

Numerical Investigation on Heat Transfer and Hydraulic Performance of Al₂O₃-Water Nanofluid as a Function of Reynolds Number and Flow Velocity

Melih YILDIZ^{1*}, Ahmet AKTÜRK¹

ABSTRACT: This study numerically investigates the heat transfer and hydraulic performance of Al₂O₃-water nanofluids flowing through a horizontal smooth pipe exposed to a constant heat flux. The nanofluids were regarded as four different varying concentrations in the range from 0.01 to 0.04 by a 0.01 increment (by volume) of the nano-particle, Al₂O₃. Numerical analyses were performed using the finite volume method to solve governing equations in the created three-dimensional domain. The heat transfer and hydraulic characteristics of the nanofluids were separately investigated as a function of both Re number and flow velocity corresponding to the turbulent flow regime. The results show that the convective heat transfer coefficients increase remarkably with the increase of Al₂O₃ fraction, and the maximum overall enhancement ratio was found by 1.30, in the case of the same Reynolds number. In contrast, in the case of the same flow velocities to the base fluid, the convective heat transfer coefficients of the nanofluids worsened with relative to the base fluid due to higher viscosity values of the nanofluids which cause a decrease in Reynolds numbers. Moreover, friction factors with nanofluids increased, which gave rise to the overall enhancement ratios to be at lower than 1.0.

Keywords: Nanofluid, Aluminum oxide, CFD, heat transfer enhancement, friction factor

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INTRODUCTION

The amount of energy consumption increases rapidly due to the growing human population and technological developments. As a result, the energy demand is getting increased each day. To meet this demand, most of the energy is obtained from fossil fuels. However, the limited amount of fossil fuels and environmental pollution caused by its use create some problems to overcome. These problems are minimized by improving energy efficiency. One way to increase energy efficiency is to enhance heat transfer since it plays a key role in many engineering systems using working fluids. Although different methods are promising to improve heat transfer in these systems, a desired heat transfer rate has not been achieved due to the low heat transfer coefficients. The improvement in heat transfer systems allows reducing the space occupied by heating/cooling systems and decreasing the total cost in applications by increasing system performance. Moreover, the improvement in heat transfer efficiency brings down the pump power required for working fluid circulation.

Various methods are carried out enhancing heat transfer efficiency. One of them is to improve the thermal conductivity of the working fluids by adding solid particles. This is because the thermal conductivities of solid particles are higher than those of working fluids such as water, ethylene glycol and oil. Therefore, creating suspensions with solid-particles improves the thermal conductivity (Ozerinç et al., 2010; Ozerinç, 2010). Suspensions created using millimeter and micron-sized particles have also drawbacks. In suspensions created with solid particles of this size, the particle is inclined to separate from the suspension quickly which in turn causes clogging particularly in mini-microchannels (Kebblinski et al., 2002). With nanotechnological developments, particle production at the nano-sized level is possible. Nanofluid for heat transfer fluids is usually obtained by adding nano-sized metal or non-metal particles to the base fluid. Due to the advantage of having small dimensions compared to the millimeter and micron-sized particles, nanoparticles do not settle out of the base liquid, thus eliminating the problem of clogging. Also, particle sedimentation occurring in the suspension can be prevented by using suitable dispersants.

A wide variety of materials can be used to prepare nanofluids. Nanoparticles created using Al₂O₃, CuO, TiO₂, SiC, TiC, Ag, Au, carbon nanotube, graphene, and graphene oxide materials are frequently used in nanofluid research (Mehrali et al., 2014). Several studies revealed that base fluid material, and particle material properties in terms of its volume ratio, shape, size affect the thermal conductivity of nanofluids (Xie et al., 2002). Masuda et al. (1993) performed the first study on the thermal conductivity of fluids containing Al₂O₃ nanoparticle with 13nm particle diameter, SiO₂ nanoparticle with 12nm particle diameter and TiO₂ nanoparticle with 27nm particle diameter. They reported a improvement in heat transfer performance. Choi and Eastman (1995) showed that copper nanoparticles added to the liquid fluid in small volumetric ratios doubled the heat transfer rate. Lee et al. (1999) studied on Al₂O₃ nanofluid with 38.5 nm particle diameter and CuO nanofluid with 23.6 nm particle diameter to determine their thermal conductivities for base fluids, water and glycol. They improved thermal conductivity by 20% using 4 vol.% CuO-ethylene glycol nanofluid. Murshed et al. (2005) conducted the research on TiO₂ / deionized water nanofluid with different volume fractions ranged from 0.5 to 5% to determine their thermal conductivities using hot wire strategy, and unlike other studies, they stated that the thermal conductivity and particle volume ratio was non-linear. Chon et al. (2005) proposed an empirical correlation to calculate the thermal conductivity of Al₂O₃/ water nanofluid. This correlation includes the parameters, the base fluid thermal conductivity, Prandtl number, and Reynolds number. According to the correlation, the effect of the Reynolds number on thermal conductivity is higher than other parameters because of Brownian motion.

Nanofluid use in practice is a promising method to improve heat transfer rate because of its superiority in thermal conductivity. Bianco et al. (2010) studied on heat transfer performance of Al₂O₃ (38nm) / water nanofluid for turbulent flow regime. It is reported that the increase in the volume particle ratio and Re enhances the heat transfer rate. Heat transfer under laminar and turbulent flow regime by adding Al₂O₃ nanoparticles to water and ethylene-glycol base fluids in a circular pipe flow was investigated by Maiga et al. (2005). They reported that the increase in heat transfer with the Al₂O₃/ethylene-glycol nanofluid is greater than that of the Al₂O₃ / water nanofluid in both cases. Namburu et al. (2009) carried out a numerical study on heat transfer performance of three different nanofluids by CuO, Al₂O₃, and SiO₂ addition under turbulent flow regime. They obtained an improvement in heat transfer rate up to 35 % with 6 % CuO nanofluids. Although many researchers reported that nanofluids provide the heat transfer enhancement, nanofluids also bring about the increase of the surface friction factor due to higher viscosity (Bahiraei and Heshmatian, 2019). Bowers et al. (2018) studied experimentally on alumina nanofluids in microchannels and, stated that most experiments resulted in more pumping power requirements due to higher friction factors. Vahidinia and Miri (2015) found that heat transfer of Al₂O₃-water nanofluid gives an improvement in the heat transfer rate with a high surface friction factor penalty. Similarly, Bellos et al. (2018) showed that the nanofluids contribute to heat transfer improvement with a higher pressure drop over base fluids.

The literature survey shows that the heat transfer and hydraulic performance of nanofluids were evaluated as a function of Re number in many studies. However, not only is Re number enough to evaluate nanofluids for a real heating/cooling system operating with a working fluid flow rate depending on heat capacity and flow velocity. Although the flow velocity is better decisive criteria for the comparison of two working fluids in terms of thermal and hydraulic performances as also stated in the reference (Sadeghinezhad et al., 2016), there is a lack of studies considering the flow velocity criteria to evaluate nanofluids. Hence, the current study, it is aimed to reveal the thermal and hydraulic performances of nanofluid, Al₂O₃-water, since Al₂O₃ nanoparticles are in the lowest thermal conductivity range of nanoparticles, at both constant Re numbers and flow velocities, corresponding to a turbulent flow regime. The thermal and hydraulic performances of the working fluids flowing through a smooth pipe exposed to a constant heat flux were numerically investigated using the finite volume methods. The analyses were conducted with four different volume fractions of Al₂O₃ particles ranging from 0.01 to 0.04 with a 0.01 increment assuming single-phase flow at different Reynolds numbers and average flow velocities.

MATERIALS AND METHODS

Geometric Model Development

A three-dimensional horizontal pipe with a diameter of 17 mm and a length of 350 mm was considered as the computational domain through which the fluids flow. The computational domain was created with the quad grid structure with 649 335 cells. Besides, the adequately fine mesh structure near to the wall, which enables $y^+ < 5$, was used to more accurately predict the velocity and pressure gradients in the boundary layer.

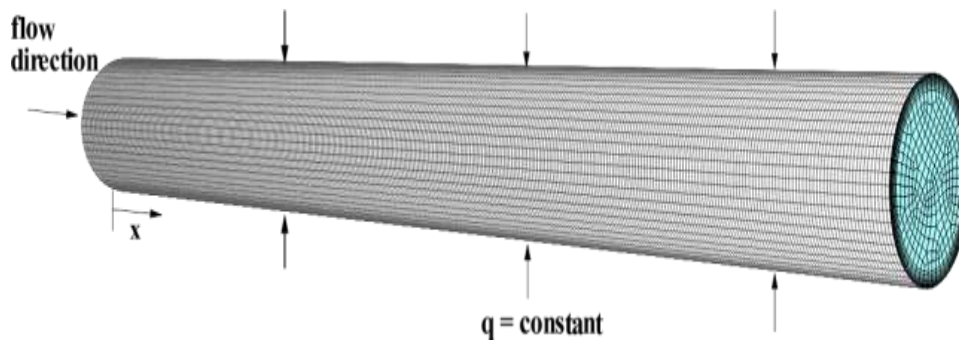


Figure 1. Geometric model and its grid structure

Mathematical Modelling

There are two different numerical approaches, which are single-phase and two-phase models. In the two-phase model, a nanofluid is considered to consist of fluid and solid phases inherently, which allows comprehending the effects of the nanofluid in detail. On the other hand, both fluid and solid phases of a nanofluid are regarded as moving together at the same velocity and in thermal equilibrium in the single-phase model. The thermophysical properties of nanofluids are crucial to determine the effect of nanoparticles. This approach is more practical in terms of computational time and, able to give reasonable results (Behzadmehr et al., 2007; Moraveji and Esmaeili, 2012). Therefore, single-phase model was used to predict the heat transfer and hydraulic performances of the nanofluids flowing through in a straight smooth pipe exposed to a heat flux at turbulent regime in the current study.

On the basis of single-phase model, the steady-state governing equations of continuity, momentum, and energy are as follows:

Continuity equation:

$$\nabla \cdot (\rho \vec{U}) = 0 \quad (1)$$

Momentum equation:

$$\nabla \cdot (\rho \vec{U} \vec{U}) = -\nabla P + \nabla \cdot [(\mu + \mu_t)(\nabla \vec{U} + \nabla \vec{U}^T)] + \rho \vec{g} \quad (2)$$

Energy equation:

$$\nabla \cdot (\rho c_p \vec{U} T) = \nabla \cdot [(k + k_t)\nabla T + (\bar{\tau}_{eff} \cdot \vec{U})] \quad (3)$$

where \vec{U} is the velocity vector, μ_t , k_t are the eddy viscosity and the turbulent thermal conductivity. The second terms on the right side of Equation 2 and 3 represent the stress tensor, and the energy transfer due to viscous dissipation, respectively. In the current work, the standard two-equation κ - ε turbulence model was used to determine μ_t , k_t , as given below.

Turbulence kinetic energy equation (κ):

$$\frac{\partial}{\partial x_i} (\rho \kappa U_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\kappa} \right) \frac{\partial \kappa}{\partial x_j} \right] + G_\kappa + G_b - \rho \varepsilon \quad (4)$$

Turbulence dissipation equation (ε):

$$\frac{\partial}{\partial x_i} (\rho \varepsilon U_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \frac{\varepsilon}{\kappa} (G_\kappa + C_{\varepsilon 2} G_b) - C_{\varepsilon 3} \rho \frac{\varepsilon^2}{\kappa} \quad (5)$$

In these equations, G_κ and G_b are the turbulence kinetic energy generation resulted from the mean velocity gradients and buoyancy, respectively. σ_κ and σ_ε denote the turbulent Prandtl numbers of κ and ε , respectively. $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are model constants.

The suitable definition of the thermophysical properties of nanofluid is of the great effects on the quantities of heat transfer rate and pressure drop (Malvandi et al., 2016). Therefore, the temperature-dependent thermophysical properties were used for Al₂O₃-water as follows (Bajestan et al., 2010; Rea et al., 2009):

Density:

$$\rho_{nf}(\phi, T) = (1 - \phi)\rho_{bf}(T) + \phi\rho_p \quad (6)$$

Specific heat capacity:

$$Cp_{nf}(\phi, T) = \frac{(1 - \phi)(\rho(T)Cp(T))_{bf} + \phi(\rho Cp)_p}{(1 - \phi)\rho_{bf}(T) + \phi\rho_p} \quad (7)$$

Dynamic viscosity:

$$\mu_{nf}(\phi, T) = \mu_{bf}(T) \exp \left[\frac{4.91\phi}{0.2092 - \phi} \right] \quad (8)$$

Thermal conductivity:

$$k_{nf}(\phi, T) = k_{bf}(T) \exp[1 + 4.5503\phi] \quad (9)$$

where ϕ is the volumetric ratio of nanoparticles, and subscripts nf , bf and p indicate the nanofluid, base fluid and particle, respectively. The thermophysical properties, density, specific heat capacity and thermal conductivity of Al₂O₃ were considered as 3970 kg/m³, 765 j/kg K and 40 W/ m K, respectively (Mercan and Yurddaş, 2019). Equations 8 and 9 are applicable in the range of temperatures from 20 to 80 °C with the volumetric fraction up to 0.06 (Rea et al., 2009). Taking into consideration the temperature dependency, the thermophysical properties of the fluids defined to the solving process are given in Figure 2.

Boundary conditions

As shown in Figure 1, the fluid flows through the pipe whose wall exposed to a uniform heat flux of 50 kW / m². The components of flow velocity were regarded as zero at the wall with no-slip boundary condition. The inlet-outlet boundaries were assumed as the periodic flow since a thermally and hydraulically developed flow is required for the investigation. The inlet fluid temperature was regarded as 293.15 K. The numerical analyses were performed under Re numbers from 4000 to 9000 with a 1000 increment and, the flow velocities in the range from 0.41 to 0.71 m/s with an 0.06 m/s increment for Al₂O₃-water nanofluids ($\phi=0.01$ to 0.04) and base fluid, water. To obtain the Re number and velocities, the mass flow rates along the flow direction(Figure 1.) were defined for periodic boundary condition by calculating as in Equation 10.a-b.

For the same Re number case

$$\dot{m} = \frac{Re}{4\pi d\mu} \quad (10. a)$$

For the same flow velocity case

$$\dot{m} = \rho u A_c \quad (10. b)$$

where d , μ and ρ denote the diameter of the pipe, dynamic viscosity and density, respectively. u and A_c are flow velocity and the cross-section area.

With these approaches, the governing equations were solved using finite volume method with pressure-based solver and, SIMPLE algorithm scheme for pressure-velocity coupling. For spatial discretization, second-order upwind schemes were employed for the transport equations. Besides, SIMPLE scheme was used to interpolate the pressure values at the faces. Thus, the equations were solved with the convergence criteria; 10^{-8} for the energy equation and, 10^{-6} for other scalars.

In the work, the thermal and hydraulic performances were investigated taking convective heat transfer coefficient (h), Nusselt number (Nu), and friction factor (f) into consideration. Once the equations were converged, the bulk and wall temperatures and, the wall shear stress were attained to calculate h and f by the following equations (Sadri et al., 2018).

$$f = \frac{8\tau_w}{\rho u^2} \quad (11)$$

$$h = \frac{q}{T_w - T_b} \quad (12)$$

$$Nu = \frac{h d}{k} \quad (13)$$

where τ_w is the wall shear stress, u is the mean velocity. T_w and T_b represent the wall and bulk temperatures, respectively. q is the heat flux.

In order to determine the performance of Al₂O₃-water nanofluid considering both thermal and hydraulic parameters, overall enhancement ratio (η) were calculated using as follows (Ghale et al., 2015):

$$\eta = \frac{Nu_{nf}/Nu_{bf}}{(f_{nf}/f_{bf})^{1/3}} \quad (14)$$

Validation of the Study

To validate the present numerical study, the Nu number and friction factor with the base fluid were compared to the results obtained with the empirical correlations of Petukhov (Eq.15), Notter-Rouse (Eq.16), Dittus-Boelter (Eq.17) for Nu number prediction and, Petukhov (Eq.18) and Blasius (Eq.18) expressions for friction factors as follows (Sadri et al., 2018; Kakaç and Liu, 2002; Bergman et al., 2011):

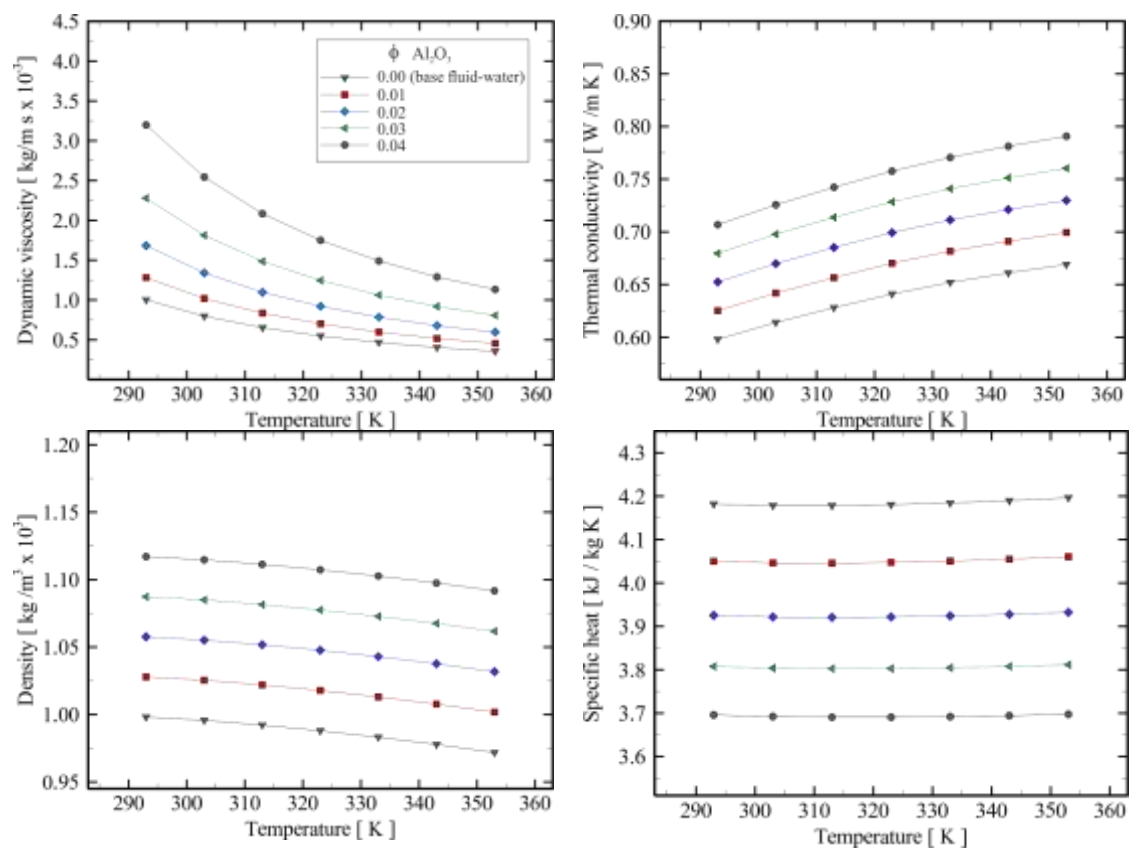


Figure 2. Temperature dependent thermophysical properties of the fluids

$$Nu = \frac{(f/8)RePr}{1.07 + 12.7(f/8)^{0.5}(Pr^{2/3} - 1)} \quad (15)$$

$$Nu = 5 + 0.015Re^{0.856}Pr^{0.347} \quad (16)$$

$$Nu = 0.023 Re^{0.8}Pr^{0.4} \quad (17)$$

The friction factor, f :

$$f = (0.79 \ln Re - 1.64)^{-2} \quad (18)$$

$$f = 0.316 Re^{-0.25} \quad (19)$$

Figure 3 shows the Nu number and f against Re number for comparison of the results between the present numerical study and the empirical correlations. The numerical results are in good agreement with those obtained from the Petukhov and Notter-Rouse correlations for Nu number. Similarly, the friction factor is more compatible with Petukhov friction factor correlations. The maximum relative errors are only 7.88 % and 6.13 % for Nu and f relative to the correlations of Petukhov. It is, thus, reasonable to estimate the parameters for the intended purposes of this study.

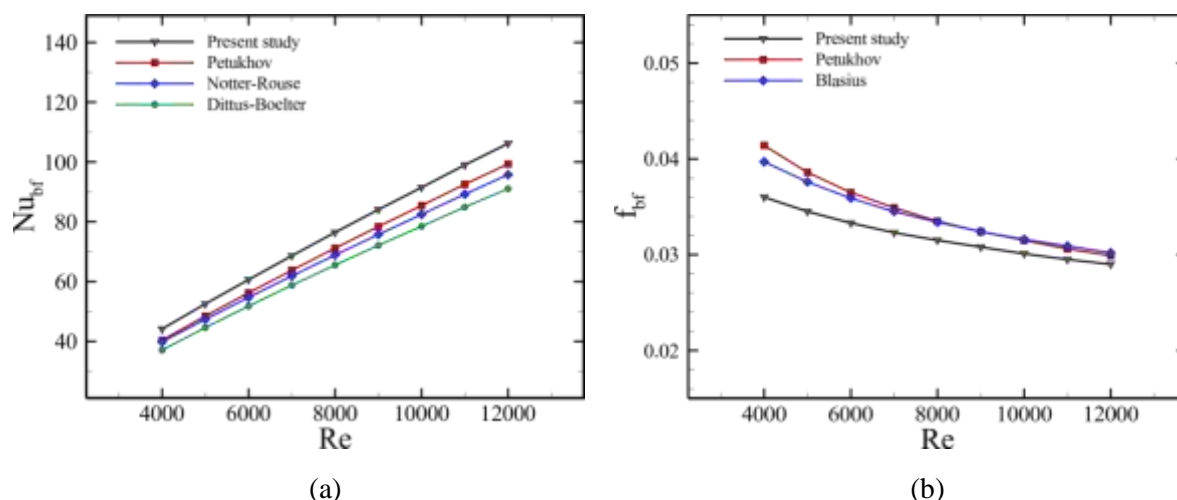


Figure 3. Comparison of the (a) Nusselt number- Nu_{br} and, (b) friction factor $-f_{br}$ of the base-fluid

RESULTS and DISCUSSION

The comparison of convective heat transfer coefficients of water and Al₂O₃-water nanofluids is illustrated as a function of Re number in Figure 4. As seen in the figure, convective heat transfer coefficients of Al₂O₃-water nanofluids are greater than those of water. Besides, convective heat transfer coefficients increase remarkably with the increase of Al₂O₃ particle fraction (ϕ). In Figure 4.b, the convective heat transfer coefficient ratios of the nanofluids with those of water are also given for all Re numbers and fractions to determine the improvement in convective heat transfer coefficient. The improvement goes up to the value of 1.53 with Al₂O₃ particle fraction of 0.04. It can be also noted that the improvement in heat transfer coefficients is nearly independent of Reynolds number as in the study conducted by Bianco et al. (2010).

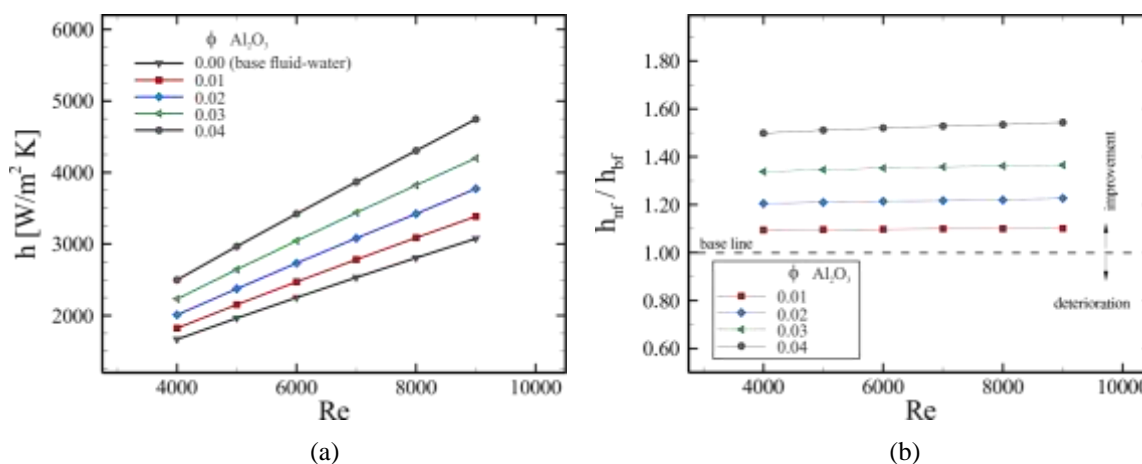


Figure 4. (a)Convective heat transfer coefficients(h) ; (b) convective heat transfer coefficient ratios versus Reynolds numbers

Figure 5 shows Nusselt numbers and friction factors to assess the thermal and hydraulic performances of nanofluids separately, as carried out by Namburu et al.(2009). The variation of Nu numbers has a similar trend to convective heat transfer coefficients. However, the increased rate of Nu number is lower than that of the convective heat transfer coefficient. The reason for this is the increase in thermal conductivity of nanofluids as seen in Figure 2. Thus, the maximum increase rate of Nusselt number ($Nunf/Nubf$) is found as 1.32. On the other hand, the increase in Al₂O₃ particle fraction

resulted in a higher friction factor as in the study of Vahidinia and Miri (2015). This implies that the nanofluids increase the required pumping work due to the increasing friction factors.

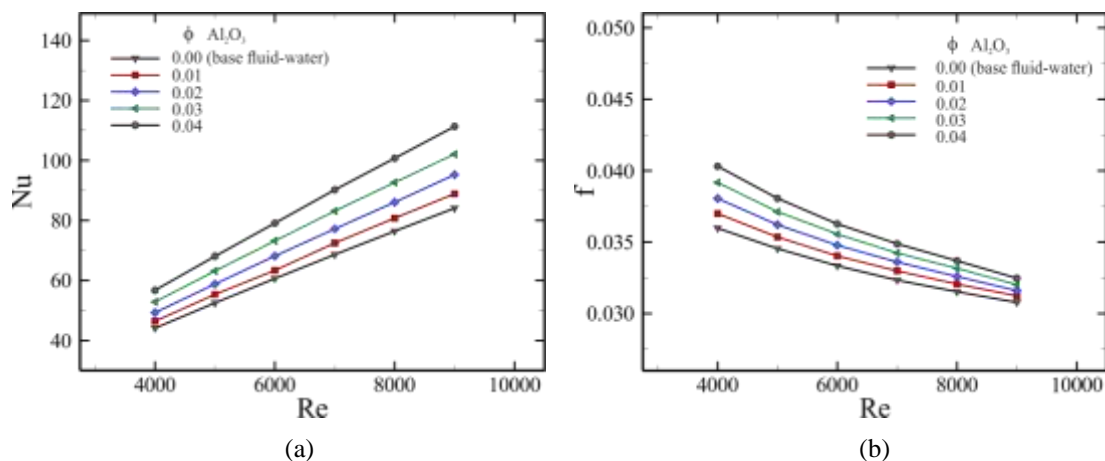


Figure 5. (a) Nusselt numbers(Nu) ; (b) friction factors (f) versus Reynolds numbers

The nanofluid at the same Reynolds number of the base fluid brings about not only an improvement in a convective heat transfer coefficient and Nusselt number but an increase in the friction factors. The overall enhancement ratio (η) is, therefore, crucial to determine the effects of the nanofluid in terms of both thermal and hydraulic performance aspects. Figure 6 illustrates the overall enhancement ratios of the nanofluids with different fractions. The figure implies that the overall enhancement ratio is nearly independent of Reynolds numbers. The overall enhancement ratios vary from 1.04 to 1.30 with the increase of the fraction Al₂O₃.

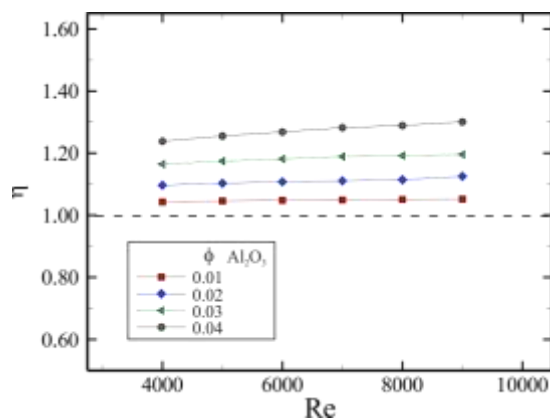


Figure 6. The overall enhancement ratios versus Reynolds numbers

The results at the constant Reynolds number show a considerable overall enhancement using the nanofluid. This can be ascribed to the increasing velocity of nanofluids to attain the same Reynolds number of the base fluid (Akbarinia et al., 2011) along with the superiority of thermal conductivity of nanofluid. However, the assessment of nanofluid in terms of thermal and hydraulic performance at the constant Re does not state the ability of nanofluid when using as a working fluid for a real heating or cooling systems. Consequently, the comparison at the constant velocity can give a better reasonable assessment of nanofluid rather than a constant Re. Figure 7 shows the comparison of the convective

heat transfer coefficient and their ratios to that of water, at the constant inlet flow velocities. In contrast to the results obtained at the constant Re, the convective heat transfer coefficient of nanofluids resulted in a lower value than the base fluid, water. The increase of Al₂O₃ fraction deteriorates remarkably the convective heat transfer coefficient. Therefore, the ratio of convective heat transfer coefficients to those of water remained below 1.0 as in Reference (Bubbico et al., 2015). This is because of the higher dynamic viscosity value of nanofluids which cause a decrease in Reynolds number.

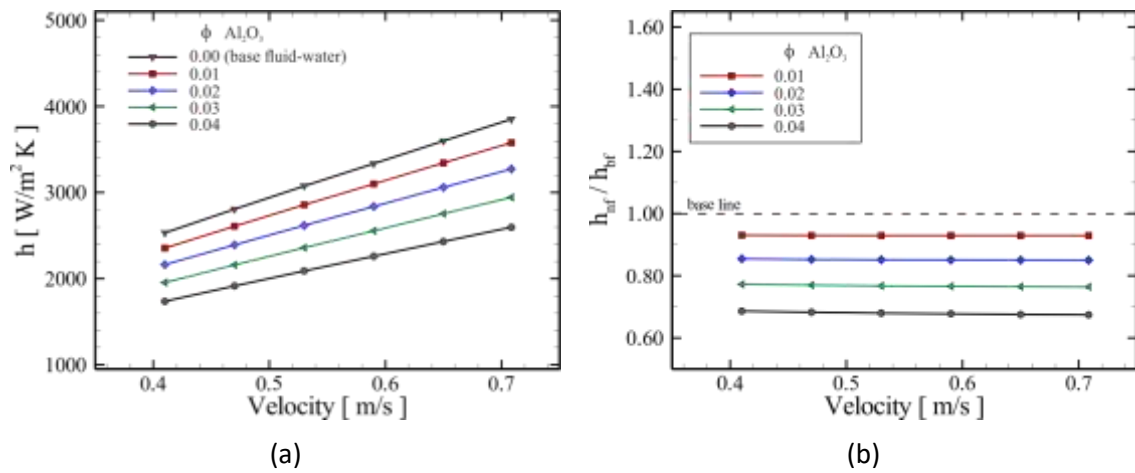


Figure 7. (a) Convective heat transfer coefficients(h) ; (b) convective heat transfer coefficient ratios versus flow velocity

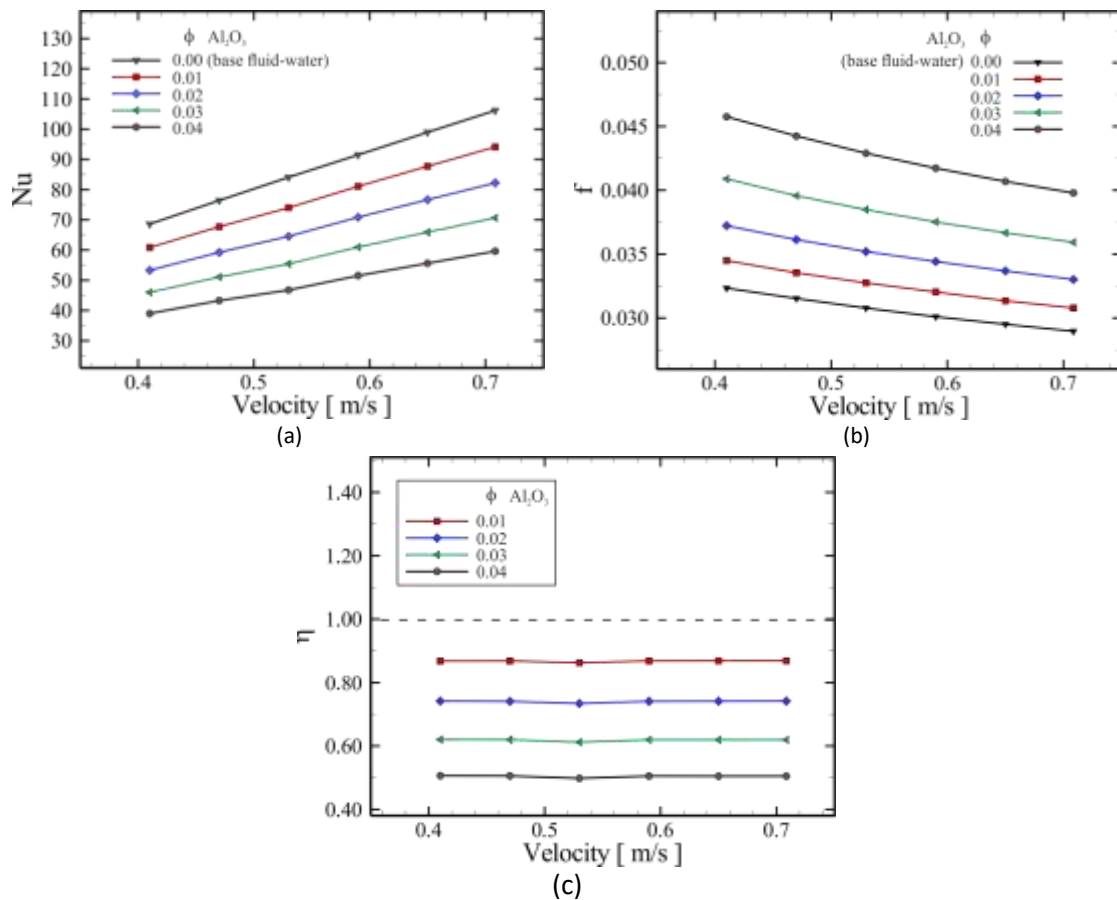


Figure 8. (a) Nusselt numbers(Nu) ; (b) friction factors (f) and ,(c) the overall enhancement ratios versus flow velocity

Figure 8 shows the variation Nusselt numbers and friction factors and the overall enhancement ratios as a function of flow velocity and the fraction of Al₂O₃. As expected due to the decrease in convective heat transfer coefficients, the Nusselt number decreases with the increase of Al₂O₃ fraction. The minimum ratio between Nu_{nf} and Nu_{bf} was found as 0.56 by the Al₂O₃ fraction of 0.04. When considering friction factors, they increase remarkably with the increase of the Al₂O₃ fraction in the nanofluid. The maximum increase in friction factor was found by about 41%. Thus, it is obvious that the thermo-hydraulic performances worsen using nanofluids, Al₂O₃ at the constant velocity comparison as also seen in Figure 3.c.

CONCLUSION

The thermal and hydraulic performances of Al₂O₃-water nanofluid were numerically examined relative to the base fluid with two assessment criteria, at the same Reynolds number and average flow velocity corresponding to the turbulent flow regime. A three dimensional flow domain exposed to a constant heat flux on its wall was considered for the numerical study using the finite volume method. Based on the results, it can be clearly stated that the effect of nanofluid on the trend of the change in the convective heat transfer coefficient and the overall enhancement ratio heavily depends on assessment criteria. In the case of the comparison at the same Reynolds number, the nanofluid with increasing the concentration of Al₂O₃ particles brings about the increase of convective heat transfer coefficient and Nusselt number up to 53 % and 32 %, respectively. Although friction factors of the nanofluid have higher values than those of base fluid, the overall enhancement ratios were obtained more than 1.0 and, reached to 1.30. On the contrary, the convective heat transfer coefficient of the nanofluid worsened increasing the concentration of Al₂O₃ at the same flow velocity. Thus, both the decrease of Nusselts number and the increase of the friction factor led to the overall enhancement ratio to be lower than 1.0, which means that nanofluids deteriorate both thermal and hydraulic performances.

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