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Analysis of turbulent flow of nanofluids in a pipe

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Abstract

The steady flow of nanofluids has been analyzed for water and ethylene glycol as base fluids and alumina oxide nanoparticles. Also they were studied in turbulent flow inside a pipe by using fluent and Gambit softwares. The numerical results show a good convergence with previous existing relations. The friction coefficient, pressure drop and viscous drag force increase with increasing the volume fraction of nanoparticles. This increase of course is not more considerable than the base fluid in the low volume fractions but with increasing volume fraction, this increase is significant. Between three alumina oxide nanoparticles AF, AR and AK, the nanofluid containing alumina oxide nanoparticles AF have the highest friction coefficient, viscous drag force and pressure drop and the nanofluid containing alumina oxide nanoparticle AR has the lowest. Because of this reason can be due to more viscous nanofluid containing alumina oxide nanoparticle AF. The increasing the Reynolds number reduces the friction coefficient and increases the pipe wall viscous drag force and the pressure drop. Finally, the use of nanofluids has no a significant impact on the developed velocity field.

Keywords: nanofluid, pipe, Turbulent flow, Simulation, Steady flow

Introduction

The commonly used fluids in heat transfer have low thermal conductivity. Solid particles due to the high conductivity with distribution in the base fluid, increase the thermal conductivity of the fluids, Cooling systems is one of the main concerns in industries such as electronics. With the advancement of technology in industries such as electronics, rapid and large operations with very high speed (multi-GHz) take place, the use of engines with high efficiency and high thermal load will be most important. Therefore, the use of advanced and optimized cooling systems is inevitable. Optimization of existing heat transfer systems, in most cases takes place by increasing their surfaces, which always increases the size of the systems**.** To overcome this problem, a new and efficient cooling method is required. Conventional heat transfer fluids such as water or ethylene glycol, used in cooling or heating applications are characterized by poor thermal properties. In the past years, many different techniques were utilized to improve the heat transfer rate in order to reach a satisfactory level of thermal efficiency. The heat transfer rate can passively be enhanced by changing flow geometry or by improving thermophysical properties for example, increasing fluid thermal conductivity. One way to enhance fluid thermal conductivity is to add small solid particles in the fluid. Maxwell (1881) was the first to show the possibility of increasing thermal conductivity of a solid-liquid mixture by more volume fraction of solid particles. He used particle of micrometer or millimetre dimensions. Those particles were the cause of numerous problems, such as abrasion, clogging, high pressure drop and poor suspension stability. Therefore, a new class of fluid for improving thermal conductivity and avoiding adverse effects due to the presence of particles is required. To meet these important requirements, a new class of fluids, called nanofluids, has been developed by Choi (1995). Wen and Ding studied the convective heat transfer in the entrance region under laminar regime using aluminium oxide nanofluid in a circular tube with constant heat flux.

Migration of nanoparticles and the subsequent disturbance of the boundary layer were attributed to the enhancement in heat transfer rate. Kim et al (2009) conducted experiments with aluminium oxide and amorphous carbonic nanofluids in the laminar and turbulent regimes and concluded that the mechanism for heat transfer enhancement was different for the two regimes. The delaying and disturbance of the thermal boundary layer was attributed to the heat transfer enhancement in the laminar regime. Whereas, in the turbulent regime, increase in thermal conductivity was responsible for heat transfer enhancement . Kumar and Ganesan (2012) performed a CFD Study of Turbulent convective heat transfer Enhancement in Circular Pipe flow. Addition of milli or micro sized particles to the fluid is one of the many techniques employed for improving heat transfer rate. Though this looks simple, this method has practical problems such as high pressure loss, clogging and erosion of the material of construction. These problems can be overcome by using nanofluids, which is a dispersion of nanosized particles in a base fluid. Nanoparticles increase the thermal conductivity of the base fluid which in turn increases the heat transfer rate. Nanoparticles also increase the viscosity of the base fluid resulting in higher pressure drop for the nanofluid compared to the base fluid. Naik, Vojkani and Ravi (2013) analyzed turbulent convection flow of CuO nanofluids with propylene glycol-water (30:70 by volume) as the base fluid and flowing in a circular tube, subjected to a constant and uniform heat flux at the wall, numerically. The effects of nanoparticles concentrations and Reynolds number are investigated on the flow and the convective heat transfer behavior of CuO nanofluids. It was discovered that nanofluids containing more concentrations have shown higher heat transfer coefficient. Syam Sundar and Sharma (2010) determined experimentally, the convective heat transfer coefficient and friction coefficient data at various volume concentrations for flow in a plain tube and with twisted tape insert for Al_2O_3 nanofluid. The thermo physical properties like thermal conductivity and viscosity of Al_2O_3 nanofluid is determined through experiments at different volume concentrations and temperatures and validated. Experiments are conducted in the Reynolds number range of 10,000–22,000 with tapes of different twist ratios in the range of $0 < H/D < 83$. The heat transfer coefficient and friction coefficient of 0.5% volume concentration of Al_2O_3 nanofluid with twist ratio of five is 33.51% and 1.096 times respectively higher compared to flow of water in a tube . Arttu Merilainen et al (2013) carried out extensive experimental studies of turbulent convective heat transfer of several water-based Al_2O_3, SiO_2, and MgO nanofluids with a nanoparticle volume fraction up to 4%. Through our nanoparticle size and shape analysis they found that in general small, spherical and smooth particles (less than 10 nm in size) are best in enhancing heat transfer and keeping the increase of pressure losses moderate. Their results showed that the nanoscale properties of the particle phase must be carefully considered in heat transfer experiments. Vincenzo Bianco et al (2011) analyzed turbulent forced convection flow of water-Al_2O_3 nanofluid in a circular tube, subjected to a constant and uniform heat flux at the wall, numerically. Two different approaches are taken into account: single and two-phase models, with particle diameter equal to 38 nm. It is observed that convective heat transfer coefficient for nanofluids is greater than that of the base fluid. Heat transfer enhancement increases with the particle volume concentration and Reynolds number . Corcione et al (2012) studied heat transfer of nanoparticle suspensions in turbulent pipe flow theoretically. The main idea upon which this work is based is that nanofluids behave more like single-phase fluids than like conventional solid - liquid mixtures. This assumption implies that all the convective heat transfer correlations available in the literature for single-phase flows can be extended to nanoparticle suspensions, provided that the thermo physical properties appearing in them are the nanofluid effective properties calculated at the reference temperature. In this regard, two empirical equations, based on a wide variety of experimental data reported in the literature, are used for the evaluation of the nanofluid effective thermal conductivity and dynamic viscosity. Conversely, the other effective properties are computed by the traditional mixing theory . According to surveys conducted, most of the studies have investigated numerically the nanofluid flow in the pipe with laminar flow regime and because of the complexity of numerical analysis of nanofluids turbulent flow inside pipe carried out the numerical work in this sector is relatively low. We are faced with turbulent flow in a pipe in the many industrial applications. Recently, the use of nanofluids increased in heat exchangers and while the flow regime in heat exchangers is often turbulent, thus for the Performance of the nanofluids, we investigate the effect of turbulent flow of nanofluids in the pipe (as a common geometry). So in a recent paper has been studied the flow parameters of nanofluids in pipe numerically and the effect of various parameters such as volume fraction of nanoparticles, type of nanoparticles, type of base fluid and Reynolds number on nanofluids flow parameters has been investigated thoroughly

Governing equations

Governing equations of fluid flow in a pipe

Steady state simulations were carried out by solving mass conservation and momentum equations, which are expressed as:

$$div(\rho\bar{v}) = 0 \tag{1}$$

$$div(\rho\bar{v}\bar{v}) = -grad(\bar{P}) + \mu\nabla^2\bar{V} - div(\rho\bar{u}\bar{u}) \tag{2}$$

In the above equations $\bar{V}$ and $\bar{P}$ represents the time-averaged flow variables and $\bar{u}$ represents the fluid velocity fluctuations. Term $\rho\bar{u}\bar{u}$ represents the turbulent shear stress.

In this paper we used the k-ε model for turbulence modeling of nanofluids. This model has been proposed by Launder and Spalding (2004) previously, and is consisting of two equations k and ε. k denotes the turbulent kinetic energy and ε represents the turbulence dissipation rate. K-ε equations are described as follows.

$$div(\rho\bar{V}k) = div\left\{\frac{(\mu+\mu_t}{\sigma_k\, grad\, k}\right\} + G_k - \rho\varepsilon \tag{3}$$

$$div(\rho\bar{V}\varepsilon) = div\left\{\frac{(\mu+\mu_t}{\sigma_\varepsilon\, grad\, \varepsilon}\right\} + C_{1\varepsilon}(\frac{\varepsilon}{k})G_k + C_{2\varepsilon}\rho(\frac{\varepsilon^2}{k}) \tag{4}$$

In the above equations, where G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients and $C_{1\varepsilon}$,$C_{2\varepsilon}$, σ_k andσ_ε are thestandard k-ε model constants. The turbulent viscosity μ_t is computed as follow*:* (5):

$$\mu_t = \frac{\rho c_\mu k^2}{\varepsilon} \tag{5}$$

Where k, ε and $c_\mu$are turbulent kinetic energy, turbulent kinetic energy dissipation rate and turbulent viscosity constant, respectively.

$c_\mu$is a constant and its value is 0.09[6].

In Eqs.(3) and (4); $C_{1\varepsilon} = 1.44$ و $C_{2\varepsilon} = 1.92$ و $\sigma_k = 1$ و$\sigma_\varepsilon = 1.3$.

Nanofluids thermo physical properties

Since the nanofluid is a suspension of nanoparticle and base fluid, as a result, their thermal properties, is a combination between the properties of the nanoparticles and the base fluid.

- *The density of nanofluids*

ρ_{nf} indicates the density of nanofluid that is discovered from the equation (6):

$$\rho_{nf} = (1-\Phi)\rho_{bf} + \Phi\rho_p \tag{6}$$

ρ_{bf} And $\rho_p$are the density of base fluid and the density of nanoparticles, respectively, and Φ is the volume fraction of nanoparticles.

•*The Viscosity of nanofluids*

μ_{nf} is the viscosity of nanofluid that is calculated from the following equation:

$$\mu_{nf} = \mu_{bf}(1 + a\Phi) \quad (7)$$

μ_{bf} is the viscosity of the base fluid, and a is a fixed number. Empirical constant a depends on the shape, size and surface properties of nanoparticles, the value of a for three aluminum oxide nanoparticles AR, AK and AF are calculated by using laboratory results of Chun and colleagues (2008) and their values are 3.5573, 4.9407 and 15.4150, respectively. The physical properties of the base fluids and Physical properties of aluminum oxide nanoparticles are shown in Tables 1 and 2.

Table 1: Physical properties of the base fluids

Fluid	Density ($^{kg}/_{m^3}$)	Viscosity ($^{kg}/_{ms}$)
Liquid water	998.2	0.001003
Ethylene Glycol	1111.4	0.0157

Table 2: Physical properties of aluminum oxide nanoparticles

aluminum oxide	AK	AR	AF
Company	Degussa	N&A Materials	
size(nm)	43	43-27	7
shape	Spherical	Spherical	Bar
Surface properties	Hydrophobic	Hydrophilic	Hydrophilic
Density ($^{kg}/_{m^3}$)	3970	3970	3970

Numerical simulation

In figure 1 the geometry of the problem is shown. The pipe diameter and length are considered 150mm and 30m, respectively. A two-dimensional geometry is considered since there is an axial symmetry in the problem. The grid was generated by using quad elements.

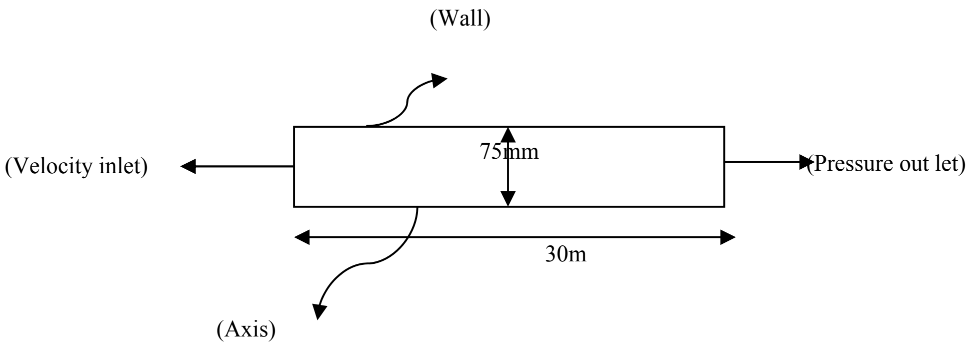

Figure 1: The pipe geometry

Finite volume method is used to solve the governing equations. The method of discretization of equations is given in table 3.

Table 3: The method of discretization of equations

Type of equation	Pressure	Momentum	Turbulent kinetic energy and turbulence dissipation rate
Discretization method	Second Order	Second Order Upwind	Second Order Upwind

The SIMPLE algorithm is used for coupling velocity and pressure. Precision of convergence is considered 10^{-6} for the equations of continuity, momentum and k-ε.

Results and discussion

Mesh study

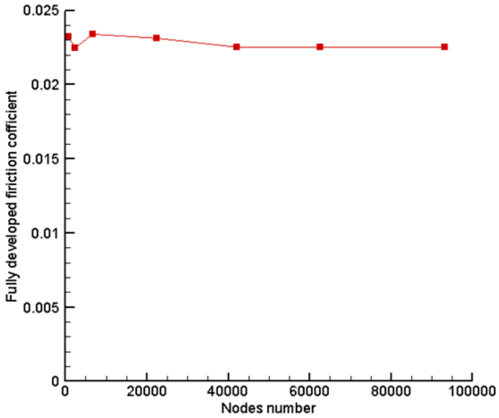

Figure 2: Results of the independent review of the created grid

As shown in Figure 2, with increasing the number of grid nodes to 42084 nodes, there were a few changes in the coefficient of friction in the fully developed region. So the grid consisting of 42084 nodes is selected because of accuracy and computational cost.

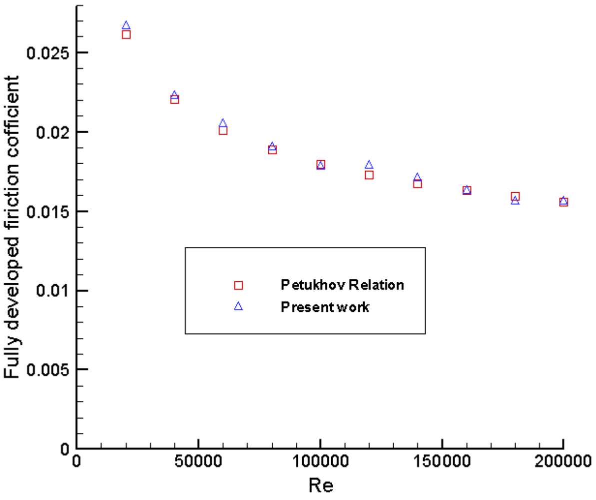

Figure 3: Comparison of present work with reference work

The accuracy of the numerical method

In order to verify the results accuracy, the friction coefficient in the fully developed region for the different Reynolds number in turbulent flow are obtained and the results are compared with numerical and experimental results of Petukhov's (1970) work . Figure 3 shows this comparison and that they highly confirm each other can be seen. The error is less than 1%.

Investigation of the effect of various factors on the nanofluids flow parameters inside the pipe

In all investigated cases the fluid outlet pressure of the pipe is equal to1 atm.

Investigation of the effects of the base fluid

In order to study the effect of the base fluid on flow parameters of the nanofluid, water - AR alumina oxide nanofluid with the 2% volume fraction was used. The inlet velocity Fluid in the pipe is considered 0.5358976m/s.

Investigation of the effect of based fluid on the fully developed friction coefficient

In order to investigate the effect of the base fluid on the friction coefficient in the fully developed region, two different base fluids such as water and ethylene glycol were used. The used nanoparticle is alumina oxide AR with a 2% volume fraction. The effect of base fluid on friction coefficient in the fully developed region has been investigated in table 4.

Table 4: Investigation of the effect of based fluid on friction coefficient in the fully developed region

Base fluid	Water	Ethylene glycol
friction coefficient in the fully developed region	0.0190154	0.0415804

As seen in Table 4, the nanofluid containing ethylene glycol- based fluid, due to higher viscosity, has the highest friction coefficient in the fully developed region and the nanofluid containing water-based fluid has the lowest fully developed friction coefficient.

Investigation of the effect of the base fluid on the created pressure drop between the inlet and outlet of pipe

In order to investigate the effect of based fluid on the created pressure drop between the inlet and outlet of the pipe, two different base fluids such as water and ethylene glycol were used. The used nanoparticle is alumina oxide AR with the 2% volume fraction. The effect of based fluid on the pressure drop has been investigated in table 5.

Table 5: Investigation of the effect of based fluid on the pressure drop

Base fluids	Water	Ethylene glycol
pressure drop (Pascal)	592	1437

As seen in Table 5, the nanofluid containing ethylene glycol-base fluid creates the highest pressure drop and the nanofluid containing water-base fluid imposes minimum pressure drop to the system. The reason for this is that the nanofluid containing ethylene glycol-base fluid has higher viscosity compared to the other one.

Investigation of the effect of base fluid on the pipe wall viscous drag force

In order to investigate the effect of based fluid on the pipe wall viscous drag force, two different based fluids such as water and ethylene glycol were studied. The used nanoparticle is alumina oxide AR with the 2% volume fraction. The pipe wall viscous drag force for various nanofluids containing base fluids has been compared in table 6.

Table 6: Investigation of the effect of based fluid on the pipe wall viscous drag force

Base fluids	Water	Ethylene glycol
Viscous drag force on the wall of pipe (N)	10.313886	24.884367

As it can be seen in Table 6, the nanofluid containing ethylene glycol- base fluid creates the most viscous drag force on the wall of the pipe and the nanofluid containing water-based fluid has the minimum viscous drag force. The reason behind this fact is that the Wall viscous drag force for the nanofluid containing ethylene glycol- base fluid is the greatest is due its higher viscosity compared to nanofluids containing water as base fluid.

Investigation of the effects of nanoparticle volume fraction

In order to study the effect of volume fraction of nanoparticle on flow parameters of nanofluids, water - AR alumina oxide nanofluid was used. The inlet velocity Fluid in the pipe is considered 0.5358976m/s.

Investigation of the effect of nanoparticle volume fraction on fully developed friction coefficient

In order to investigate the effect of nanoparticle volume fraction on the fully developed friction coefficient water - AR alumina oxide nanofluid was used. Figure 4 shows the friction coefficient in the fully developed region when utilizing of the water as base fluid and AR nanoparticle alumina oxide for various volume fractions.

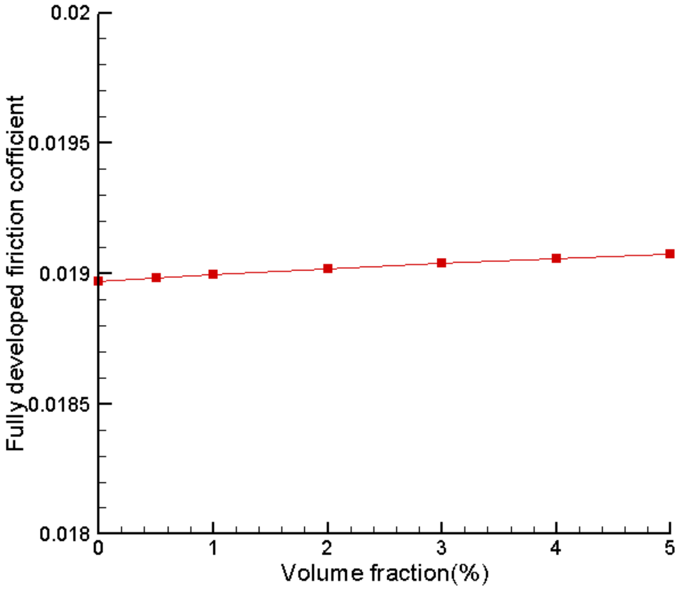

Figure 4: Investigation of the effect of volume fraction of nanoparticle on friction coefficient along the length of pipe

As seen in Figure 4, the nanofluids friction coefficient is higher than the base fluid and increases by increasing volume fraction of the nanoparticle.

Investigation of the effect of nanoparticle volume fraction on pressure drop

In order to investigate the effect of volume fraction of the nanoparticle on the created pressure drop between the inlet and outlet of the pipe, nanofluids containing alumina oxide nanoparticles AR with 2% volume fraction and water-based fluid are used. Figure 5 shows the pressure drop in terms of volume fraction of nanoparticle.

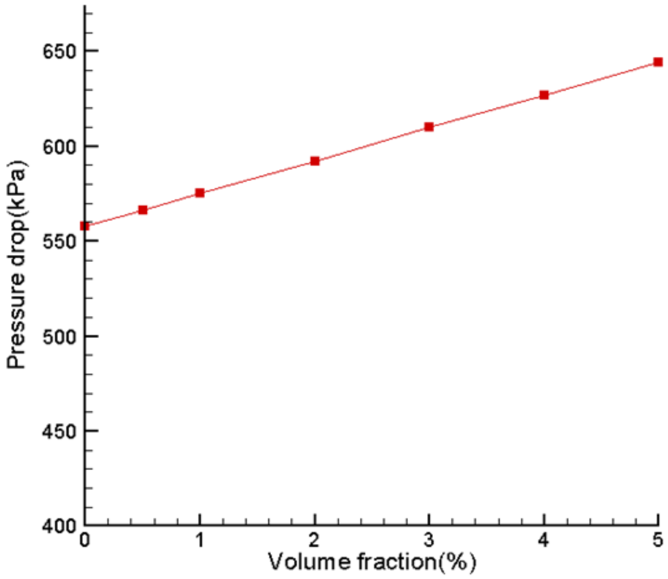

Figure 5: Investigation of the effect of nanoparticle volume fraction on pressure drop

As shown in Figure 5, the created pressure drop caused by nanofluids is greater than the base fluid and increases with increasing volume fraction of the nanoparticle. Nanofluid with 0.5% volume fraction increases the pressure drop 1.4% compared to the base fluid and nanofluid with 2% volume fraction of nanoparticle which increases the pressure drop by 6.1 %. Therefore, by using nanofluids with low volume fraction of nanoparticle, the pressure drop does not increase substantially, but by using a nanofluid with high volume fraction of nanoparticles, this additional pressure drop imposes additional costs of pumping.

Investigation of the effect of nanoparticle volume fraction of on the pipe wall viscous drag force

In order to investigate the effect of volume fraction of nanoparticle on the pipe wall viscous drag force, nanofluids containing alumina oxide nanoparticles AR with 2% volume fraction and water-based fluid were used. The pipe wall viscous drag force in terms of volume fraction of nanoparticles is shown in Figure 6.

As seen in Figure 6, viscous drag force on the wall of the pipe for nanofluids is greater than the base fluid and linearly increases with increasing volume fraction of nanoparticles.

Investigation of the effects of nanoparticle type

In this section, the inlet velocity is uniform and the value is 0.5358976 m/s. The outlet pressure is atmospheric pressure.

Investigation of the effect of nanoparticle type on the friction coefficient

In order to investigate the effect of nanoparticle type on the friction coefficient, three types of alumina oxide nanoparticles AF, AR and AK are used. Liquid water is used as Base fluid and the volume fraction of nanoparticles is 2 %. Figure 7 shows the friction coefficient with nanofluids containing water as base fluid and alumina oxide nanoparticles AF, AR and AK with 2% of the volume fraction.

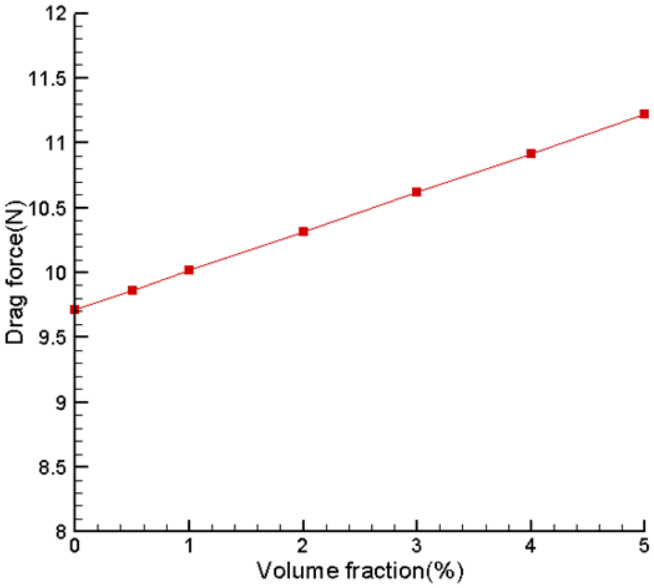

Figure 6: Investigation of the effect of nanoparticle volume fraction on the pipe wall viscous drag force

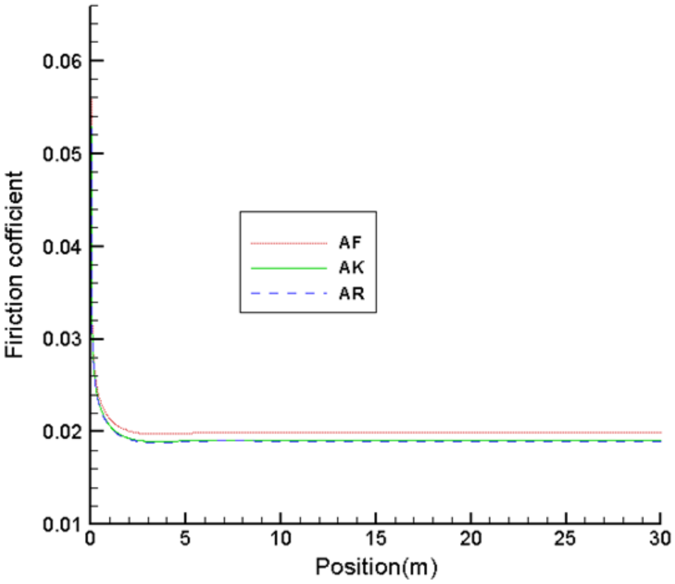

Figure 7: Investigation of the effect of type of nanoparticle on the friction coefficient along the length of pipe

As seen in Figure 7, the nanofluid containing AF nanoparticle has the most friction coefficient and the nanofluid containing AR nanoparticle creates the lowest friction coefficient. This is due to the higher viscosity of the nanofluid containing AF nanoparticle.

Investigation of the effect of nanoparticle type on the pressure drop

In order to investigate the effect of nanoparticle type on the pressure drop, three types of alumina oxide nanoparticles AF, AR and AK are used. Liquid water is used as Base fluid and the volume fraction of nanoparticles is 2 %. Figure 8 shows the created pressure drop along the length of pipe between the inlet and outlet of pipe under condition using of nanofluid containing water as base fluid and alumina oxide nanoparticles AF, AR and AK with 2% of the volume fraction.

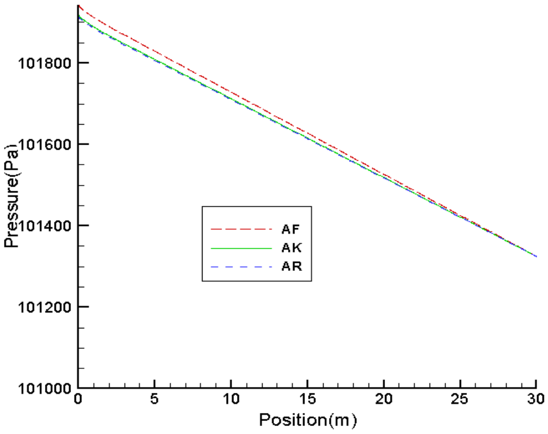

Figure 8: Investigation of the effect of type of nanoparticle on the pressure drop along the length of the pipe

As shown in Figure 8, the nanofluid containing AF nanoparticle has the most and the nanofluid containing AR nanoparticles creates the lowest pressure drop.

Investigation of the effect of the nanoparticle type on the pipe wall viscous drag force

The effect of the nanoparticles type on the pipe wall viscous drag force is investigated in table 7. Liquid water is used as Base fluid and the volume fraction of nanoparticles is 2 %.

Table 7: Investigation of the effect of type of the nanoparticles type on the pipe wall viscous drag force

nanoparticles type	AF	AR	AK
Viscous drag force (N)	10.80007	10.313886	10.372993

As seen in Table 7, the nanofluid containing AF nanoparticle has the most pipe wall viscous drag force and the nanofluid containing AR nanoparticle creates the lowest the pipe wall viscous drag force. The reason behind this can be due to the higher viscosity of nanofluid containing AF nanoparticle.

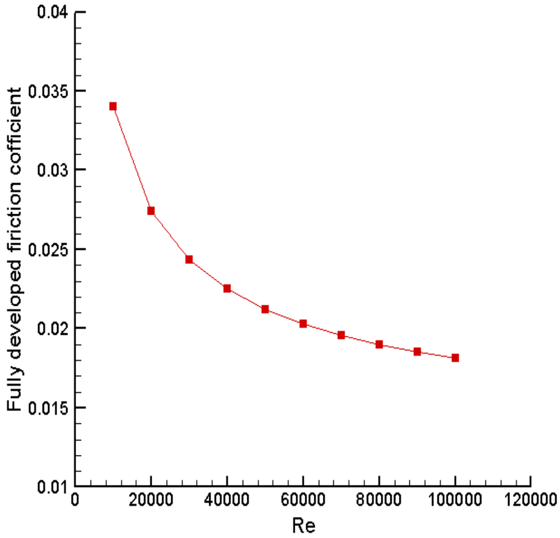

Figure 9: Investigation of the effect of increasing the Reynolds number on the fully developed friction coefficient

Investigation of the effects of increasing the flow Reynolds number

Investigation of the effect of increasing the flow Reynolds number on the fully developed friction coefficient

To investigate the effect of the Reynolds number on the friction coefficient in the fully developed region, nanofluids containing alumina oxide nanoparticles AR with 2% volume fraction and water-based fluid are used. Figure 9 shows the changes of the friction coefficient in the fully developed region with increasing the flow Reynolds number.

As shown in Figure 9, the friction coefficient in the fully developed region decreases with increasing the flow Reynolds number.

Investigation of the effect of increasing the Reynolds number on pressure drop

To investigate the effect of the Reynolds number on the pressure drop between the inlet and outlet of the pipe, nanofluids containing alumina oxide nanoparticles AR with 2% volume fraction and water-based fluid were used. Figure 10 shows the changes of pressure drop with increasing the flow Reynolds number.

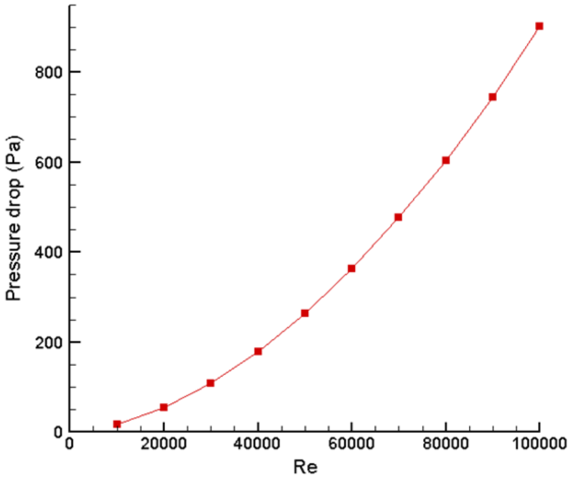

Figure 10: Investigation of the Effect of increasing Reynolds number on pressure drop

As shown in Figure 10, increasing the Reynolds number from 10,000 to 30,000 increases the pressure drop 5.4 times and with increasing the Reynolds number from 10,000 to 100,000, the pressure drop multiplies 53.05 times. Therefore, increasing the Reynolds number increases the pressure drop and imposes additional costs for pumping the nanofluids.

Investigation of the effect of increasing the Reynolds number on pipe wall viscous drag force

To investigate the effect of the flow Reynolds number on the pipe wall viscous drag force, nanofluids containing alumina oxide nanoparticles AR with 2% volume fraction and water-based fluid are used. Figure 11 shows the changes of the pipe wall viscous drag force with increasing the flow Reynolds number.

As shown in Figure 11, increasing the Reynolds number increases the viscous drag force on the wall of the pipe.

Investigation of the effect of using nanofluids on developed velocity field

In order to investigate the effect of using nanofluids on the developed velocity field, the velocity in the center line of the pipe for the base fluid compared with velocity in center line of pipe for nanofluid water - alumina oxide AF with volume fractions 2 and 4 % %. Figure 12 shows the comparison of velocity along the length of the pipe:

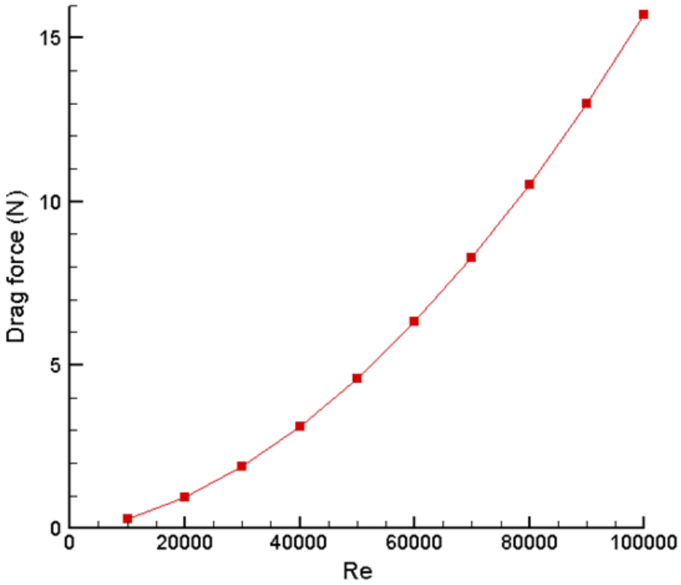

Figure 11: Investigation of the effect of increasing the Reynolds number on the pipe wall viscous drag force

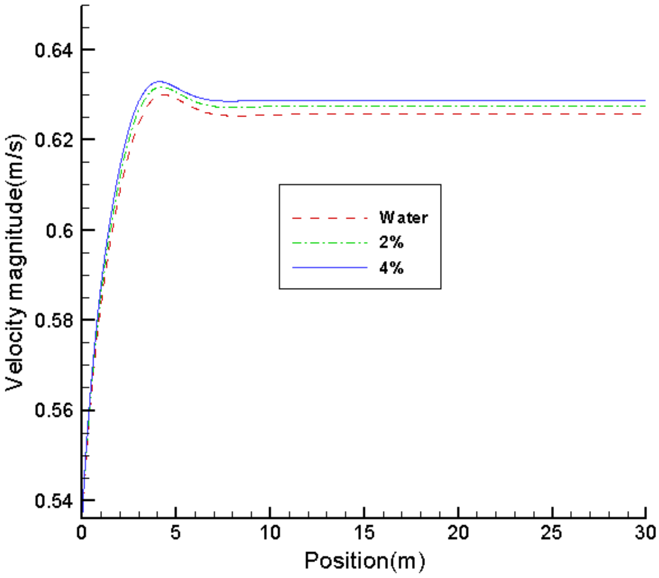

Figure 12: The effect of nanofluids on the developed velocity field

As shown in Figure 12, using nanofluids has no noticeable effect on the developed velocity field, although the velocity increases with increasing volume fraction of nanoparticles.

Conclusion

In this research, with using Gambit and Fluent CFD softwares, we investigated numerically the flow of nanofluids consisting water and ethylene glycol base fluids and nanoparticles of alumina oxide AF, AR and AK in the turbulence regime inside the pipe. After the investigation of the independency of results of the created grid, the numerical results of friction coefficient are compared with experimental results of Petukhov relation, which show good convergence. In a recent study the effect of different parameters such as nanoparticle volume fraction, base fluid type, nanoparticle type and the Reynolds number on the friction coefficient, wall pipe viscous drag force and pressure drop has been studied thoroughly. Nanoparticle volume fraction is variable from 0 to 5%. With increasing the volume fraction of nanoparticles, the fully developed friction coefficient, pressure drop and the pipe wall viscous drag force increases. Through the investigation of two Base fluids, the water has the lowest friction coefficient, viscous drag force and the pressure loss in the wall of the pipe. The use of ethylene glycol in nanofluid suspension, due to the higher viscosity emits the highest pressure drop, friction coefficient and viscous drag force. So through the investigation of two Base fluids, the water in nanofluid suspension is economically preferred. Nanofluid containing alumina oxide nanoparticle AF due to the higher viscosity, the pressure drop and friction coefficient is greater. Also, the viscous drag force is greater than the other two nanoparticles and nanofluids consisting alumina oxide nanoparticle AR causes the lowest of pressure drop, viscous drag force and friction coefficient Because of its low viscosity. So using nanofluid containing alumina oxide nanoparticle AR is preferred over the other two nanoparticles. Increasing the flow Reynolds number increases the created pressure drop between the inlet and outlet pipe, the viscous drag force and friction coefficient. The use of nanofluids has no significant impact on the developed velocity field. Generally and with considering the costs of pumping nanofluids, the using of water base fluid and alumina oxide nanoparticle AR have greater economic benefits.

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