

Heat transfer enhancement using aluminium oxide nanofluid: effect of the base fluid

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Abstract – The flow and heat transfer is an important phenomenon in engineering systems due to its wide application in electronic cooling, heat exchangers, double pane windows etc.. The enhancement of heat transfer in these systems is an essential topic from an energy saving perspective. The lower heat transfer performance when conventional fluids, such as water, engine oil and ethylene glycol are used hinders improvements in performance and a consequent reduction in the size of such systems. The use of solid particles as an additive suspended into the base fluid is a technique for heat transfer enhancement. Therefore, the heat transfer enhancement in a horizontal circular tube that is maintained at a constant temperature under laminar regime has been investigated numerically. Nanofluid was made by dispersion of Al₂O₃ nanoparticles in pur water and ethylene glycol. Results are validated by comparison with results reported in the literature.

Résumé –Le transfert de chaleur est un processus d'une grande importance dans le domaine de l'industrie et des technologies. On cite en particulier, le refroidissement des processus, les réacteurs nucléaires, les composants électroniques, les radiateurs, les échangeurs de chaleur, etc ...L'intensité du transfert de chaleur dépend principalement de la conductivité et de la capacité thermiques des fluides caloporteurs. Or il s'avère que la conductivité thermique d'un liquide non métallique est faible. Ce qui n'est pas intéressant d'un point de vue industriel et énergétique où l'on cherche souvent à améliorer les transferts thermiques. Une façon de surmonter cet inconvénient est d'ajouter des nanoparticules, dotées d'une bonne conductivité thermique, dans le fluide de base. Grace à celles-ci, le mélange résultant (appelé alors nanofluide) se trouve avec des performances thermiques suffisantes pouvant répondre aux attentes industrielles. Dans ce travail, nous nous proposons d'étudier numériquement l'effet du fluide de base sur l'amélioration du transfert thermique. Pour cela, nous étudierons le cas d'un écoulement des nanofluides dans une conduite cylindrique dont la paroi est maintenue à une température constante.

Nomenclature

C_p	Specific heat capacity [J/kg K]	Greek symbols	
D	Diameter [m]	ϕ	Nanoparticle fraction
L	Length of cylinder [m]	μ	Dynamic viscosity [kg/m s]
q	Heat flux density [W/m ²]	ρ	Density [kg/m ³]
Re	Reynolds number		
Pr	Prandtl number	Subscripts	
Pc	Peclet number	f	fluid
p	Static pressure [Pa]	nf	nanofluid
r	Radius [m]	bf	base fluid
T	Temperature [K]		
u, v	Velocity components [m/s]		
x, r	Axial and radial coordinates [m]		

1. Introduction

One of the most important needs of modern industries is high performance heat transfer equipments. In the past few decades, many techniques for heat transfer enhancement have been proposed. One idea involves improving the performance of heat transfer fluids by the addition of solid particles [1].

Suspensions of nano-sized (< 100 nm) particles in conventional heat transfer fluids (such as water, ethylene glycol, and engine oil) were named nanofluid by Choi [2]. To understand and describe various features of flow and heat transfer behaviour of nanofluids, numerous investigations have been carried out [3]. Almost all previous investigations show that the thermal conductivity of nanofluids increases significantly over that of the base fluid [3-5].

Oxide nanoparticles [6-7], carbon nanotubes [8] and other types of nanoparticles [9-10] have been used in the preparation of nanofluids. Conventional heat transfer fluids such as water, ethylene glycol and transformer oil have been employed as base fluid. Results of these investigations show that the heat transfer coefficient of nanofluids is considerably higher than that of the base fluid and the enhancement of heat transfer coefficient increases with nanoparticle concentration and nanofluid flow rate.

Most investigators experimentally studied the heat transfer characteristics of nanofluids, however, very few studies relate to numerical investigations on convective heat transfer.

Therefore, the objective of this work is to numerically simulate the convective heat transfer characteristics of water- Al_2O_3 and ethylene glycol- Al_2O_3 nanofluids in horizontal circular tube maintained at a constant temperature in the laminar flow. A computational code by use of the finite volume method is developed [11]. Laminar model was used to simulate the flow and heat transfer using the SIMPLE scheme for pressure-velocity coupling. This code is validated by comparison to results reported in the literature. The major contribution of this study is to showing the effect of the base fluid on the convective heat transfer performance.

2. Formulation of the problem

The geometry under investigation is shown in Fig. 1. We consider a horizontal circular tube with a finite length and a diameter D . The flow will be considered as axi-symmetric and therefore it is two dimensional so that it can be represented by the axial and radial coordinates only. The tube contains water- Al_2O_3 or ethylene glycol- Al_2O_3 . These Al_2O_3 particles are assumed to be in the same size and shape. In addition, the solid particles are in thermal equilibrium with the base fluid and they have the same velocity. Table 1 show thermophysical property of Al_2O_3 nanoparticle.

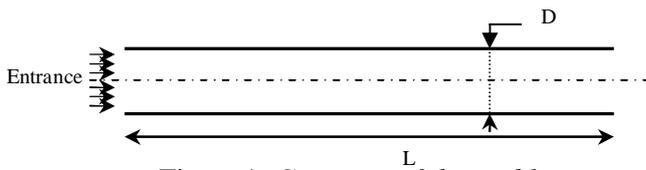


Figure 1: *Geometry of the problem*

Average particle diameter [nm]	Particle Shape	thermal conductivity [W/mK]	Density [Kg/m ³]	Specific heat [J/KgK]
31	Sphere	36	3970	765

Table 1: *Thermophysical property of Al_2O_3 nanoparticle*

The physical properties of the nanofluid are assumed to be independent of temperature but of course are functions of the volume fraction ϕ of the suspended nanoparticles. The buoyancy effects are neglected.

The governing equations for nanofluid in axi-symmetric cylinder are the continuity, momentum, and energy equations with their density, thermal conductivity, and viscosity modified for nanofluid application. The continuity written in cylindrical coordinates in an axi-symmetric geometry is:

$$\frac{\partial(\rho_{nf}u)}{\partial x} + \frac{1}{r} \frac{\partial(\rho_{nf}rv)}{\partial r} = 0 \quad (1)$$

Momentum equations in the axial and radial directions are:

$$\rho_{nf} \frac{\partial(uu)}{\partial x} + \rho_{nf} \frac{1}{r} \frac{\partial(rv u)}{\partial r} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x} \left(\mu_{nf} \frac{\partial u}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \mu_{nf} \frac{\partial u}{\partial r} \right) \quad (2)$$

$$\rho_{nf} \frac{\partial(uv)}{\partial x} + \rho_{nf} \frac{1}{r} \frac{\partial(rv v)}{\partial r} = -\frac{\partial P}{\partial r} + \frac{\partial}{\partial x} \left(\mu_{nf} \frac{\partial v}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \mu_{nf} \frac{\partial v}{\partial r} \right) - \mu_{nf} \frac{v}{r^2} \quad (3)$$

The axi-symmetric form of energy equation is:

$$\rho_{nf} \frac{\partial(uT)}{\partial x} + \rho_{nf} \frac{1}{r} \frac{\partial(rv T)}{\partial r} = \frac{\partial}{\partial x} \left(\frac{k_{nf}}{c_{p_{nf}}} \frac{\partial T}{\partial x} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{k_{nf}}{c_{p_{nf}}} \frac{\partial T}{\partial r} \right) \quad (4)$$

As mentioned before, nanofluid properties are combinations of base fluid and particle properties. The effective density of nanofluid is predicted by mixing theory:

$$\rho_{nf} = \rho_{particle} \phi + \rho_{bf} (1 - \phi) \quad (5)$$

Specific heat is also defined by mixing theory:

$$c_{p_{nf}} = \frac{\rho_{particle} c_{p_{particle}} \phi + \rho_{bf} c_{p_{bf}} (1 - \phi)}{\rho_{nf}} \quad (6)$$

The thermal conductivity of nanofluid was evaluated from the model proposed by Maxwell [12] namely:

$$k_{nf} = k_{bf} + 3\phi \frac{k_{particle} - k_{bf}}{k_{particle} + 2k_{bf} - \phi(k_{particle} - k_{bf})} k_{bf} \quad (7)$$

The effective viscosity of fluid containing small particules is given by Brinkman [13] as:

$$\mu_{nf} = \frac{\mu_{bf}}{(1 - \phi)^{2.5}} \quad (8)$$

The dimensionless form of the governing equations can be obtained by use of dimensionless variables defined as:

$$U = \frac{u}{U_0} \quad ; \quad P = \frac{p}{\rho U_0} \quad ; \quad R = \frac{r}{D} \quad ; \quad \theta = \frac{T - T_0}{T_{wall} - T_0} \quad (9)$$

The problem is characterized by the following parameters of similarity:

$$\text{the Reynolds number:} \quad Re = \frac{\rho_{nf} U D}{\mu_{nf}} \quad (10)$$

$$\text{the Prandtl number:} \quad Pr = \frac{\mu_{nf} c_{p_{nf}}}{k_{nf}} \quad (11)$$

$$\text{the Peclet number:} \quad Pe = Re Pr \quad (12)$$

The Nusselt number of the nanofluids is expected to depend on a number of factors such as thermal conductivity and specific heat capacity, the volume fraction of the suspended particles, the flow structure and the viscosity of the nanofluid. The Nusselt number of the nanofluid can be expressed as [14]:

$$Nu = \begin{cases} 1.953 \left(RePr \frac{D}{x} \right)^{\frac{1}{3}} & \left(RePr \frac{D}{x} \right) \geq 33.3 \\ 4.364 + 0.0722 RePr \frac{D}{x} & \left(RePr \frac{D}{x} \right) \leq 33.3 \end{cases} \quad (13)$$

The mean temperature of the fluid for an axi-symmetric case at any cross-section of the tube is:

$$T_{mean} = \frac{\int_0^{D/2} 2\pi\rho C_p T u r dr}{\int_0^{D/2} 2\pi\rho u r dr} = \frac{2}{U_{mean} (D/2)^2} \int_0^{D/2} T(r,x) u(r,x) r dr \quad (14)$$

where T is the temperature at a distance r from the axis where the axial velocity is u .

The boundary conditions in this geometry are summarized in Fig. 2 and Table 2.

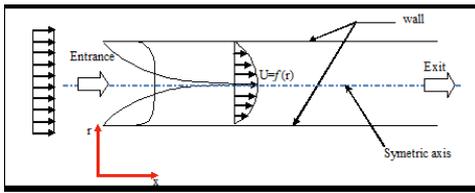


Figure 2: *Boundary conditions*

The condition	Entrance	Wall	Symmetric axis
Axial velocity U	$U_0 = \frac{Re\mu}{\rho D}$	$U = 0$	$\frac{\partial U}{\partial r} = 0$
Radial velocity V	$V = 0$	$V = 0$	$V = 0$
Temperature T	$T_0 = 288 \text{ K}$	$T = T_{wall} = 320 \text{ K}$	$\frac{\partial T}{\partial r} = 0$

Table 2: *Boundary conditions*

The numerical simulation is based on the finite volume formulation. The governing equations are integrated over each control volume to obtain a set of linear algebraic equations. These equations were solved by employing SIMPLE algorithm for the pressure correction processes, and convective and diffusive terms were discretized by upwind and central difference schemes, respectively. Second order discretization scheme were employed for all simulation. For cylinder's diameter less than 10 cm and a length equal to 5 m, a grid independence study was carried out with three different (301x31, 401x31 and 421x31) grid sizes. These studies are performed for 10% volume fraction of CuO. Mean temperature profiles along of the cylinder are plotted for Reynolds number equal at 25 as shown in Fig. 3.

From Fig. 3 it is very clear that grid size 401x31 and 421x31 gave same results. The 401x31 and non-uniform grid is chosen for computation, allowing fine grid spacing near the wall of cylinder (Fig. 4).

The convergence of the numerical solution is based on residuals of governing equations that were summed over all cells in the computational domain. Convergence was achieved when the summation of residuals decreased to less than 10^{-8} for all equations.

Furthermore, in order to validate the numerical code used for the present study, the steady-state solutions obtained as time-asymptotic solutions for a vertical square cavity with differentially heated sidewalls and adiabatic top and bottom walls, have been compared with the results of Hadjisophocleous [15], Tiwari [16] and Kuang [17]. In particular, the average Nusselt numbers, the maximum horizontal and vertical velocity components obtained at

Rayleigh numbers in the range between 10^3 and 10^6 are summarized in the Table 3. A very good agreement has been archived.

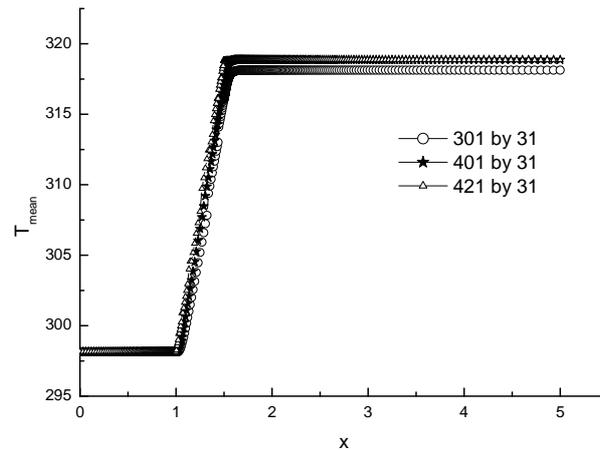


Figure 3: Temperature profiles at $Re=25$ for 10% volume fraction of CuO



Figure 4: Schematic of grid

	Hadjisophocleous [15]	Tiwari [16]	Kuang [17]	Present study
$Ra=10^3$				
u_{max}	3.544	3.642	3.597	3.643
y	0.814	0.804	0.819	0.818
v_{max}	3.586	3.702	3.669	3.690
x	0.186	0.178	0.181	0.179
\overline{Nu}	1.141	1.087	1.118	1.108
$Ra=10^4$				
u_{max}	15.995	16.144	16.185	16.164
y	0.814	0.822	0.819	0.821
v_{max}	18.894	19.665	19.648	19.665
x	0.103	0.110	0.112	0.111
\overline{Nu}	2.29	2.195	2.243	2.228
$Ra=10^5$				
u_{max}	37.144	34.30	36.732	36.720
y	0.855	0.856	0.858	0.857
v_{max}	68.91	68.77	68.288	68.260
x	0.061	0.059	0.063	0.060
\overline{Nu}	4.964	4.450	4.511	4.489
$Ra=10^6$				
u_{max}	66.42	65.59	66.47	66.48
y	0.897	0.839	0.869	0.890
v_{max}	226.4	219.73	222.34	219.55
x	0.0206	0.04237	0.03804	0.0399
\overline{Nu}	10.39	8.803	8.758	8.765

Table 3: Comparison between Present Study and Results Reported in the literature

3. Results

The heat transfer performance has been investigated for the Reynolds number range $25 < Re < 600$ and for different volume fractions. The Nusselt number and the pressure loss coefficient profiles are presented for the different cases.

Fig. 5 represents variations of mean Nusselt number with Reynolds number at different nanoparticle volume fractions (1%, 3%, 5%, and 10%). We evidence that Nusselt number is a increasing function of Reynolds number for all nanoparticle volume fractions. Also, ethylene glycol base fluid significantly enhances heat transfer comparatively to water.

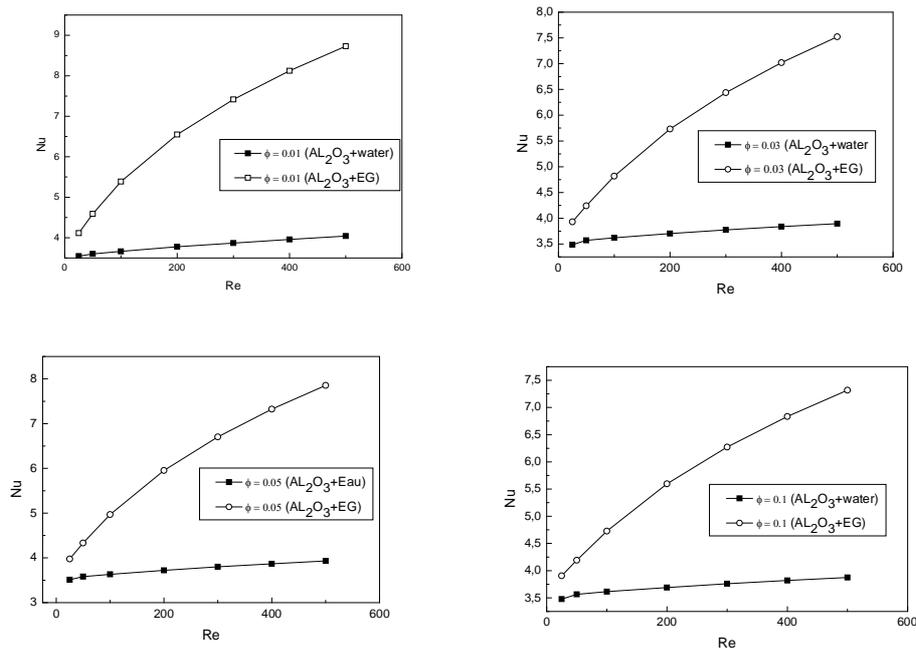


Figure 5: Nusselt number for different Reynolds number and different particle volume fractions

In order to show the importance of the ethylene glycol base fluid on heat transfer, we have calculated the Nusselt number enhancement by the following equation:

$$Nu(\%) = \frac{Nu_{nf(EG)} - Nu_{nf(water)}}{Nu_{nf(water)}} \quad (15)$$

We observe in figure 6, that the Nusselt number enhancements calculated for the ethylene glycol base fluid are much higher than those calculated for water base fluid and are an increasing function of Reynolds number for all nanoparticle volume fractions. These results show that the heat transfer is very sensitive to the base fluid of which they emphasize their importance in the computation or the design of the thermal system.

Figure 7 illustrates the pressure loss coefficient as a function of Reynolds number for different volume fraction and for Reynolds number $Re=200$. The figure shows that the Al₂O₃-EG nanofluid and the Al₂O₃-water nanofluid give the same pressure loss coefficient. From this result, we can say that the base fluid don't have any effect on the pressure loss.

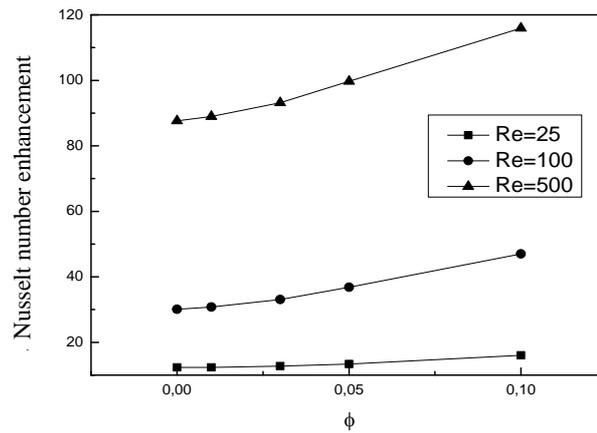


Figure 6: *Nusselt number enhancement for different Reynolds number and different particle volume fractions*

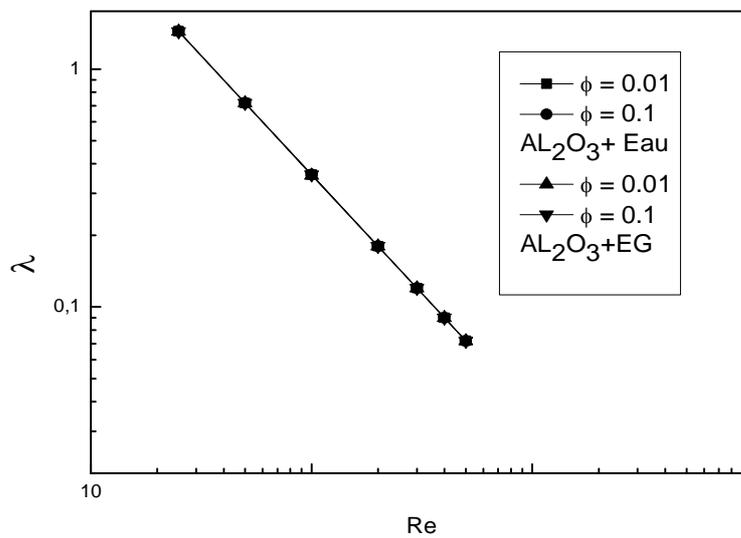


Figure 7: *Pressure loss coefficient for $Re=200$ as a function of Reynolds number as particle volume fraction*

4. Conclusion

The effect of using two different base fluids on the heat transfer in a horizontal cylinder was studied numerically for a range of Reynolds numbers and nanoparticles volume fraction. Indeed, the results revealed that the suspended nanoparticles increase the heat transfer with an increase in the nanoparticles volume fraction and at any given Reynolds number. The results show the influence of the base fluid on the heat transfer identified the kind of base fluid that gives better heat transfer. The kind of base fluid doesn't have any effect on the pressure loss.

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