The Nanofluid Flow and Heat Transfer in a Circular Duct: Swirl and Side Mass Injection Impact

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Abstract-In the present research work, the analysis of the flow geometry and the conjugate heat transfer of nanofluids in a circular duct using CuO-Water, Al_2O_3-Water and TiO_2-Water respectively have been conducted numerically. The study investigates the influence of swirl and side mass injection on the flow dynamics and heat transfer characteristics of nanofluids in a circular duct. The fluid flow is assumed to be steady, axi-symmetric laminar and incompressible with no chemical reaction. A constant inlet temperature and constant wall temperature have been adopted and a swirl is imparted at the inlet. Also side mass injection effect has also been investigated. The friction factors, overall heat transfer coefficient along with the Nusselt number variation have been estimated. The detail velocity field, has been found, validated and presented for a particular Reynolds number and particle volume fraction of the nanoparticles considered. The most important achievement is the enhancement of the overall heat transfer coefficient and Nusselt number indicating those parameter increases with the increase in swirl.

Keywords: heattransfer,circular duct, nanofluid, particle, volume fraction, swirl, side mass injection.

NOMENCLATURE

List of symbols

C_p	Specific Heat at Constant Pressure (J/Kg-K)
D_h	Hydraulic Diameter (m)
h	Heat Transfer Coefficient (J/K-m^2)
K	Thermal conductivity (J/m-K)
Nu	Nusselt Number(dimensionless)
P	Pressure (N/m^2)
Re	Reynolds Number (dimensionless)
T_w	Temperature at wall (K)
T_{nf}	Temperature of nanofluid (K)
U,V,W	Velocity along x, r and tangential direction respectively (m/s)

Greek Symbols

θ	Dimensionless Temperature (dimensionless)
μ	Coefficient of viscosity
ρ_{nf}	Density of nanofluid (Kg/m^3)
ρ_s	Density of nanoparticles (Kg/ m^3)
φ	Particle volume fraction of nanofluid (%)

Subscripts

nf	Nanofluid
s	Nanoparticles
w	Water

1. INTRODUCTION

The nano fluid flow and heat transfer research has got attention recently and it has got strong momentum because it is emerging and new topic in fluid flow and heat transfer having higher heat removal property. Several studies have established the benefits of using nanofluids for heat transfer applications. Choi and Eastman [1] first introduced the concept, demonstrating enhanced thermal conductivity in nanoparticle suspensions. Experimental and numerical investigations have confirmed that nanofluids significantly improve heat transfer performance in various systems, including circular ducts, heat exchangers, and cooling channels by Kakac and Pramuanjaroenkij [2]. Numerical investigations are performed by Sadeghi et al. [3] using finite volume method to study laminar convective heat transfer and nanofluids flows through a circular tube fitted with helical tape insert. The wall of tube was subjected to a uniform heat flux boundary condition. Vasefi and Alizadeh [4] numerically investigatedCuo-Waternanofluid in different geometries by two-phase Euler-Lagrange method. They have thoroughly estimated the velocity field and found that with increase in percentage of nano particle the heat transfer rate increases as the overall heat transfer coefficient increases. Bouhalleb and Abbassi [5] also estimated numericallythe heat transfer rate using CuO–Water nanofluid in rectangular geometries. Irmawati and Mohammed [6] later analysed mixed convective heat transfer in water-Based Al_2O_3 nanofluid in horizontal rectangular duct. Ziaei-Rad and Elyasi [7] considered laminar pulsating nanofluid flow and heattransfer in a rectangular channel. They considered sinusoidal inlet flow and their results are very much useful in pulsating nano fluid flow. Barad and Makwana [8] performed numerical experimentation considering single phase and estimated the heat transfer rate in rectangular micro channel using nanofluids as acooling liquid. The most important findings of all of the researchers are that the heat transfer rate in enhanced since by increasing percentage of nano fluid particle the overall heat transfer coefficient increases. Present authors are motivated to do research on nanofluid anticipating the fact that such an analysis would be useful in heat exchanger design and development and industrial applications from the point of view of inlet swirl and side mass injection.

2. MATHEMATICAL FORMULATION

2.1 Problem Description

In the figure 1 the schematic geometry of the physical problem has been described. The inlet flow is uniform with constant velocity U_{in}. The walls are fixed and impermeable and a no-slip condition is valid there. The length to diameter is sufficient to consider a fully developed flow at the outlet. The wall thermal conditions are considered as constant heat wall temperature. The governingequations in cylindrical co-ordinate are given below.

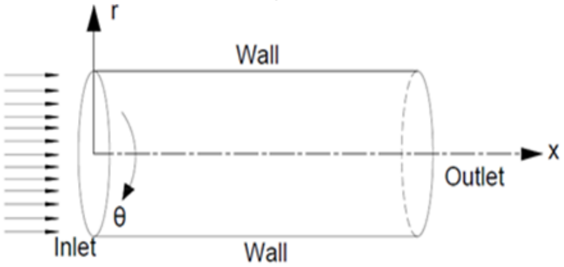

Fig. 1,The physical geometry of the circular duct

2.2 Governing Equations

Continuity Equation:

$$\frac{\partial U}{\partial x}+\frac{V}{r}+\frac{\partial V}{\partial r}=0$$

X-Momentum Equation:

$$U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial r}=-\frac{1}{\rho_{nf}}\frac{\partial P}{\partial x}+\frac{\mu_{nf}}{\rho}\left[\frac{\partial^2 U}{\partial x^2}+\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial U}{\partial r}\right)\right]$$

r-Momentum Equation:

$$U\frac{\partial V}{\partial x}-\frac{W^2}{r}+V\frac{\partial V}{\partial r}=-\frac{1}{\rho_{nf}}\frac{\partial P}{\partial r}+\frac{\mu_{nf}}{\rho}\left[\frac{\partial^2 V}{\partial x^2}+\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(rV)}{\partial r}\right)\right]$$

Azimuthal-Momentum Equation:

$$U\frac{\partial W}{\partial x}+V\frac{\partial W}{\partial r}+\frac{VW}{r}=\frac{\mu_{nf}}{\rho}\left[\frac{\partial^2 W}{\partial x^2}+\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(rW)}{\partial r}\right)\right]$$

Energy Equation:

$$U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial r}=\alpha_{nf}\left[\frac{\partial^2 T}{\partial x^2}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right]$$

2.3 Mathematical Modelling

Nanofluids of CuO, Al_2O_3 and TiO_2 nanoparticleswith 10% volume fractions in distilled water were used to study heat transfer characteristics in laminar flow.

The density of a nanofluid

$$\rho_{nf}=\varphi.\rho_s+(1-\varphi)\rho_w$$

Viscosity of the nanofluid

$$\mu_{nf}=\mu_w.(1+2.5\varphi)$$

The equation of specific heat of the nanofluid

$$C_{p_{nf}}=\frac{\varphi.\left(\rho_s.C_{p_s}\right)+(1-\varphi).\left(\rho_w.C_{p_w}\right)}{\rho_{nf}}$$

Effective thermal conductivity of the nanofluid

$$k_{nf}=\left[\frac{k_s+2k_w+2(k_s-k_w)(1+\beta)^3\varphi}{k_s+2k_w-(k_s-k_w)(1+\beta)^3\varphi}\right]k_w$$

Convective heat transfer coefficient

$$h_{nf}=\frac{q}{(T_W-T_b)_{nf}}$$

Where$(T_w-T_b)_{nf}$ is the mean temperature difference.

Nusselt Number of the nanofluid

$$\overline{Nu_{nf}}=\frac{\overline{h_{nf}}.D_h}{k_{nf}}$$

2.4 Boundary Conditions

WALLS

U = V = W = 0, $T=T_W$

INLET

U =Uin, V=0, W=Win, T=Tin

EXIT

$\frac{\partial(\phi)}{\partial x}=0$, (Fully developed condition),

Where $\phi=f(U,V,W,T)$ etc.

The dimensionless forms are interpreted as follows:

$X = x / D_h$; $R = r / Dh$

$U = u / U_{in}$; $V = v/U_{in}$; $W = w/U_{in}$

$\theta = (T-T_{in}) / (T_{in}- Tw)$

3. SOLUTION METHODOLOGY

The mathematical models described above consist of sets of differential equations subjected to appropriate boundary conditions for their solutions. To provide the algebraic form of the governing equations, a fully staggered grid system have been adopted for the velocity components and the scalar variables and these equations were discretized using a control volume formulation. The numerical solution in the present work is accomplished by using Semi implicit method for pressure linked equation revised (SIMPLER) and the power-law scheme proposed by Patankar [9].

4. RESULTS AND DISCUSSION

Numerical investigation of conjugative heat transfer are performed with CuO-Water for, TiO_2-Water and Al_2O_3 respectively. The axisymmetric geometry with swirl at inlet and injection at the wall has been adopted.Results are presented for a fixed Reynolds number 100 and for different boundary conditions of either inlet swirl or side mass injection with particle volume concentration of 10% respectively.The nanofluids have been considered as a homogenous mixture which enters the duct with uniform temperature and velocity.

4.1 Grid Independent Study and Validation

For the dependability of the inhousecomputer code the grid independence studuy has to be performed. A grid independence study has been performed with two grid sizes 191 x 51 and 91 x 41and it has been found that the results almost collapse on eachotheras shown in figure 2. However to avoid any complexities the higher grid size(191 X 51) is used.Results are presented for Reynolds number Re = 500 and concentration ofnanofluid φ = 0.1%. The results are very good and a pure collapse of the result have been observed.

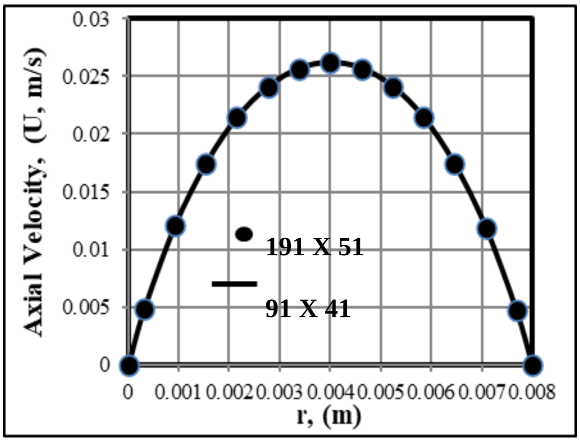

Fig. 2, TheGrid Independent Study

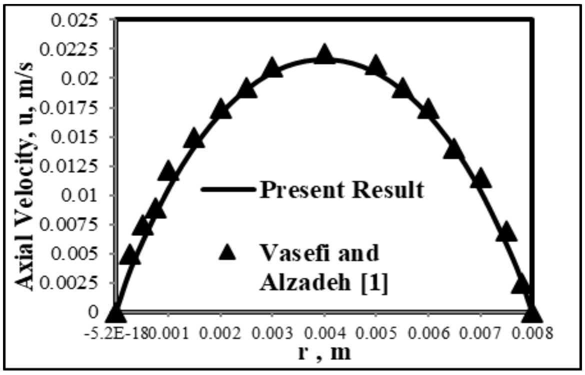

Fig. 3 Validation of Present Study

The validation of the present computer code for conjugative heat transfer in a cylindrical geometry is carried out by comparing present results with the numerical study obtained by I. Vasefi and M. Alizadeh in 2013 [4] shown in Figure 3. It is clear that there is no difference between the present results and the bench mark solution [4].

4.2 SWIRL AND MASS INJECTION EFFECT ON CuO-WATER NANOFLUID FLOW.

The effects of swirl and side mass injection is very much clear from the figures 4(a) to 4(e). From this figures it is revealed that the inlet swirl increases all parameters i.e. the friction facor, the overall heat transfer co-efficient and Nusselt Number respectively. This means if the CuO nanofluid is used alongwith swirl imparted at inlet the heat transfer is enhanced considerably. However the friction factor also increases. But for the case of side mass injection the effect is marginal.

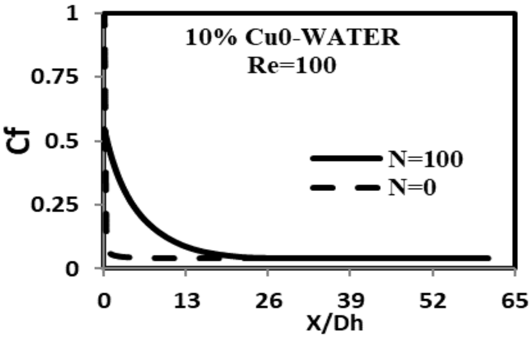

Fig. 4a, Variation of friction factor

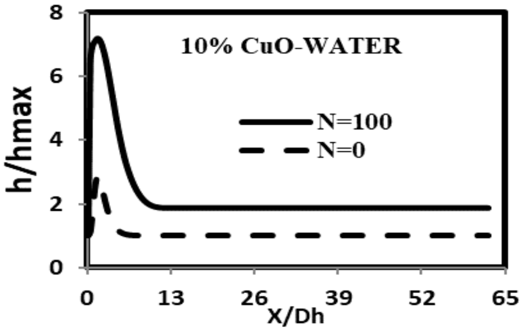

Fig. 4b, Variation of overall heat transfer co-efficient

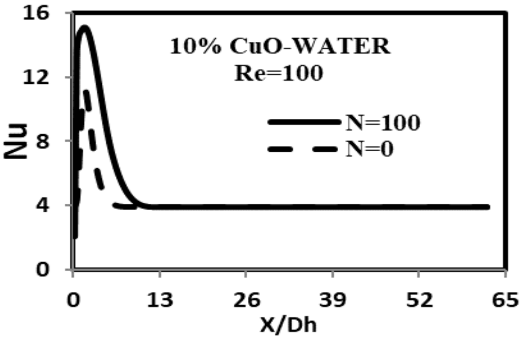

Fig. 4c, Variation of Nusselt number

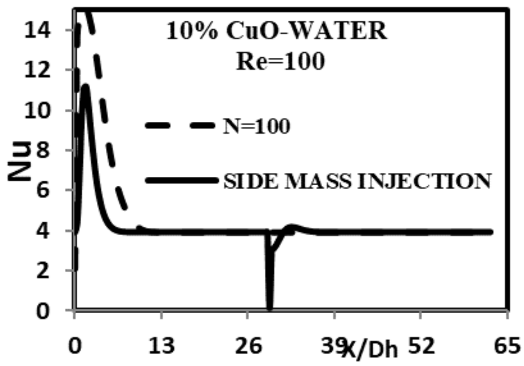

Fig. 4d, Variation of Nusselt number for side mass injection.

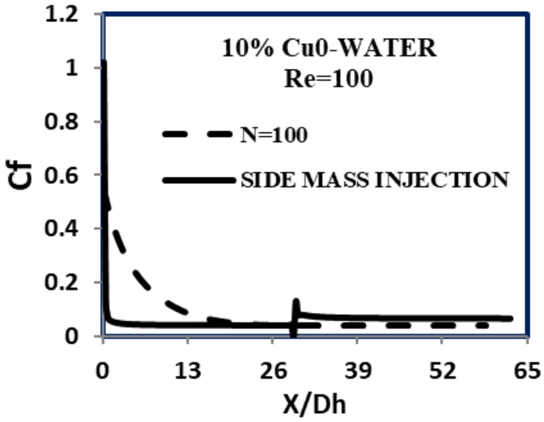

Fig. 4e, Variation of friction factor for side mass injection.

The effects of swirl and side mass injection is very much clear from the figures 4(a) to 4(e). From this figure it is revealed that the inlet swirl increases all parameters i.e., the friction factor, the overall heat transfers co-efficient and Nusselt Number respectively. This means if the CuO nanofluid is used along with swirl imparted at inlet the heat transfer is enhanced considerably. However, the friction factor also increases. But for the case of side mass injection the effect is marginal.

4.3 EFFECT OF SWIRL AND SIDE MASS INJECTION ON Al_2O_3-WATER NANOFLUID FLOW.

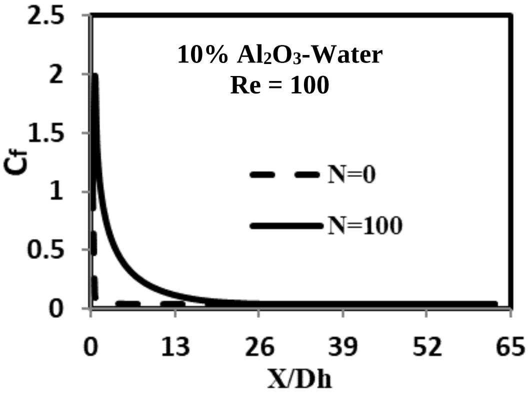

Fig. 5a, Variation of friction factor

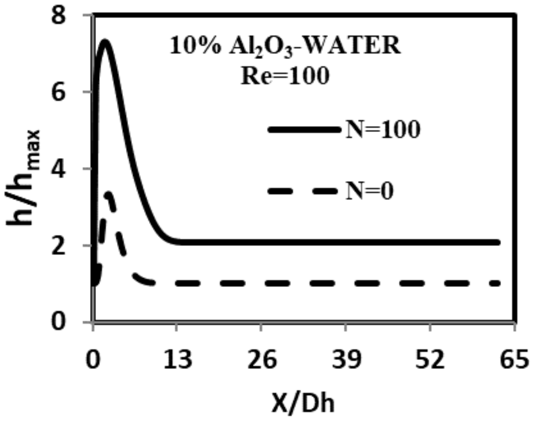

Fig. 5b, Variation of overall heat transfer co-efficient

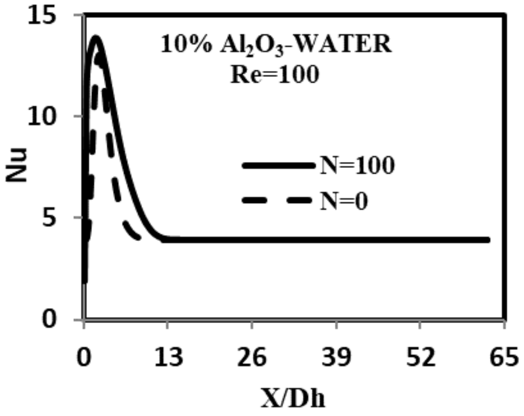

Fig. 5c, Variation of Nusselt number.

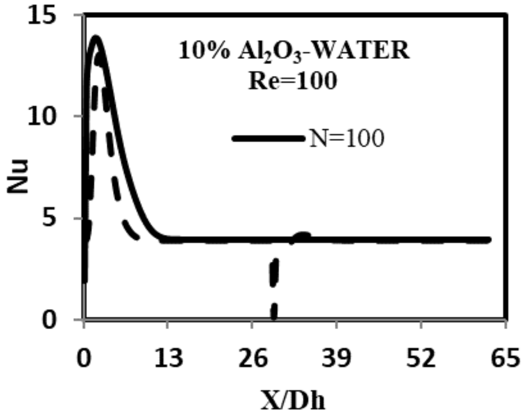

Fig. 5d, Variation of Nusselt number for side mass injection

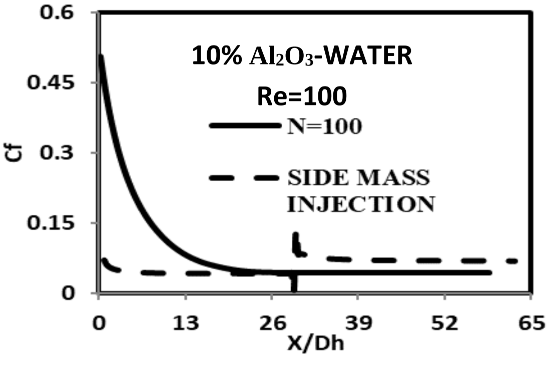

Fig. 5e, Variation of friction factor for side mass injection

The effect of swirl and side mass injection on Al_2O_3 Nanofluid flow is depicted in the figures 5(a) to 5(e) very clearly. The swirl is imparted at the inlet while the side mass injection site is middle wof the axial length with some stretch of 0.004 m. The inlet fluid temperature is kept constant as 293 K, while the wall temperature is kept constant as 323 K respectively. Other parameters and boundary conditions are same as earlier. Here also we can observe that the Nusselt number and overall heat transfer coefficient increases with the impartation of the swirl at the inlet. However the variations are similar to the earlier case. But the side injection of mass shows moderate decrease in those variables. Actually the energy intake for thid case is little higher since the side injected mass also carries some thermal energy. The friction factor has been found to be drooping in nature in this case which is very obvious for this case.

4.4 EFFECT OF SWIRL AND SIDE MASS INJECTION ON TiO_2-WATER NANOFLUID FLOW

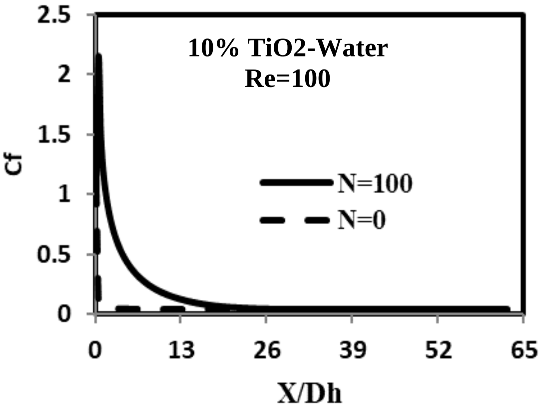

Fig. 6a, Variation of friction factor

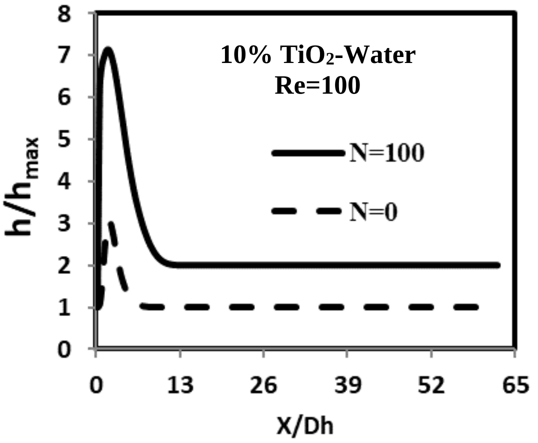

Fig. 6b, Variation of overall heat transfer co-efficient

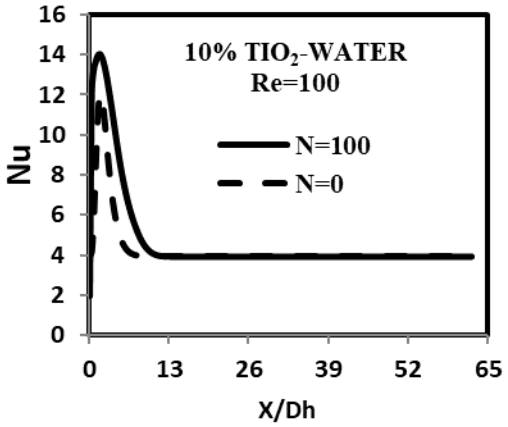

Fig. 6c, Variation of Nusselt number

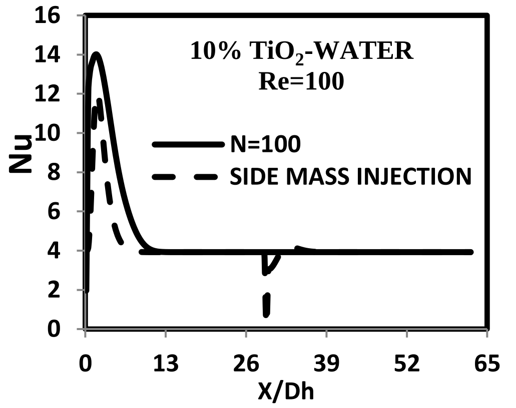

Fig. 6d, Variation of Nusselt number for side mass injection

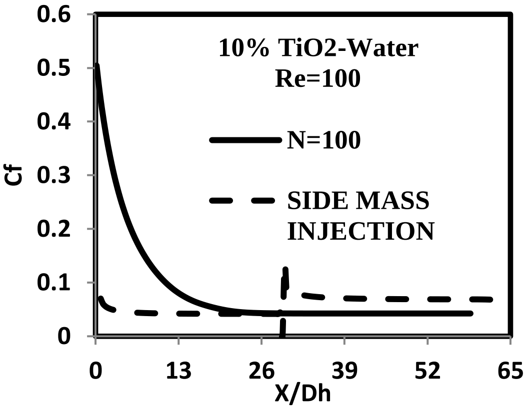

Fig. 6e, Variation of friction factor for side mass injection

The boundary conditions particularly the swirl imparted at inlet and the side mass injection is same for this case also. The solution obtained shows that there are similar effects of swirl and side mass injection on the friction factor, overall heat transfer coefficient and the nusselt number. Actually the 10 % nano particles for all of the solids have been constant so the viscosity is constant for all of them. However the thermal conductivity, density, Prandtl number etc. changes with the change in solid. So he results are found that the swirl imparted increases the heat taransfer coefficient for the TiO_2-water nanofluid. Also the Nusselt number also increases with the impatition of the swirl at the inlet. The friction factor increases as expected likewise the other two cases. The side mass injection has significant effects particularly at the site of the side mass injection where we can see that there is a drooping nature of overall heat transfer coefficient, Nusselt number and the coefficient of friction respectively. All of this phenomena is due to the side mass injection which causes and addition of not only the mass but also the thermal energy some extent.

5 CONCLUSIONS

The effect of the swirl imparted at the inlet and the side mass injection for the different nanofluids of CuO-water, Al_2O_3-water and TiO_2-water have been estimated.It has been found that the swirl has significant effect on heat transfer and friction aspects. The heat removal rate increase due to the impartation of the swirl, but consequently the flow resistance also increases. An optimisation particularly keeping the objective of heat removal for industrial applications is required with this opposing phenomena. The side mass injection causes the changes mainly proximity to the side mass injection otherwise.

REFERENCE

[1] Choi and Eastman, 1995, “Enhancing Thermal Conductivity of Fluidswith Nanoparticles”, Energy Technology Division and Materials Science Division, Argonne National Laboratory, Argonne.

[2] Kakaç, S. and Pramuanjaroenkij, A., 2009, “Review of Convective Heat Transfer Enhancement with Nanofluids”, International Journal of Heat and Mass Transfer, 52, pp. 3187-3196.

[3] Sadeghi, O., Mohammed, H. A., Bakhtiari-Nejad, M and Wahid, M.A., 2016, “Heat transfer and nanofluid flow characteristics through a circular tube fitted with helical tape inserts”, International Communications in Heat and Mass Transfer, 71, pp. 234-244.

[4] Vasefi, I. and Alizadeh, M., 2013, “A Numerical Investigation of Cuo-Water Nanofluid in Different Geometries by Two-Phase Euler-Lagrange Method”,World Applied Sciences Journal,26 (10): 1323-1329.

[5] Bouhalleb, M. and Abbassi, H., 2016, “Numerical Investigation of Heat Transfer by CuO–Water Nanofluid in Rectangular Enclosures”, Heat Transfer Engineering, 37(1):13–23, DOI: 10.1080/01457632.2015.1025003.

[6] Irmawati, N. and Mohammed, H.A., 2014, “Mixed Convective Heat Transfer in Water-Based Al_2O_3 Nanofluid in Horizontal Rectangular Duct”, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, Vol:8, No:12.

[7] Ziaei-Rad, M. and Elyasi, P., 2013 “Investigation of Laminar Pulsating Nanofluid Flow and HeatTransfer in a Rectangular Channel”, Journal of Nanostructures, 3, 289-301.

[8] Barad, V.S. and Makwana, N.M., 2014, “Numerical Investigation of Single Phase Fluid Flow and HeatTransfer In Rectangular Micro Channel Using Nanofluids as A Cooling Liquid”, Int. Journal of Engineering Research and Applications, Vol. 4, pp.133-137.

[9]Patankar, S.V., 1980, “*Numerical Heat Transfer and Fluid Flow*”, Hemisphere Publishing Corporation, New York, USA.