully-developed laminar flow regime were measured. The experimental results showed that Darcy’s equation for one phase flow is applicable for predictions of the friction factor for nanofluids, while the convection heat transfer coefficient increased by up to 8% with a volume fraction of 0.3 vol% compared with that of water for this enhancement, which could not be predicted by the Shah correlation. The correlation of heat transfer in the entrance region was suggested depending on the experimental results for the flow of nanofluids in a tube with constant heat flux. The effect of the size of the alumina nanoparticles suspended in water on convective heat transfer at the entrance laminar region was studied. The smaller size of nanoparticles gave a better enhancement in terms of heat transfer in the developing region\(^12\). The enhancement of heat transfer was experimentally studied and reported to be much higher than the heat transfer obtained by the correlations used with nanofluid properties as suggested in the literature\(^13\). The study numerically examined the enhancement of the heat transfer coefficients for CuO, Al\(_2\)O\(_3\) and SiO\(_2\)-EG-water nanofluids in a circular pipe for the turbulent regions. The heat transfer coefficient was found to increase with an increase in the Reynolds’s number and volume fractions, and at the same time the pressure drop along the pipe depended on the nanoparticle size suspended in the base fluid\(^14\). The alumina-water nanofluids flowing in a horizontal and an inclined tube was studied\(^15\), where by the maximum heat transfer enhancement of the nanofluid obtained was 15%. Researchers Balla et al. studied the enhancement of heat transfer for different metallic oxide nanoparticles. They found the nanofluid was highly affected by the nanoparticle properties.

However, the purpose of this paper is to numerically study the enhancement of heat transfer for hybrid nanofluids flowing in a circular pipe with constant heat flux and compare the results with mononular nanofluids. The temperature dependency for thermal conductivity and dynamic viscosity were measured for use in numerical modelling.

### 2 EXPERIMENTAL PROCEDURES

#### 2.1 Preparation of the nanofluid

The preparation of a nanofluid is a prerequisite before experiments can be conducted. A two-step method was used to prepare the nanofluid samples. The nanoparticles CuO, Cu and CuO-Cu of sizes (50, 50, 50nm) were suspended in a base fluid (distilled water) at different concentrations (0.2, 0.4, 0.6, 0.8and 1%). Ultrasonic vibration was used for ten hours to ensure proper mixing and dispersal of the nanoparticles into the base fluid. No sediment was observed for the suspended nanofluids even after one day. As additives and a stabilizer can alter the properties of the nanofluids they were not used. The time for measuring thermal conductivity and dynamic viscosity of the nanofluids was reduced to avoid the effect of aggregation on the nanofluid properties.

To determine the mass dispersed throughout the base

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fluid, first the volume for the nanoparticles at each volume fraction was calculated. The volume fraction of nanoparticles is given by:

$$\phi = \frac{V_p}{V_t} \quad (1)$$

Assume the volume for CuO and Cu nanoparticles is $V_p = V_{CuO} = V_{Cu}$, and for the hybrid nanoparticles the volume fraction given in Equation 2 will be used.

$$V_p = V_{CuO} + V_{Cu} \quad (2)$$

The two volume fraction ratio for the hybrid nanofluid used in this study followed 2CuO-1Cu and 1CuO-2Cu, so an illustrated in ref. S2 refers to the hybrid nanofluid with 2CuO-1Cu and S2 refers to the hybrid nanofluid with 1CuO-2Cu.

$$\phi = \frac{V_{Cu}}{V_{t}} \quad (3)$$

The total mass for the suspended nanoparticles is:

$$m_p = 1 \times 10^{-3} V_p \rho_p \quad (4)$$

The properties of the material of the nanoparticles are illustrated in Table 1. The 20 samples, five for each type of nanofluid (2CuO-1Cu, 1CuO-2Cu, Cu and CuO) were prepared with volume fractions of 0.2, 0.4, 0.6, 0.8 and 1%. S1 refers to the hybrid nanofluid with 2CuO-1Cu and S2 refers to the hybrid nanofluid with 1CuO-2Cu.

### 2.2 Measurement of thermal conductivity

The transient coated hot wire method is widely used to determine the thermal conductivity of nanofluids. The transient coated hot wire technique was used to measure the thermal conductivity of the nanofluids in this study (S1, S2, Cu and CuO). The measurements for the range of temperatures (10°C to 60°C) and volume fraction range (0.2-1%) were undertaken to determine the heat transfer and pressure losses for nanofluids flowing in a pipe.

### 2.3 Measurement of dynamic viscosity

A sine-wave Vibro Viscometer SV-10 was used to measure the dynamic viscosity at an accurate temperature for the nanofluids (S1, S2, Cu and CuO). The dynamic viscosities of the nanofluid samples were measured for different volume fractions ranging from 0.2 vol% to 1 vol% and at a temperature range of 10°C to 60°C.

However, experimental work to establish the viscosity of the nanofluids showed that the measured viscosity was at an accepted variance with the existing theoretical predictions for water. For calibration of the device, the viscosity of water was measured before and after each measurement of the nanofluid sample.

### 3 MATHEMATICAL MODEL

#### 3.1 Governing Equation

The case set for this investigation is a three-dimensional steady state incompressible flow with forced laminar convection of nanofluids flowing through a circular pipe having a diameter of 10 mm and a length of 2 m with the thickness of the pipe being 1 mm. The flow enters the pipe at a constant temperature of 300 K and a uniform velocity. Outlet boundary conditions were enforced for the outlet section. The above boundary conditions imply zero normal gradients for the flow variables except pressure. The no-slip boundary condition was imposed on the wall of the tube. The wall was subjected to a constant heat flux of 1000 W/m² as shown in Fig. 3. The Reynolds number varied from 100 to 1100.

The relevant governing equations used can be written as follows:

Conservation of Mass

$$\nabla \cdot \rho \vec{V} = 0 \quad (5)$$

Momentum Equation

$$\nabla \cdot (\rho \phi \vec{V} \vec{V}) = -\nabla P + \nabla \cdot (\mu \nabla \vec{V}) \quad (6)$$

Energy Equation

$$\nabla \cdot (\rho \phi C_{pf} \vec{V}) = \nabla \cdot (K_{nf} \nabla T) \quad (7)$$

The governing equations of the nanofluid flow are coupled partial differential equations and a non-linear equation. It was assumed that the boundary conditions applied at the tube entrance section of the pipe were a temperature $T_{in}$ and a uniform axial velocity $V_{in}$. At the outlet of the pipe section, the temperature fields and flow were assumed to be fully-developed ($x/D > 10$). The nanofluids specific heat capacity $C_{pf}$ was determined through energy balances as follows:

$$C_{pf} = \frac{\phi \rho_p C_p + (1-\phi) \rho_n C_n}{\rho_f} \quad (8)$$

Similarly for the density of the nanofluid this was determined from the equation below:

### Table 1 Properties of the nanoparticles.

<table>
<thead>
<tr>
<th>nanoparticles</th>
<th>Mean diameter nm</th>
<th>Density kg/m³</th>
<th>Thermal conductivity W/m K</th>
<th>Specific heat J/kg K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuO</td>
<td>50</td>
<td>6500</td>
<td>17.65</td>
<td>533</td>
</tr>
<tr>
<td>Cu</td>
<td>50</td>
<td>8940</td>
<td>401</td>
<td>385</td>
</tr>
<tr>
<td>S1</td>
<td>50</td>
<td>7113.3</td>
<td>measured</td>
<td>483.6</td>
</tr>
<tr>
<td>S2</td>
<td>50</td>
<td>8126.6</td>
<td>measured</td>
<td>434.3</td>
</tr>
</tbody>
</table>

3.2 Heat Transfer Enhancement Calculation Process

A half-tube was used to reduce the calculation time as a result of a symmetry approach to the modelling. To solve the present problem, the Computational Fluid Dynamics (CFD) module in the COMSOL Multiphysics software was employed, which utilizes the governing equations (5-7) to generate the pressure, velocity and temperature fields. The solution was obtained based on the spatial integration of the conservation equations using the finite-element method, converting the governing equations into a set of algebraic equations. The algebraic linear equations resulting from this spatial integration process, were sequentially solved throughout the physical domain considered. COMSOL solves the systems resulting from linearization schemes using a numerical method. The residuals resulting from the integration of the governing equations (5-7) are considered as convergence indicators and uniform. In order to ensure the accuracy as well as the consistency of the numerical results, several non-uniform grids were subjected to an extensive testing procedure for each of the cases considered.
The results obtained for each particular test case showed that for the tube flow problem under consideration, the 757,817 elements appeared to be satisfactory to ensure the precision of the numerical results as well as their independency with respect to the number of nodes used. The computer model was successfully validated with correlations reported by Shah [2006] for thermally and hydraulically developing flow, which showed an average error of less than 2%, as reported in Fig. 2 and Fig. 3, where the local Nusselt number was calculated according to the following definition:

\[ \text{Nu}(z) = \frac{h(z) \cdot D}{K} \]  

(10)

where \( D \) is the diameter of the circular duct and the local heat transfer coefficient \( h(z) \) is defined as:

\[ h(z) = \frac{q}{T(z)_w - T(z)_b} \]  

(11)

Where \( T(z)_w \) is the local temperature at the wall of the tube while \( T(z)_b \) is the bulk temperature of the nanofluid. From the previous equation, the average heat transfer coefficient \( h_{avg} \) is calculated as:

\[ h_{avg} = \frac{1}{L} \int_0^L h(z) \, dz \]  

(12)

Where \( L \) is the length of the pipe, the average Nusselt number becomes

\[ \text{Nu}_{avg} = \frac{h_{avg} \cdot D}{K} \]  

(13)

3.3 Validation of the Numerical Results

Figure 4 shows a comparison of the pressure drop for water in a copper pipe estimated from the Blasius Equation (15) and the numerical results in the present study.

Comparison of the numerical results with the theoretical data validated the numerical model for conventional fluids. The Darcy friction factor \( f \) was given by Blasius [200], which can be derived from Equation (14) and Equation (15), i.e.:

\[ f = \frac{64}{\text{Re}} \]  

(14)

\[ \Delta p = f \left( \frac{l}{D} \right) \left( \frac{1}{2} \rho V^2 \right) \]  

(15)

Figure 5 shows a comparison of the pressure drop with volume fraction observed to be in good agreement with a maximum deviation of 3% from the theoretical equation over a range of Reynolds numbers. The Nusselt number for...
fully-developed laminar flow for water was compared with the empirical correlation given by Shah Equation\(^{10}\),

\[
\text{Nu} = \frac{1.953 (Re \cdot Pr \cdot D/L)^{1/3}}{4.364 + 0.0722 (Re \cdot Pr \cdot D/L)^{1/3}} \quad (16)
\]

Figure 5 shows the comparison of the Nusselt number for water calculated using equation 13 with the Nu determined by Shah Equation 16. The results give a good agreement with this correlation for water.

4 RESULTS AND DISCUSSION

4.1 Thermophysical Properties of the Nano/fluids

Figure 1 shows the enhancement of the thermal conductivity ratio for Cu, CuO, S1 and S2 nanofluids with temperature with a 1% volume fraction. The figure shows that an increase in temperature increases the thermal conductivity ratio. The magnitude of enhancement depends on the thermal conductivity of the nanoparticles suspended in water. The metallic nanoparticles have a higher thermal conductivity ratio compared to the other nanofluid types at the same temperature of 60°C, 1% volume fraction. The time of the suspension as well the time used to measure the thermal conductivity of the nanofluid were reduced in order to reduce the aggregation of the nanoparticles.

A vibro viscometer was used to measure the dynamic viscosity of the nanofluids with temperatures in the range 10-60°C. The dynamic viscosity ratio for all types of nanofluids measured is illustrated in Fig. 2. The figure shows the decrease of the dynamic viscosity ratio with an increase in the temperature. The nanofluid behaves like its base fluid with increasing temperature. In addition, the increase in the volume fraction will increase the dynamic viscosity of the nanofluids\(^{21}\).

4.2 Enhancement of Heat Transfer with Monocular Nanoparticles

The heat transfer of the CuO, and Cu nanofluids is illustrated in Fig. 6 and 7 respectively. For the two figures, the heat transfer coefficient decreases with the flow flowing through the pipe, while the heat transfer coefficient is higher at the inlet of the pipe. The increase in the volume fraction will increase the heat transfer coefficient of the nanofluids, but the nanofluids have the same trend along the pipe. For the same nanofluid volume fraction, the heat transfer coefficient is higher for the Cu compared to the CuO nanofluids.

4.3 Enhancement of Heat Transfer with Hybrid Nanoparticles

Figure 8 and 9 show the variation of the heat transfer coefficient for different volume fractions for two different hybrid nanofluids at a range of x/D. It shows that the heat transfer coefficient increases with the rise in the volume fraction and at the same time the heat transfer coefficient decreases with an increase in x/D at Reynolds number 1100. This is due to the increase of the Prandtl number of the nanofluid and also to an increase in volume fraction. Here, the results are similar to that observed by Bianco et al.\(^{10}\) and He et al.\(^{21}\). The figures show the increase of the Cu content in the nanofluid instead of the CuO tends to increase the heat transfer coefficients for the same volume fraction nanofluid.

4.4 Effect of Nanoparticles on Heat Transfer Enhancement

Figure 10 shows the effect of the material type of the nanoparticles where the Cu-water nanofluids have the best enhancement over the S2, S1 and CuO nanofluids for the same volume fraction and Reynolds number. The enhancement of the heat transfer coefficient may be due to the increase in the thermal conductivity of the suspended nanoparticles. A comparison was made of the enhancement of the nanofluid heat transfer coefficient compared to the base fluid. The highest enhancement was obtained with Cu 40% at a Reynolds number of 1100 and 1% volume fraction.

5 CONCLUSION

In this paper, the hydrodynamic and thermal behaviours of Cu, CuO and S1 and S2 nanofluids flowing inside a uniformly-heated tube were numerically investigated in a stationary condition and for laminar flow for a range of Reynolds numbers from 100 to 1100 with a range of volume concentrations from 0 to 1%. The results show that the heat transfer coefficient of nanofluids is strongly dependent on the nanoparticles and increases with an increasing volume concentration of nanoparticles. Also for each investigated concentration value, the heat transfer enhancement is higher for the highest Reynolds number. The results illustrate that by increasing the volume fraction, the pressure losses increase. The hybrid nanofluids present a good enhancement for the heat transfer coefficient with higher enhancement in Nusselt number ratio for S1 is 35% while for the S2 is 30% in compare with water. These results are in a good agreement with other well-established correlations. So, these correlations could possibly be used to predict the heat transfer behaviour of these types of nanofluids.

References

1) Choi, U. S. Enhancing Thermal Conductivity of Fluids
Numerical study of the enhancement of Heat Transfer for hybrid CuO-Cu Nanofluids flowing in a circular pipe


