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Fluid Dynamics Characteristics of Nanofluids in a Rectangular Duct

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Abstract— This paper is a numerical investigation of fluid dynamics characteristics of nanofluids in a rectangular duct. Al_2O_3 and CuO are used as nanoparticles while water has been used as base fluid. The analysis is being carried out with three different diameters – 10nm, 50nm and 100 nm, particle volume concentrations of 0% to 5% and Reynolds number Re = 500. The variation of physical properties of base fluid is taken as temperature dependent. The velocity of nanofluids increases as the diameter is increased. The effect of nanoparticle volume concentration and size on wall shear stress is also analysed. This shows that wall shear stress increases with increase in particle volume concentration as well as particle size.

Index Terms— Nanofluids, Laminar flow, Rectangular duct, Numerical, Control volume, Two-phase, Convective heat transfer

1 Introduction

Cooling is one of the most important technical challenges industry faces today. With the demand for faster and smaller devices thermal loads increase and conventional cooling methods that use extended surfaces (fins, micro channels, etc.) are reaching their limits. Therefore there exists a pressing need to improve heat removal technologies. Convective heat transfer can be enhanced passively by changing flow geometry, boundary conditions or by enhancing thermal conductivity of fluid. Various techniques have been proposed to enhance the heat transfer performance of fluids. Researchers have also tried to increase the thermal conductivity of base fluid by suspending milli or micro sized solid particles in fluids, since the thermal conductivity of solid is two to three orders of magnitude higher than that of the liquids. However, adding micrometer size particles cause several problems arising out of sedimentation, clogging, pressure drop and erosion of channels, pipes and conduits. Modern nanotechnology provides new opportunities to process and produce materials with crystal sizes on the order of nanometers. Fluids with nanoparticles suspended in them are called nanofluids. Nanofluid can be defined as engineered colloids made of a base fluid and nanoparticles (1-100 nm). The term was proposed in 1995 by Choi of the Argonne National Laboratory; U.S.A. Compared with suspended conventional particles of milli or micro meter dimensions, nano fluids show better stability, high thermal conductivity with negligible pressure drop Successful applications of nanofluids would support the current trend toward component miniaturization by enabling the design of smaller but higher-power heat exchanger systems.

The heat transfer enhancement using nanofluids has been proved by most of the literatures even though the increase in heat removal rate varies from study to study. A 15% increase in Nusselt number Nu by using CuO–water nanofluid with particle volume concentration of ϕ = 1% has been reported by [2] while an increase of 4.57% with Reynolds number Re = 100 has been reported by [1]. When Re is increased from 100 to 1500, percentage increase in Nu increased to 5.92%. They have identified a maximum of 34.83% increase in Nu by using CuO–water nanofluid with ϕ = 5% and Re = 500. They have used homogeneous model for their study. While modeling the same nanofluid by two phase method increased Nu from 34.83% to 67.76% with ϕ = 5% and Re = 500. This has been reported by [3]. They have also identified an increase of 30% in heat transfer coefficient when particle diameter decreased from 100 nm to 30 nm. These results show that modeling nanofluid as a single phase fluid lead to lower increase in heat transfer.

This study aims to formulate the transport equations considering nanofluid as a homogeneous fluid using two - dimensional finite volume method. By using the formulated equations, the laminar flow characteristics of different nanofluids through a rectangular duct are analysed. The nanofluid is a mixture of water as the base fluid and Al_2O_3 and CuO as nanoparticles with different volume concentrations and particle sizes. The variation of physical properties of base fluid is taken as temperature dependent.

2 Mathematical Formulation

2.1 Problem Statement

The geometry of the present problem has been shown in Fig. 1. The geometry consists of a two-dimensional rectangular duct of height h = 0.002 m and length l = .02 m (l/h = 10). Two symmetric isothermal flush heaters of temperature $T_H = 100^0C$ is mounted on the top wall and bottom wall of the duct. Two different nanofluids Al_2O_3 -

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Water and CuO - Water with particle diameters d_P varying 10 nm, 50 nm and 100 nm and particle volume concentration ϕ varying from 0 to 5% have been used. Cold nanofluid of temperature T_C = 300C flows from left to the right. The nanofluid is incompressible and the flow is laminar. The inlet velocity of nanofluids is determined by calculating Reynolds number Re. In this study Re = 500. As the fluid flows through the duct, it takes away heat from the heat sources placed at the top and bottom. Also it is assumed that the liquid and solid are in thermal equilibrium and they flow at same velocity.

The thermo-physical properties of the base fluid are taken as temperature dependent. In the present case the effect of buoyancy has been neglected, as its effect is not so significant in comparison with the flow.

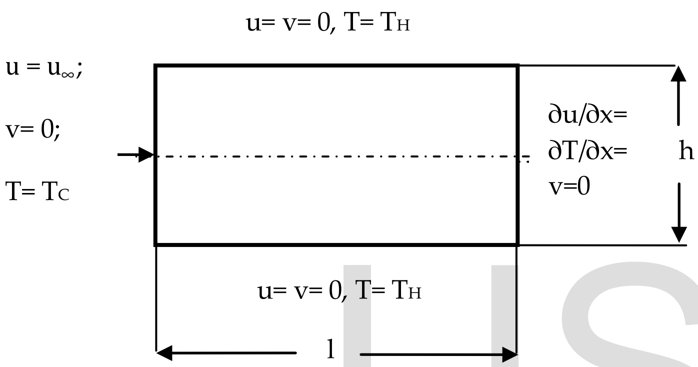

Fig. 1 Geometry of the problem

2.2 Thermo-physical Properties of Nanofluids

The effective density of nanofluid at reference temperature

$$\rho_{nf,0} = (1-\emptyset)\rho_{f,0} + \emptyset\rho_{p,0} \quad (1)$$

And the heat capacitance of nanofluid is

$$(\rho C_P)_{nf} = (1-\emptyset)(\rho C_P)_f + \emptyset(\rho C_P)_p \quad (2)$$

The effective thermal conductivity of nanofluid

$$\frac{k_{nf}}{k_f} = \frac{k_p+(n-1)k_f-(n-1)\emptyset(k_f-k_p)}{k_p+(n-1)k_f+\emptyset(k_f-k_p)} \quad (3)$$

where n is a shape factor and is equal to 3 for spherical nanoparticles.

The effective dynamic viscosity of nanofluid is given by

$$\mu_{nf} = \frac{\mu_f}{(1-\emptyset)^{2.5}} \quad (4)$$

2.3 Governing Equations

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (5)$$

x - Momentum equation:

$$\rho_{nf}\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (6)$$

y – Momentum equation:

$$\rho_{nf}\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \mu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \quad (7)$$

Energy equation:

$$\nabla.(T\vec{v}) = \nabla.(\alpha_{nf}\nabla T) \quad (8)$$

Where, $\vec{v}$ is the velocity vector,

Where thermal diffusivity of nanofluid is

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_P)_{nf,0}} \quad (9)$$

2.4 Boundary Conditions

$u = u_\infty, v = 0, T = T_C$ at $x = 0$ and $0 \leq y \leq h$;

$\frac{\partial u}{\partial x} = v = \frac{\partial T}{\partial x} = 0$ at $x = l$ and $0 \leq y \leq h$; i. e.

$u = v = 0, T = T_H$ at $y = 0, y = h$ and $0 \leq x \leq l$; i. e.

3 Numerical Procedure

Control volume approach with two phase homogenous model has been used for developing the numerical codes. The upwind and central differencing schemes were used, respectively, to approximate the convective and diffusion terms in the differential equation. The SIMPLE algorithm has been used to solve the pressure-linked equations.

4 Results And Discussions

Results are presented for Reynolds number Re = 500, ϕ varying from 0% to 5% and three different particle diameters of 10 nm, 50 nm and 100 nm. The nanofluid has been considered as a homogenous mixture which enters the duct with uniform temperature and velocity.

A grid independence study has been carried out and the result is shown in Fig. 2. From this 40x40 grid structure has been adopted.

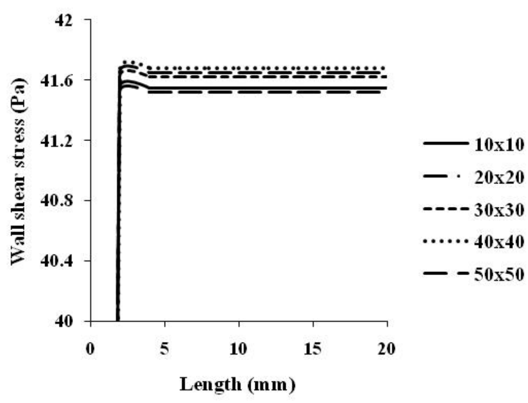

Fig. 2 Grid independence study

The velocity profile for pure water flow obtained in this study and the developing flow profile given by Shirley et al. (2006) are compared in Fig. 3. This shows that the velocity profile obtained by coding is in accordance with standard profile.

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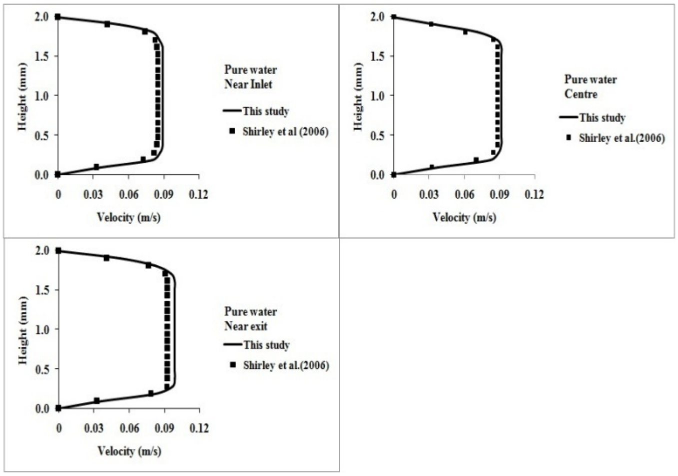

Fig. 3 Comparison of velocity profile for pure water with available literature

The effect of nanoparticle diameter on velocity profile for alumina-water nanofluid is shown in Fig. 4. This shows that the velocity is increasing as the diameter is increased since the larger particles offer less resistance to flow.

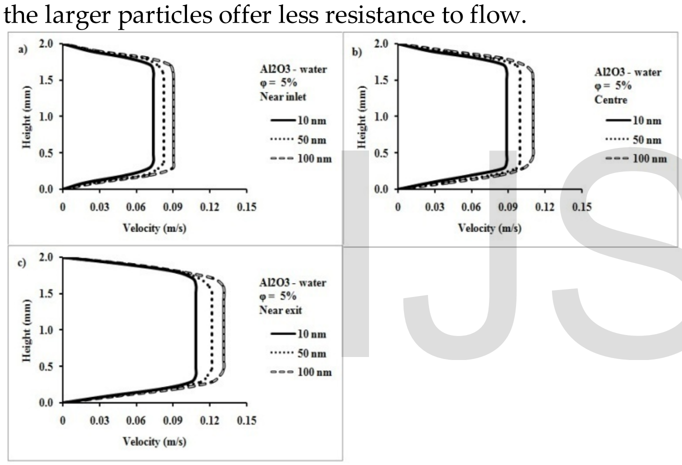

Fig. 4 Velocity profile for Alumina-water nanofluid

The effect of nanoparticle volume concentration and diameter on wall shear stress has been analysed and the result shows that wall shear stress increases with the increase in volume concentration and decrease in particle diameter.

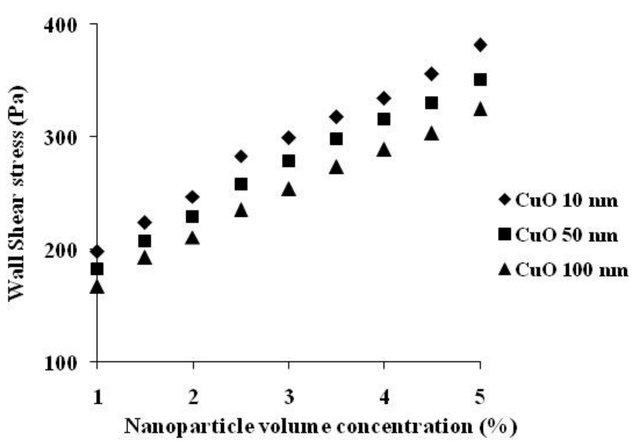

Fig. 5 The effect of nanoparticle volume concentration and diameter on wall shear stress for CuO-water nanofluid

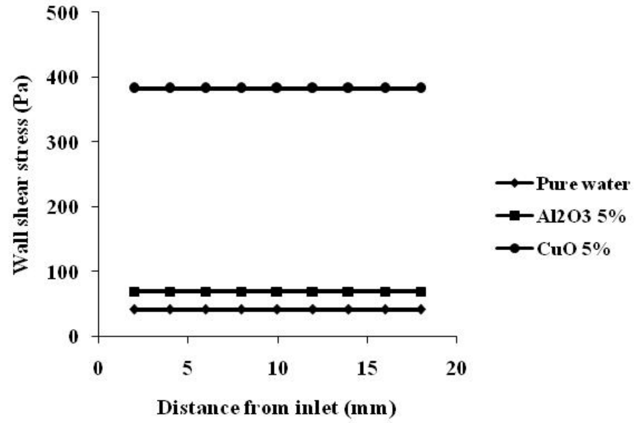

Fig. 6 Comparison of different nanofluids with pure water

5 CONCLUISIONS

The velocity profiles for nanofluids flow with particle diameters of 10 nm, 50 nm and 100 nm, particle volume concentration φ = 5% and Re = 500 are analysed at near inlet portion, at the centre portion of the duct and at near exit portion. The velocity of nanofluids increases as the diameter is increased. At near inlet portion of the duct, velocity increases by 22.22% for alumina-water nanofluid by increasing particle diameter from 10 nm to 100 nm. The effect of nanoparticle volume concentration and size on wall shear stress is also analysed. This shows that wall shear stress increases with increase in particle volume concentration as well as particle size. The CuO-water nanofluid has higher value of shear stress than Al_2O_3-water nanofluid since CuO has high viscosity than Al_2O_3.The percentage increase in wall shear stress when concentration is changed from 0% to 5% is 75% for Al_2O_3-water nanofluid with particle size 10nm. For CuO-water very high increase is noticed due to high viscosity of CuO. The percentage increase in wall shear stress when the diameter is reduced from 100 nm to 10 nm is 17.53% with particle volume concentration 5% for CuO-water nanofluid.

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