NUMERICAL ANALYSIS OF NANOFLUIDS USED IN HEAT EXCHANGERS APPLICATIONS

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Abstract: *In this article, both laminar and turbulent convective heat transfer in a twodimensional microtube with 10 mm diameter and variable length with constant heating temperature was numerically investigated. Also, some properties for nanofluids were discussed. The governing (continuity, momentum and energy) equations were solved using the finite volume method with the aid of SIMPLE algorithm on FLUENT commercial code. Water - alumina nanofluids with different volume fractions ranged from 1% to 4% were used. This investigation covers Reynolds number in a large range. The results have shown that convective heat transfer coefficient for a nanofluid is enhanced than that of the base liquid. Wall heat transfer flux is increasing with the particle volume concentration and Reynolds number. Moreover, a study on tube length influence on heat transfer was inserted.*

Keywords: *nanofluids, simulation, flow, heat transfer, heat exchangers*

1. Introduction

There is a great need to enhance heat transfer in a lot of industrial areas. Usual methods to enhance heat transfer rates such as active and passive techniques [1, 2] have the disadvantage to increase the required pumping power of the cooling fluid. The development of advanced fluids with improved electrical and thermal characteristics is of dominant importance to achieve higher flux densities. Electrical and thermal conductivities of solids may be orders of magnitude greater than that of fluids and it is therefore expected that dispersion of solid particles will significantly improve the thermal and electrical behavior of fluids.

The use of solid particles as an additive suspended in the base fluid is a technique to augment the heat transfer. Choi[3] found that the particles of nanometer size, suspended in conventional fluids, enhance the heat transfer. These innovative heat transfer fluids consisting of suspended nanometer-sized solid particles are called "nanofluids." Nanofluids can be considered to be the next generation heat transfer fluids as they offer exciting new possibilities to enhance heat transfer performance compared to pure liquids [4-7]. The much larger relative surface area of nanoparticles, compared to those of conventional particles, not only significantly improves heat transfer capabilities, but also increases the stability of the suspensions. Suspended nanoparticles in various base fluids can alter the fluid flow and heat transfer characteristics of the base fluids. Necessary studies need to be carried out before wide application can be found for nanofluids.

The Maxwell model [8] was the first model developed to determine the effective electrical or thermal conductivity of liquid–solid suspensions. This model is applicable to statistically homogeneous and low volume fraction liquid–solid suspensions with randomly dispersed, uniformly sized and noninteracting spherical particles. The Maxwell equation predicts that the effective conductivity of the suspension (k_{eff}), is a function of the conductivity of the particles (k_p), conductivity of the base fluid (k_{bf}) and the volume fraction (φ) of the particles, and is given by:

$$\frac{k_{eff}}{k_{bf}} = 1 + \frac{3(\alpha - 1)\varphi}{(\alpha + 2) - (\alpha - 1)\varphi} \tag{1}$$

where $\alpha = k_p/k_{bf}$, is the conductivity ratio of the two phases.

The applicability of the Maxwell's model has been successfully verified by experimental data [9] for dilute suspensions ($\varphi \ll 1$) with large particles (particle size larger than tens of micrometers). The present experimental situation corresponds to Case (a) in the Maxwell's model (alumina particles have very poor electrical conductivity characteristics). Therefore, it is expected that the mixture's electrical conductivity is reduced. Moreover, the experimental study is based on $\varphi \geq 1$ suspension with very small particles (nanoparticles).

Another important model used for conductivity estimation is The Bruggeman Model. In this experimental study, it shall generalize Bruggeman effective medium theory (EMT) to investigate the effective electrical conductivity in alumina – water nanofluid. It considers an alumina nanofluid in which the nano particles with volume fraction φ and alumina particles with conductivity k_p are randomly mixed. For simplicity, it assumes that particles are spherical.

The theoretical results on effective electric conductivity of the nanofluid suspensions are found to be in disagreement with experimental data. This disagreement appears mainly because the alumina electrical conductivity is very low (10^{-8} μS/cm) and it was expected a decrease in effective conductivity. Further, the experiment is described along with its interpretation.

2. Experimental observation

γ-Al_2O_3 nanoparticles in 20% wt. aqueous solution (Nanostructured and Amorphous Material, Inc., USA) were used for this investigation. The base fluid was distilled water. The suspensions of nanoparticles in water were subjected to ultrasonic vibration for about 1 h to ensure uniform nanoparticle dispersion was obtained. Then, appropriate amounts of distilled water were added to the suspensions and thoroughly mixed to achieve the desired concentration of nanofluids. It should be noted that the suspension stability of nanoparticles within the base fluid, distilled water, has been found to be very good even after a relatively long resting period, even few months. To investigate the effect of nanoparticle concentration, nanofluids of 1, 2, 3 and 4% by volume were prepared.

For a better description of the nanofluid, few imagistic techniques were employed. Fig. 1 shows the field emission of a TEM microscope Tesla BS 613 at a tension U=100kV and an intensity I=100μA. The image was obtained from an aqueous suspension of Al_2O_3 particles with volume fraction of 1%. It can be observed that although there are signatures of agglomeration present in the micrograph, the particles are truly nanometric. Major part of the agglomeration seen in the image occurred during drying of the base liquid. However, since the photographs were taken only after drying the nanofluid, the intrinsic dispersion of nanoparticles in the fluid cannot be clearly ascertained from the figure.

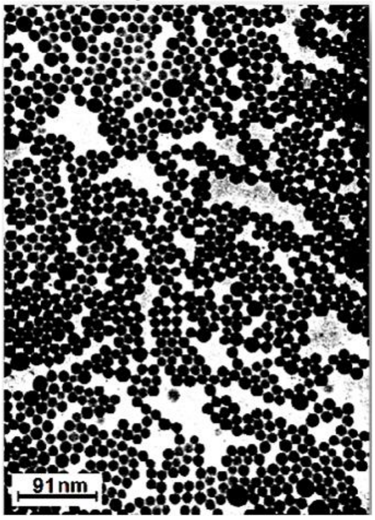


Figure 1: *TEM image of the alumina nanoparticles after dispersion [5]*

To measure the electrical conductivity of nanofluids, a precision conductivity cell (Multiparameter Consort C 831) with an application range of 1 μS/cm– 200 mS/cm has been used. The resolution is 0.01 μS/cm. The electrical conductivity of Al_2O_3-water nanofluid was measured at different temperatures starting with the room temperature(25 °C) until 70°C and subsequent measurements were conducted to examine the effects of volume fractions (1- 4%) on the effective electrical conductivity of the nanofluid. For each case, five to six measurements were performed, and the mean value was reported. Table 1 contains the mean experimental data.

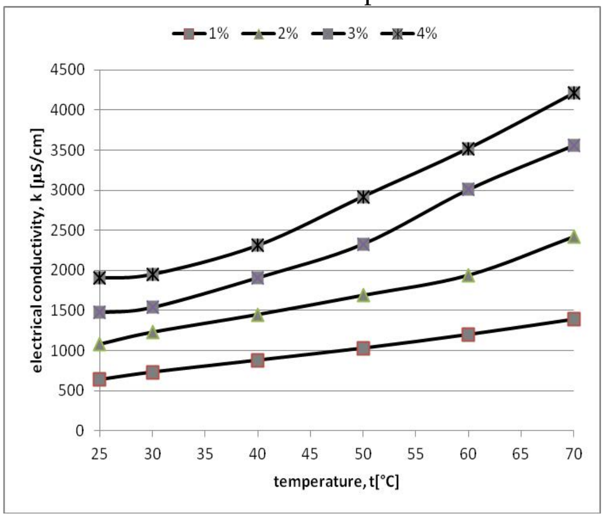
Table 1: *Experimental for electrical conductivity at 25 °C [5,6]*

volume concentration, φ [%]	electrical conductivity, k [μS/cm]
distilled water	5
1	638
2	1081
3	1474
4	1903

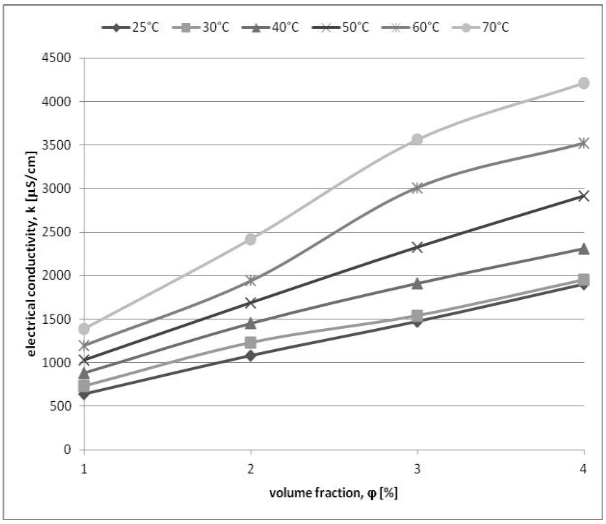
3. Results and discussions on electrical conductivity

The electrical conductivity of alumina is reported as 10^{-8} μS/cm in the literature [6]; conductivity of the base fluid (distilled water) used in the present study varies from 5 μS/cm to 11 μS/cm in the present experimental temperature range. Table 2 shows the measured electrical conductivity of water and of the nanofluid at room temperature. It can be seen that the conductivity values obtained from the experiment agree well with the reference values available in literature [10, 11], in an order of magnitude sense.

Fig. 2 shows the effective electrical conductivity of alumina nanofluid at different volume fractions and temperatures. The temperatures considered are from 25 to 70°C. It is seen that the electrical conductivity of alumina nanofluid increases almost linearly with increase in the volume fraction of the alumina nanoparticles and temperature. The highest value of electrical conductivity, 4210 μS/cm, was recorded for a volume fraction of 4% at a temperature of 70 °C.



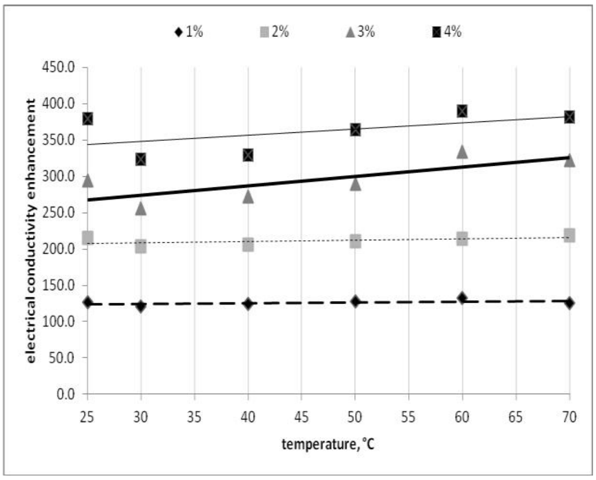
a.



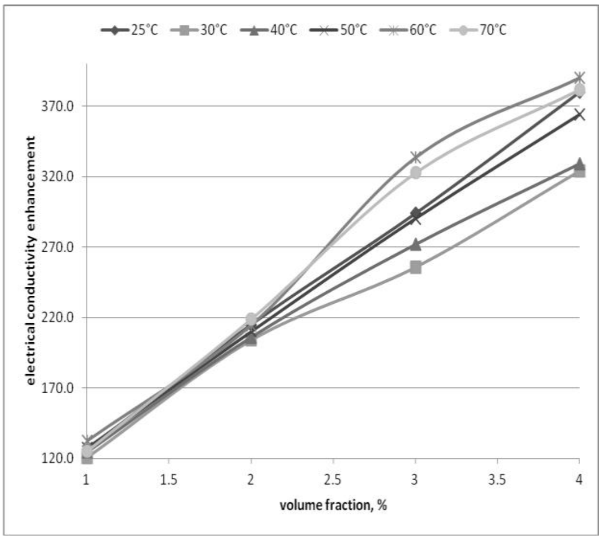
b.

Figure 2: *Measured electrical conductivity: a. variation with temperature; b. variation with volume fraction[5]*

It is of interest to examine the enhancement in electrical conductivity of the alumina nanofluid with respect to the base fluid. For this purpose, the rate of enhancement of the effective electrical conductivity, defined as the difference between the electrical conductivity of the nanoparticle suspension and the electrical conductivity of the base fluid, divided by the electrical conductivity of the base fluid, is plotted as a function of temperature, at volume fractions of 1, 2, 3 and 4% and as a function of volume fraction for different temperatures. As illustrated in Fig. 3a, the rate of electrical conductivity enhancement is almost constant on different temperatures for the same volume fraction. Some minor increases are for 3% and 4% volume fractions. In Fig. 3b, the rate of enhancement increases with respect to increase in the nanoparticle volume fraction, which indicates a dependence on volume fraction, the greater is the enhancement.



a.



b.

Figure 3: *Electrical conductivity enhancement of Al_2O_3-water nanofluid: a. variation with temperature; b. variation with volume fraction[5]*

A maximum of 390.11 % increase in the electrical conductivity was observed for 4% (φ=4) volume concentration of alumina nanoparticles in water at a temperature t=60 °C. Also, one can notice a stronger dependence of the electrical conductivity enhancement on volume fraction and a lower one on temperature variation.

If it refers to Case (a) in the Maxwell's model (alumina particles have very poor electrical conductivity characteristics), it is expected that the mixture's electrical conductivity is reduced. However, from Fig. 4, it can be seen that the measured electrical conductivity of the suspension increases with volume fraction of the nanoparticles. Therefore, the theoretical models, which compared well with the measurements of dispersions with large size (micrometer or larger) particles, underpredicts the conductivity increase in nanoparticle- fluid mixtures. This is due to the fact that, apart from the physical properties of fluid and conductivity of particles and fluids, the effective electrical conductivity of colloidal nanosuspensions in a liquid exhibits a complex dependence on the EDL characteristics, volume fraction, ionic concentrations and other physicochemical properties, which is not effectively captured by the standard models [5,6].

4. Numerical model

The 2-D Navier–Stokes and energy equations were used to describe the flow and heat transfer in a tube enclosure. The following assumptions are adopted: (1) the nanofluid is Newtonian and incompressible, (2) the flow is turbulent, (3) the nanoparticles are assumed to be spherical, (4) single phase model was used and (5) constant thermophysical properties were considered for the nanofluid.

Similar to any fluid mechanic and heat transfer problem, a numerical study for a nanofluid in a particular geometry is achieved by solving the main conservation laws for the flow. In general, a CFD (computational fluid dynamics) code follows three main steps when solving a problem [4]: first integrating the conservation equations over the generated control volumes; next changing the obtained integral equations into algebraic equations with the aid of discretization methods; and finally using numerical iterative methods to solve the algebraic equations. Incompressible flow, Newtonian behavior, Boussinesq approximation for buoyancy force in natural convection and steady-state condition seem to be reasonable simplifications when doing a numerical process.

At the tube inlet, different velocities depending on the values of Reynolds number were used, and the inlet temperature was taken as 293 K. The constant heating temperature was 343K to heat up the outer wall. At the domain outlet the flow and heat transfer are assumed to be fully developed.

4.1. Nanofluids thermophysical properties

In order to obtain credible numerical results when modeling, one must focus on available correlations and choose the most proper one to apply for various properties of a nanofluid which then becomes essential to know while solving the governing conservation equations. These properties might include thermal conductivity, viscosity, density and heat capacitance depending on what form the governing equations are written. By assuming the nanoparticles are well dispersed within the base fluid, the effective physical properties of the mixtures studied can be evaluated using some classical formulas as well known for the nanofluids [4 – 7].

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\rho_{bf} \tag{2}$$

$$c_{nf} = \frac{\varphi\rho_p c_p + (1-\varphi)\rho_{bf} c_{bf}}{\rho_{nf}} \tag{3}$$

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + (n-1)k_{bf} - (n-1)\varphi(k_{bf} - k_p)}{k_p + (n-1)k_{bf} + \varphi(k_{bf} - k_p)} \tag{4}$$

$$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 123\varphi^2 + 7.3\varphi + 1 \tag{5}$$

Eqs. (2) and (3) are general relationships used to compute the density and specific heat for a classical two-phase mixture. Eq. (4) for calculating the thermal conductivity of the nanofluid has been obtained by Hamilton and Crosser [12] by the use of spherical particles assumption. The dynamic viscosity of nanofluids has been calculated through Eq. (5), which was obtained, by Maiga et al. [13].

4.2. Numerical method

The CFD code Fluent 13.1 [14] was employed to solve the present problem. The governing equations were solved by control volume approach. The control volume approach employs the conservation statement or physical law represented by the entire governing equations over finite control volumes. First order upwind scheme was employed to discretize the convection terms, diffusion terms and other quantities resulting from governing equations. Grid schemes used are staggered in which velocity components are evaluated at the center of control volume interfaces and all scalar quantities are evaluated in the center of control volume. Pressure and velocity were coupled using Semi Implicit Method for Pressure Linked Equations [SIMPLE]. For all simulations performed in the present study, converged solutions were considered when the residuals resulting from iterative process for all governing equations were lower than 10^{-6}.

In order to ensure the accuracy as well as the consistency of numerical results, several nonuniform grids have been submitted to an extensive testing procedure for each of the cases considered. Preliminary tests were carried out to test the accuracy of the numerical solution. To this scope five different meshes varying from 100 x 800 to 200 x 1000 have been tested and compared in terms of Nusselt number and the relative errors are reported as 5%. Results have shown that, for the problem under consideration, the 150x1000 non-uniform grid appears to be satisfactory to ensure the precision of numerical results as well as their independency with respect to the number of nodes used. Such grid has, respectively, 150 and 1000 nodes along the radial and axial directions, with highly packed grid points in the vicinity of the tube wall and especially at the entrance region [4, 7].

5. Results and discussion on simulation

The effects of the nanoparticle volume fraction, Reynolds number and tube length on both the heat transfer enhancement and the relative wall shear stress are calculated for different values of the Reynolds number of the base fluid Re as well as for different microtubes length, respectively.

The results obtained for the heat transfer flux and wall heat transfer coefficient enhancement at constant heating temperature produced by suspending Al_2O_3 nanoparticles into pure water are displayed and discussed first. Subsequently, the results pertaining to the relative wall shear stress at constant heat transfer rate for the same Al_2O_3 - H_2O nanofluid are shown and commented. Finally, the roles played by both the nanofluid volume fraction and the microtube length are analyzed.

The computer model has been successfully validated with correlation reported by Gnielinski and Petukhov in [15, 16] for thermally and hydraulically developing flow with uniform heat flux on the wall, showing an average error of 4%.

After confirming that the computational model is generating correct results, nanofluids with varying concentrations were analyzed at various Reynolds numbers with applied constant temperature on the upper wall.

The case study presents the hydrodynamic and thermal behaviors of turbulent forced convective flow of a nanofluid inside a circular tube with constant heating temperature. The nanofluid consists of Al_2O_3 nanoparticles with an average diameter of 24 nm. The tube has a diameter of 10 mm and a variable length from 800 to 1400 mm. The fluid enters the tube with a constant inlet temperature of 293 K and with uniform axial velocity. The Reynolds number was varied from 10^4 to 10^5. The nanofluids heat transfer performance was defined in terms of the convective heat transfer coefficient (h) and wall heat flux (q).

5.1. Particle volume fraction effect

Fig. 4 illustrates the effect of particle volume fraction on the wall heat transfer flux for various nanofluids in turbulent convection for a tube length of 0.8m.

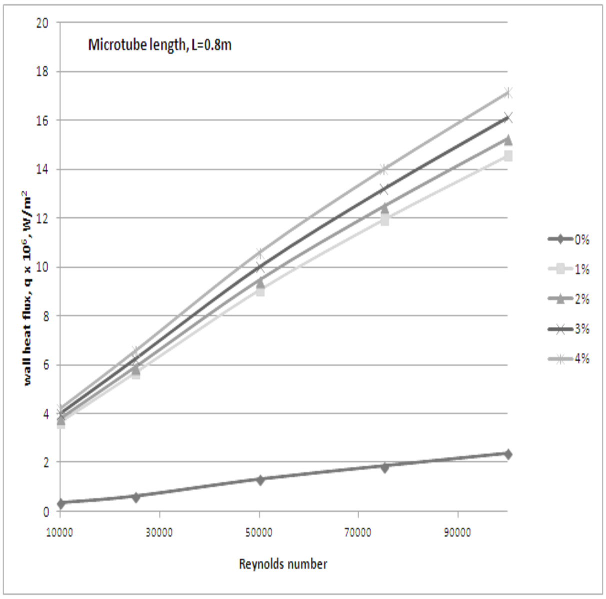


Figure 4: *Particle volume fraction effect on the wall heat transfer flux: L=0.8m [4]*

As it was expected, wall heat flux is highly increasing with both the Reynolds number and particle volume fraction. Also, the wall heat flux is highly increasing with the particle volume fraction, the heating efficiency going up for the nanofluid with 4% volume fraction at Re = 10^4.

5.2. Reynolds variation effect

Fig. 5 illustrates the effect of the Reynolds number on the wall heat transfer flux for various nanofluids with particle volume fractions of 1- 4% and for a tube length of 1.4m.

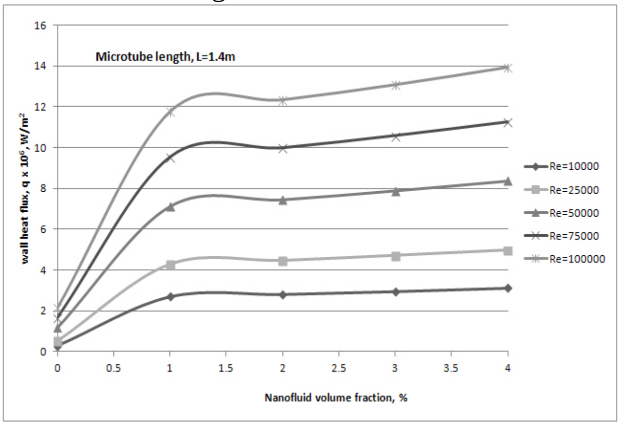


Figure 5: *Reynolds number effect on the wall heat transfer flux: L=1.4m [4]*

Reynolds number highly influences the heat transfer of the studied nanofluids. From the present study numerical data presented in Fig. 5 one can see the strong influence of the Reynolds number and tube length influence on wall heat flux. A higher wall heat flux was obtained for the shorter tube due to a higher concentration of the wall heating flux determined by the heating temperature imposed at outer wall. The heat flux have a stronger dependence on Reynolds number than on the particle volume fraction.

5.3. Microtube length effect

Fig. 6 illustrates the effect of the tube length on the heat transfer coefficient for various nanofluids with particle volume fractions of 1%, 2%, 3% and 4%. The results are presented for a Reynolds number, Re = 10^4.

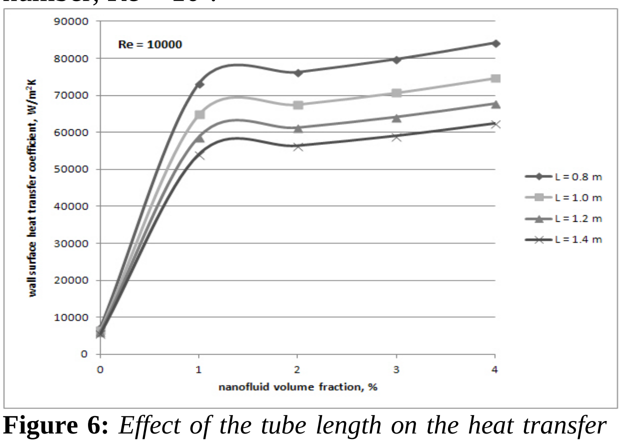


Figure 6: *Effect of the tube length on the heat transfer [4]*

The tube length influences the heat transfer flux by diminishing it along with microtube length increasing. A maximum 26.06% wall heat flux decreasing was noticed for a 0.6 m microtube length increasing for the 1% nanofluid. Similar decreasing in the range of 21.76% (for water) to 26.06% was calculated from the numerical study. As for the surface heat transfer coefficient similar results were obtained: the coefficient is decreasing by 22.22%-26.25% with a 0.6m tube length increasing.

Moreover, an attempt on establishing an equation for estimating the heat transfer coefficient based on numerical simulation was accomplished using a Table Curve 3D commercial code [18]. This code was employed for statistical analysis in order to ascertain a formula for heat transfer coefficient evaluation based on tube length and nanofluid volume fraction for a Reynolds number Re = 10^5, as seen in Fig. 7.

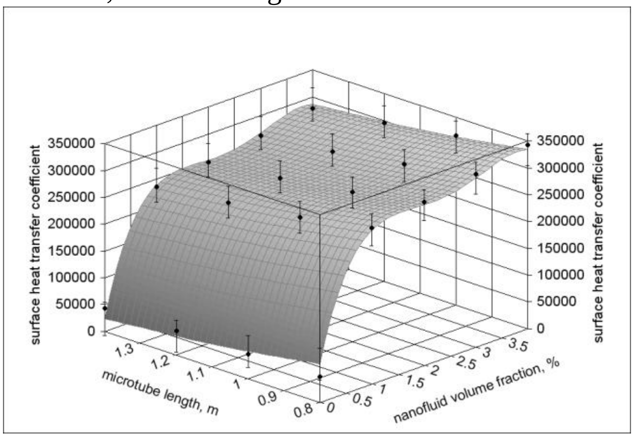


Figure 7: *Heat transfer coefficient evaluation based on microtube length and nanofluid volume fraction for Re=10^5 [4]*

This statistical study can be extended to all studied turbulence degrees and nanofluids volume fractions.

The equation related to this study on statistical, along with the standard error, are[4]:

$$\begin{aligned} h = & -296750.868 + 438364.53\cdot\varphi - \\ & 300725.4\cdot\varphi^2 + 86644.99\cdot\varphi^3 + \\ & 1.72\cdot10^6\cdot L - 2.7\cdot10^6\cdot L^2 + \\ & 1.73\cdot10^6\cdot L^3 - 403152\cdot L^4 \end{aligned} \tag{6}$$

Equation (6) helps on evaluating the heat transfer coefficient based on nanofluid volume fraction and microtube length. This relation was obtained based on numerical simulation and has a standard deviation of R^2 = 0.99, which guarantees its accuracy. This correlation might help researchers to have an idea of process developing at high Reynolds numbers and tube length influence on heat transfer.

5.4. Laminar flow

As was stated, nanofluids with varying concentrations were analyzed at various Reynolds numbers with applied constant temperature on the upper wall.

The case study presents the thermal behaviors of laminar, turbulent and transitory forced convective flow of a nanofluid inside a circular tube. The fluid enters the tube with a constant inlet temperature of 293 K and with uniform axial velocity. The Reynolds number was varied accordingly.

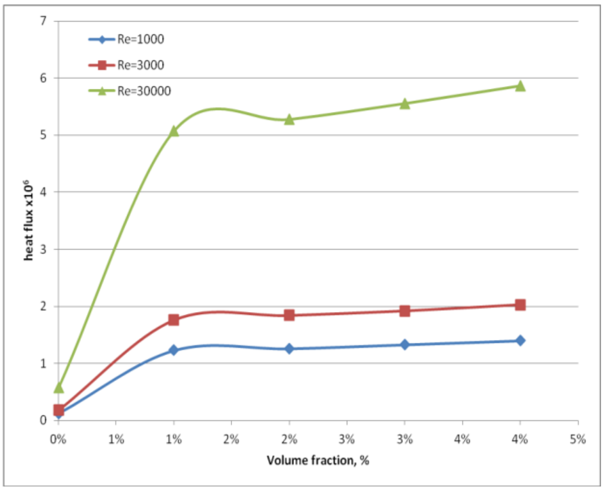


Figure 8: *The influence of the particle volume fraction* φ *on the wall heat transfer flux*

As the primarily interest is in quantifying the heat transfer enhancement benefits of nanofluids, Fig. 8 shows the increase of the total wall heat transfer flux as a function of the nanoparticle volume fraction φ. As one can notice, significant increases of the total heat transfer rates can be found with the use of suspended nanoparticles. For example, for φ = 4%, one can see 167 % increases in wall heat transfer flux for laminar forced convection. Fig. 8 also shows the total heat transfer rates calculated using the numerical procedures for the Reynolds number considered. Fig. 9 contains some more data about heat flux but compared to the Reynolds number applied for the four different nanofluids.

Moreover, the heat flux efficiency is calculated as the ration between the heat transfer flux of the base fluid and the one of the nanofluid (q_{bf} / q_{nf}) [19, 20]. For other Reynolds numbers, these values are varying accordingly and the heat transfer efficiency is about 10 times bigger for the 4 % nanofluid compared to the base fluid (water).

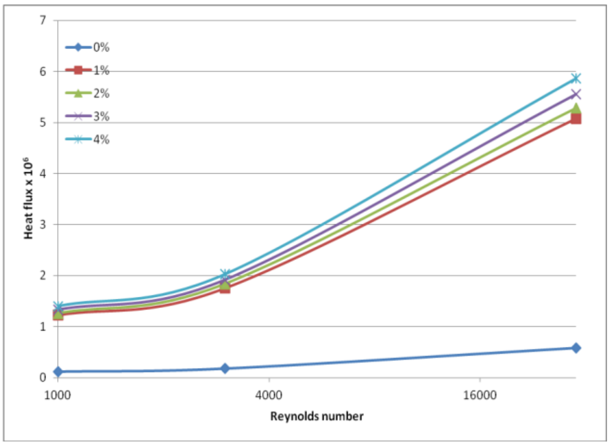


Figure 9: *The influence of the Reynolds number on the wall heat transfer flux*

6. Conclusion

Systematic experiments were carried out to investigate the effects of nanoparticle volume fraction on the effective electrical conductivity of Al_2O_3-water nanofluid. The experimental results show that the electrical conductivity of alumina nanofluid is significantly greater than the base fluid. The increase in electrical conductivity is a function of volume fraction of nanoparticles and temperature. At room temperature (25 °C), an increase of 379.6 % in effective electrical conductivity of nanofluid is observed for a volume fraction of 4%. The electrical conductivity of the nanofluid increases almost linear with increase in the volume fraction. The present analysis indicates the relative influence of volume fraction on the electrical conductivity values. Al_2O_3–water nanofluid seems to be promising as electrical medium.

The main numerical results obtained may be summarized as follows:

- wall heat flux is highly increasing with both the Reynolds number and particle volume fraction.
- Reynolds number highly influences the heat transfer of the studied nanofluids.
- higher wall heat flux was obtained for the shorter microtube
- the heat flux have a stronger dependence on Reynolds number than on the particle volume fraction.
- the tube length influences the heat transfer flux by diminishing it along with tube length increasing. A maximum 26.06% wall heat flux

decreasing was noticed for a 0.6 m tube length increasing for the 1% nanofluid.

- the surface heat transfer coefficient is decreasing by 22.22%-26.25% with a 0.6m tube length increasing.

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