Numerical Simulation of Turbulent Nano-Fluid Flow in a Circular Elbow

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Abstract: force convection heat transfer of turbulent nano fluid flow in 90 and 60 degree elbow is simulated by using FLUENT. Single phase model has been implemented to study such a flow field and standard k-ε model is employed. The considered nanofluids are mixtures of Al_2O_3 nanoparticles and water as the base fluid. Simulation effect of Reynolds number and nano concentration on Nusselt number and friction coefficient have been presented and discussed. The computed results are compared with previously published data for a base fluid (0% nano concentration) and good agreement between the results is observed. It is seen that by increasing Reynolds number and nano concentration, heat transfer increase and friction coefficient decrease. Heat transfer in 90 and 60 degree elbow is compared and result shows by increasing the angle, heat transfer will decrease.

Keywords: Circular elbow, Fluent, Forced convection heat transfer, Nano-fluid, Turbulent flow.

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1 INTRODUCTION

Most of the time optimizing heat transfer systems work by increasing their level and always it cuases increasing volume and size of these systems. So to overcome this problem, some new system is needed and nano-fluid is mentioned as a new solution [1]. During the past decade, the technology to make particles in nanometer dimensions was improved and a new kind of solid–liquid mixture that is called nano-fluid, appeared [2].

About a century ago, Maxwell [3] showed that by adding solid in micro size, we can increase thermal conductivity. Simulation nano-fluid heat transfer was analyzed by choi [4] for the first time. He showed that using nano-fluid leads to increasing in thermal attribute and heat transfer. Present researches also confirm choi's result. Rostami et al. [5] analyzed turbulent nano-fluid flow with different nano concentration in numerical mode. The nano particle used in this research is CuO, Al_2O_3, Ti_2O and water base fluid. Result showed that by increasing nano concentration, heat transfer and shear stress of wall will increase. For a constant volume concentration and Reynolds number, the effect of CuO nanoparticles to enhance the Nusselt number was better than Al_2O_3 and TiO_2 nanoparticles.

Sharifi et al. [6] experimentally and numerically analyzed Al_2O_3 nano particle and water base fluid in the pipe. The convective heat transfer in nano-fluid enhanced with increasing of nanoparticle concentration and flow Reynolds number. Increasing of ethylene glycol in the base fluid composition resulted in decreasing of heat transfer coefficient. Haghighi et al. [7] experimentally analyzed turbulent nano-fluid flow in a circular section pipe. In nano-fluid, heat transfer increased up to 15%. Davarnejad et al. [8] in 2012 numerically simulated heat transfer of water and Al_2O_3 by using FLUENT software. The maximum convection heat transfer coefficient was presented in maximum nano concentration and it was concluded that heat transfer coefficient increases with the Peclet number. Akbarnia and behzadmehr [9] fully developed laminar mixed convection of a nano-fluid consisting of water and Al2O3 in a horizontal curved tube numerically. Three-dimensional elliptic governing equations have been used. Simultaneous effects of the buoyancy force, centrifugal force and nanoparticles concentration has been presented and discussed. The nanoparticles volume fraction does not have a direct effect on the secondary flow, axial velocity and the skin friction coefficient.

Heyhat and Kowsari [10] performed a numerical study to analyze the wall shear stress and heat transfer coefficient of Al_2O_3-water nano-fluids under laminar forced convection through a circular pipe. It is assumed that the distribution of nanoparticles in the flow field is nonhomogeneous. The results obtained show that addition of Al_2O_3 nanoparticles to pure water effectively enhances the convective heat transfer. Bianco et al. [11] in 2010 simulated Al_2O_3 nano particle and water base fluid with constant wall temperature. Result showed that convection heat transfer coefficient in nano-fluid is higher in comparison with water base fluid. Ebrahimi and Niazmand [12] numerical simulated laminar flow and heat transfer of water mixture with carbon nanotubes (CNT) as nano-fluids in a 90 degree curved pipe. The results indicated that due to the secondary flows induced by curvature effects, the heat transfer rate is improved, and enhanced remarkably further using nano-fluids. Sajadi and Dizaji [13] in 2012 experimentally analyzed nano-fluid containing Al_2O_3 nano particle and water base fluid. Result showed that by increasing nano concentration, the convection heat transfer coefficient increases up to 12% and the pressure drop of nano-fluid was higher than that of the base fluid and increased with increasing the volume concentration of nanoparticles.

Yarmand et al. [14] numerically investigated the thermal characteristics of turbulent nano-fluid flow in a rectangular pipe. The numerical results indicate that SiO2-water has the highest Nusselt number compared to other nanofluids while it has the lowest heat transfer coefficient due to low thermal conductivity. The Nusselt number increases with the increase of the Reynolds number and the volume fraction of nanoparticles. Tony et al. [15] performed incompressible flow simulation in a square duct featured with 90 bend and curvature radius of 2.3. The solutions for the flow investigated at Reynolds number of Re = 790. The simulated results revealed that centrifugal force convects the quickly moving fluid particles towards the outer wall. The axial velocity, as a result, shows twin peaks and secondary flow in the curved channel.

As shown last researches mostly were about direct pipes we have to study more about analyze of elbow so we analyze 90 and 60 degree elbow in this study. Thus turbulent forced convection of a nano-fluid consisting of water and Al_2O_3 in a horizontal elbow with constant wall temperature has been considered. The single phases are assumed to be interpenetrating meaning that the fluid phase and particles are in thermal equilibrium and move with the same velocity. The average Nusselt number and the skin friction at different nano concentration and Reynolds number are shown and discussed.

2 BOUNDARY CONDITION AND GEOMETRY

Fig. 1 shows the geometry of the considered problem. The computation domain is composed of a 60 and 90 circular elbow with pipe diameter (D) 2.5cm and 2.5 curve radius (R). The physical properties of the fluid and elbow wall temperature are assumed constant. At the pipe inlet profiles, uniform axial velocity v and temperature T_0 = 300 K are assumed. The boundary conditions are reported in table 1.

Table 1 Boundary conditions

Name of B.C	Type of B.C	B.C
inlet	Mass flow inlet	u=w=0, T=300, v
Outlet	Pressure outlet	P=0
Wall	Wall	T=385, u=v=w=0

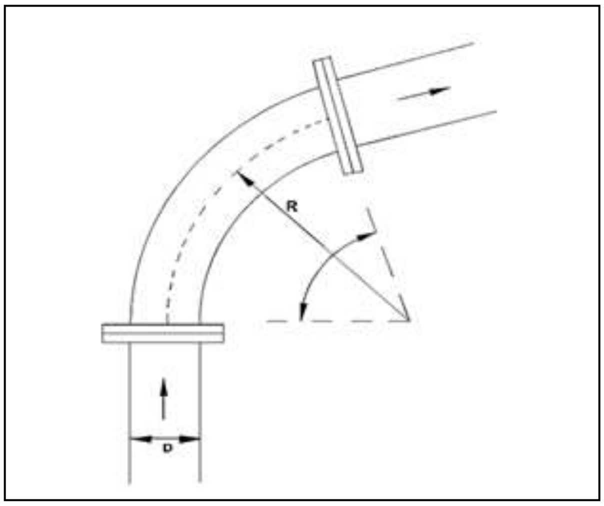

Fig. 1 Schematic diagram of elbow

3 GOVERNING EQUATIONS

Turbulent flow is one of the most complicate kinds of flow. To analyze turbulent flow, Navier stocks equation is used [9]. They are non-linear kind of equation that solving them by analytical method is impossible so numerical method are developed to solve this equation. By using conservation principles, we can extract continuum, momentum and energy equation for convective flow. The equation are as below:

Navier-Stockes equation [16]:

$$-\nabla p + \mu \nabla^2 V + \rho g = 0 \qquad (1)$$

Conservation of mass [16]:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \qquad (2)$$

Momentum equation [16]:

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = \rho g_j - \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_i}\left(\tau_{ij} - \overline{\rho u_i' u_j'}\right) \qquad (3)$$

Energy equation [16]:

$$\frac{\partial(\rho C_p u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i} - \rho C_p \overline{u_i' T}\right) + \mu\varphi \qquad (4)$$

Non dimensional Nusselt equation, Reynolds number and friction coefficient equation are as follows:

Nusselt number [17]:

$$Nu = \frac{q'' D}{K_{eff} \Delta T} \qquad (5)$$

In equation (5) D is pipe diameter, q" is elbow wall heat flux, k_{eff} is effective Heat conductivity.

Reynolds number [17]:

$$\mathrm{Re} = \frac{\rho v d}{\mu} \qquad (6)$$

In equation (6) ρ is density, v is inlet velocity, d is pipe diameter and μ is viscosity.

Surface friction coefficient [16]:

$$f = \frac{8\tau}{\rho v^2} \qquad (7)$$

Where τ is shear stress of elbow wall and v is inlet velocity. The specification of nano-fluid is complex of base fluid and nano particle. The equation of nano-fluid are:

Nano-fluid density [17]:

$$\rho_{nf} = \varphi \rho_p + (1-\varphi)\rho_f \qquad (8)$$

Where ρ_P is density of nano particle, φ is nano concentration and ρ_f is density of base fluid.

Nano-fluid Specific Heat [17]:

$$C_{p_{nf}} = \frac{(1-\varphi)(\rho C_p)_f + \varphi(\rho C_p)_p}{(1-\varphi)\rho_f + \varphi \rho_p} \qquad (9)$$

In above equation $(\rho C_P)_f$ is base fluid specific Heat and $(\rho C_P)_P$ is nano particle specific Heat.

Nano-fluid viscosity [8]:

$$\mu_{nf} = (123\varphi^2 + 7.3\varphi + 1)\mu_f \tag{10}$$

Where μ_f is the base fluid viscosity.

Nano fluid Heat conductivity [8] :

$$k_{nf} = \left(\frac{k_P + 2k_f - 2\varphi(k_f - k_P)}{(k_P + 2k_f + \varphi(k_f - k_P))}\right) k_f \tag{11}$$

k_P is nano particle heat conductivity and k_f is the base fluid conductivity.

4 CFD SIMULATION

We used the FLUENT software to solve the problem. For turbulent flow simulation, standard k-ε model was used. It is an experimental model on the base of transforming equation for kinetic energy k and losses rate ε. The equation of this model is written as [18]:

$$\rho v_j \frac{\partial v_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left(-\rho\overline{v_i v_j}\right) + \rho g_i \tag{12}$$

$$\rho v_j \frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i}\left(-\rho\overline{T' v_i}\right) \tag{13}$$

$-\rho\overline{v_i v_j}$ and $-\rho\overline{T' v_i}$ appear in momentum and energy equation.

$$\rho v_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_i}\right) + \rho P + \rho G - \rho\varepsilon \tag{14}$$

$$\rho v_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_k}\frac{\partial \varepsilon}{\partial x_i}\right) + c_1\frac{\varepsilon}{k}\rho P + c_3\frac{\varepsilon}{k}\rho G - c_3\rho\frac{\varepsilon^2}{k} \tag{15}$$

$$P = \frac{\mu_t}{\rho}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)\frac{\partial v_i}{\partial x_j} \tag{16}$$

$$G = -\beta g \frac{\mu_t}{\rho\sigma_t}\frac{\partial T}{\partial y} \tag{17}$$

The constant parameter of equation is defined as:

$C_{\varepsilon 2} = 1.92$, $\sigma_K = 1.0$, $\sigma_\varepsilon = 1.3$, $C_\mu = 0.09$, $C_{\varepsilon 1} = 1.44$

To relate the velocity and pressure equations, SIMPLE algorithm is used. The first studying of SIMPLE algorithm was done by Patankar and Spalding [19].

5 GRID STUDY

After reaching to convergence in answer, we have to make sure that the answer is not related to solution and the quality of mesh. Usually to grid study, we study several mesh with different number of element. At the present research, we have 3 meshes. The elements of mesh are 150000, 300000 and 500000. If we multiply the mesh by 1.5 (from 300000 to 500000), there is no change in the result. Fig. 2 shows that increasing the grid numbers does not change significantly the Nusselt number at the centerline region of 90º elbow and 1000 Reynolds number. (L*= r/d)

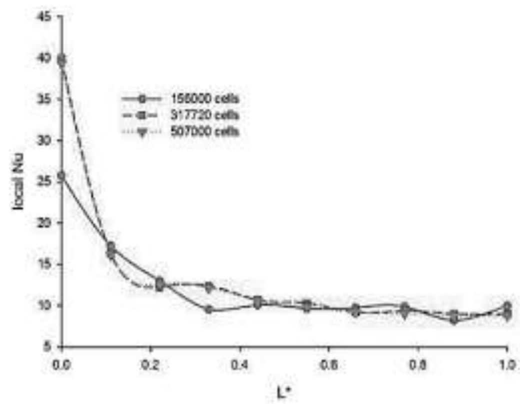

Fig. 2 Grid Study in 90º elbow

6 VALIDATION

To make sure of result, we compare the result of 90º elbow simulation with Ghaffari et al. (2010) [20]. They have analyzed two phase heat transfer of turbulent nano-fluid flow in 180 degree curve pipe and diameter of 28 nm in nano particle. This research is also compared with Patankar et al. [21]. They studied 3D curve pipe with the angle of φ theorically. The flow inside a pipe is hyrodynamically developing. To solve the research, Patankar et al. [21] method was used. Also we compare the result with experimental researches done by Hogg [22]. Hogg (1968) calculated the velocity and temperature profile for air flow. The results showed good agreement with the numerical, theoretical and experimental prediction (Figs. 3 and 4).

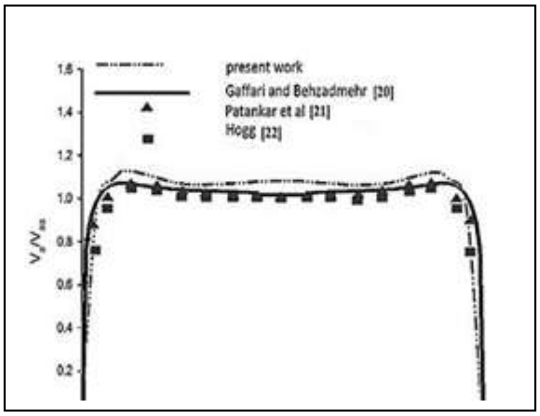

Fig. 3 The comparison of dimensionless axial velocity in vertical plane

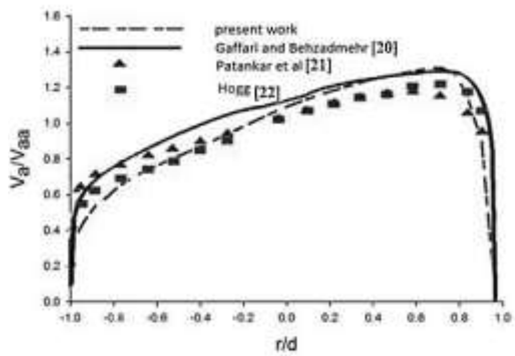

Fig. 4 The comparison of dimensionless axial velocity in horizontal plane

7 RESULT AND DISCUSSIOM

Simulation in Reynolds 10000, 30000, 45000, 70000 and 80000 for nano concentration of 0%, 1%, 3%, 4% Al_2O_3 was done. Figures 5 and 6 show the effect of increasing Reynolds number and nano concentration in 90º and 60º elbow and addition of Al_2O_3 nano particles to pure water effectively enhances convective heat transfer. Nasselt number was calculated by Eq. (5). It will increase due to increasing thermal conductivity, centrifuge force and buoyancy force. The level of heat transfer increase depends on the volume concentration. In base fluid, Nusselt number is minimum and in 4% nano concentration, Nusselt is maximum.

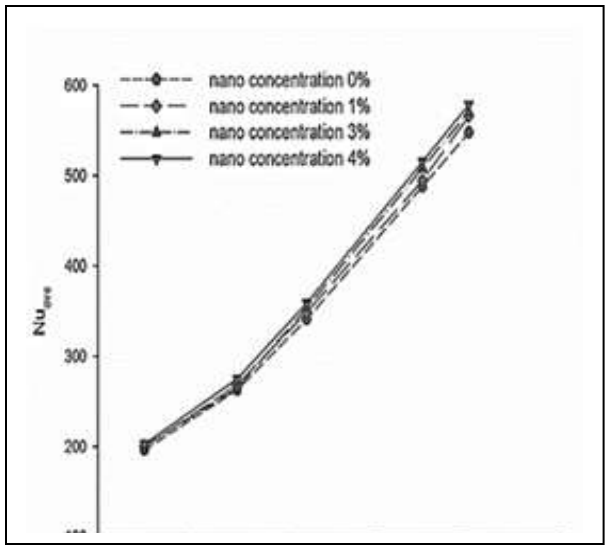

Fig. 5 The effect of increasing nano concentration Al_2O_3 and Reynolds number on heat transfer in 90º degree elbow

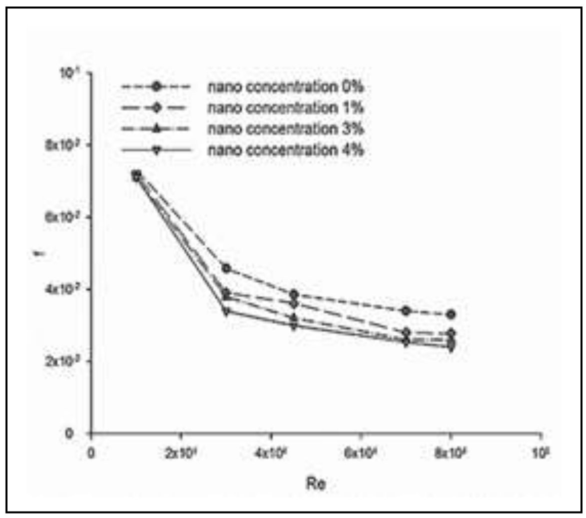

Fig. 6 The effect of increasing nano concentration Al_2O_3 and Reynolds number on Nusselt number in 60ºelbow

Figure 7 compares 90 and 60 elbow. It shows that heat transfer in 90 degree elbow is more than 60 degree elbow. When curve angle increases, heat transfer increase too, because of reverse pressure gradient and separate flow after curve.

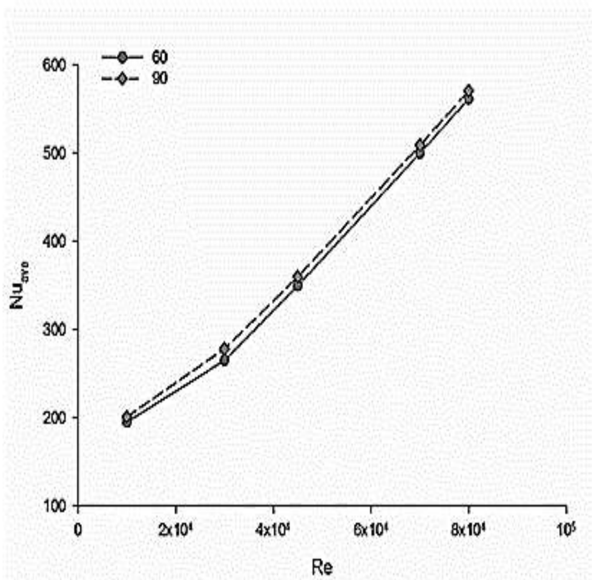

Fig. 7 Comparison the Nusselt number at the 90º and 60º elbow in the nano concentration 3%

In figures 8 and 9, it is shown that friction coefficient decrease by increasing nano concentration and Reynolds number, as it is presented in experimental Petukhov [23] research. As shown in the figures, friction factor in 0% nano concentration or base fluid is maximum and in 4% nano concentration is minimum in different Reynolds number.

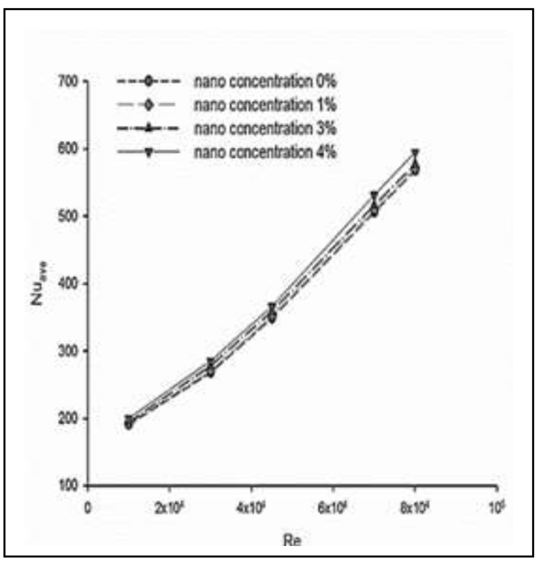

Fig. 8 The effect of increasing nano concentration Al_2O_3 and Reynolds number on surface friction coefficient in 90º elbow

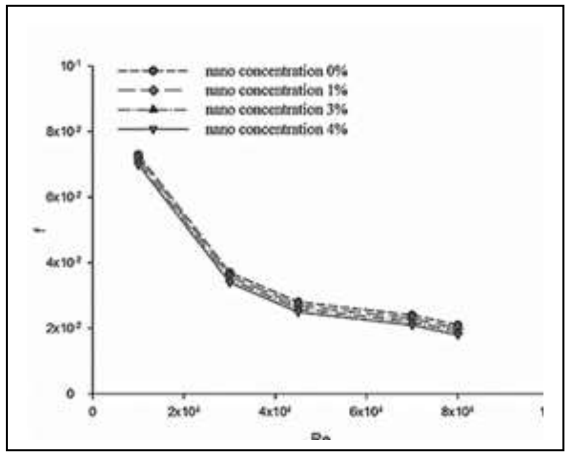

Fig. 9 The comparison of increased nano concentration Al_2O_3 and Reynolds number on surface friction coefficient heat transfer in 60º elbow.

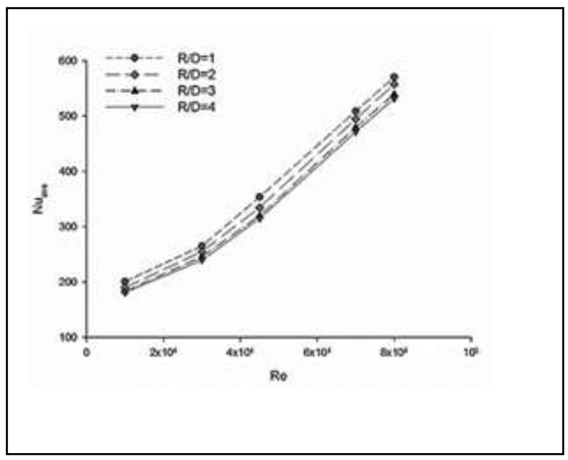

Fig. 10 The effect of R / D on heat transfer in 90° elbow

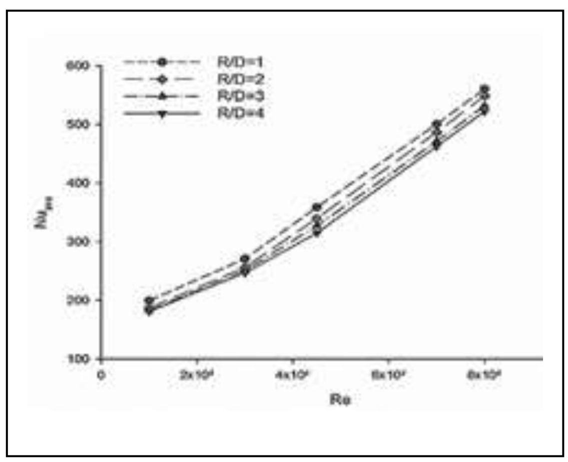

Fig. 11 The effect of R / D on heat transfer in 60° elbow

Figures 10 and 11 show that Nusselt number decrease by increasing curve radius because of increasing buoyancy and centrifuge force. In R/D=4, Nusselt number is minimum and in R/D=1, Nusselt is maximum.

8 CONCLUSION

Convection heat transfer of nano fluid in 90 and 60 degree elbow is simulated in the FLUENT software. The model of nano fluid heat transfer simulation is one phase. The nano particle is Al_2O_3 and the base fluid is water. Nano concentration is 0%, 1%, 3% and 4%. The effect of Reynolds number and nano concentration on Nusselt number and friction coefficient have been analyzed. The results show that Reynolds number and nano concentration have direct effect on heat transfer and reverse effect on friction coefficient. Analyze shows that by increasing curve radius (R), Nusselt number decreases. Also by increasing curve angle, Nusselt increase.

Nomenclature

Specific Heat	C_P
Pipe diameter	D,d
Surface friction coefficient	f
Gravity acceleration	g
Heat conductivity	K
Nusselt number	Nu
Pressure	P
Elbow radius	R,r
Temperature	T
Velocity	u,v,w

Greek symbols

Nano concentration	φ
Viscosity	μ
Density	ρ
Shear stress	τ

Subscripts

Average	ave
Effective	eff
Fluid	f
Nano fluid	nf
Nano particle	P

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