Trans. Phenom. Nano Micro Scales, 4(2): 9-16, Winter and Spring 2016
7508/tpnms.2016.02.002

ORIGINAL RESEARCH PAPER

Effect of Inserting Coiled Wires in Tubes on the Fluid Flow and Heat Transfer Performance of Nanofluids

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Received 4 April 2015; revised 21 May 2015; accepted 25 May 2015; available online 28 June 2016

ABSTRACT: In the present study, numerical study of Al_2O_3-water nanofluid flow in different coiled wire inserted tubes are performed to investigate the effects of inserting coiled wires in tubes on the fluid dynamic and heat transfer performance ofv nanofluids. The numerical simulations of nanofluids are performed using two phase mixture model. The flow regime and the wall boundary conditions are assumed to be laminar and constant heat flux respectively. The effects of inserting coiled wires in tubes on different parameters such as heat transfer coefficient, pressure drop, temperature distribution, velocity distribution and secondary flows are presented and discussed. The results show that using coiled wire in tubes leading to increase in $\bar{h}$ about 13.44% but increase the Δp about 14.66% with respect to the flow without nanofluid and coiled wire. Similarly, using nanofluid leading to increase in $\bar{h}$ about 5.52% but increase the Δp about 8.92%. Finally, using both of the mentioned heat transfer enhancement mechanisms leading to increase in $\bar{h}$ about 17.51% but increase the value of Δp about 22.86%.

KEYWORDS*: CFD; Coiled wires*; *Mixture model; Nanofluid; Two phase model*

Introduction

Heat Transfer Enhancement (HTE) in the tubes used in various industrial applications and consequently reducing the volume of industrial equipment is a subject that has been investigated by engineers and researchers for many years. In general, the heat transfer enhancing methods can be divided into active and passive approaches; which the passive method, due to its ease of use and lower cost, has greatly attracted the attention of the researchers and engineers. An important and useful way of passively enhancing the amount of heat transfer in tubes is the use of a nanofluid instead of base fluid. A nanofluid refers to a compound in which solid, and mostly metallic, particles at nano sizes (usually less than 100 *nm*) are added to an ordinary fluid and help increase the value of the mixture conductivity and thus improve the amount of heat transfer in that fluid. Due to a considerable enhancement of heat transfer and a negligible pressure drop achieved by nanofluids, relative to base fluids, the use of nanofluids has become very commonplace in recent years [1-7]. Das et al. [1] experimentally investigated the effects of different parameters (e.g., temperature, nanoparticle volume fraction, etc.) on the thermal conductivity of nanofluids. They ultimately presented a relation for thermal conductivity of nanofluids as a function of temperature, nanoparticle volume fraction, etc.

In addition to costly experimental studies, the numerical simulation of nanofluids using Computational Fluid Dynamics (CFD) techniques is another effective approach in analyzing the performance of nanofluids [4, 5]. In general, for the numerical simulation of nanofluids, there are two methods called the single-phase and two-phase, with the two-phase method being much more exact [6]. The two-phase method itself has different categories, including the Eulerian-Eulerian method, mixture method, etc. Using the three methods of two-phase Eulerian-Eulerian, two-phase mixture, and single-phase homogeneous, Lotfi et al. [7] simulated the Al_2O_3-water nanofluid flow in circular tubes. By comparing the simulation results with the experimental data, they came to the conclusion that the two-phase mixture method is the most exact method among the existing approaches. In this article also, the two-phase mixture method is used for the numerical simulation of nanofluid flow in coiled wire inserted tubes.

The other method to enhance the heat transfer value is using tube inserts like twisted tapes, brushes, and coiled wires. Due to low cost and their capability for easy installing or removing inside the tubes (for cleaning purposes), the coiled wire inserts usage is growing [8]. Some researchers have studied heat transfer and pressure drop during forced convection in tubes with inserts. Salimpour and Gholami [8] used coiled wires to augment heat transfer coefficient in condensation of R-404A vapor. Kumar et al. [9] studied heat transfer enhancement during

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Tel.: +988632625726; Note. This manuscript was submitted on April 4, 2015; approved on May 21, 2015; published online June 28, 2016.

	Nomenclature
a	Acceleration (m s^{-2})
C_p	Specific heat (J kg^{-1} K^{-1})
C_f	Skin friction coefficient
C	Constant in Eq. (14)
d	Coil diameter (m)
D	Tube diameter (m)
d_p	Diameter of nanoparticles (m)
g	Gravitational acceleration (m s^{-2})
h	Local heat transfer coefficient (W/m^2K)
Gr	Grashof number ($=g\beta_m q'' D_h^4/k_m \nu_m^2$)
k	Thermal conductivity (W m^{-1} K^{-1})
k_B	Boltzmann constant ($=1.3807 \times 10^{-23}$ J K^{-1})
L	Length of tubes (m)
Nu	Nusselt Number ($=hD_h/k$)
p	Coil pitch (m)
Pr	Prandtl number ($=\alpha_m/\nu_m$)
	Heat flux (W m^{-2})
Re	Reynolds number ($=VD_h/\nu_m$)
T	Temperature (K)
	Greek Symbols
β	thermal expansion coefficient (K^{-1})
ε	porosity
η	similarity variable
λ	transverse curvature $\left(= 2\xi/\mathrm{Re}_x^{1/2}\right)$
ζ	dimensionlessstreamwise coordinate $(= x/r_o)$
θ	dimensionless temperature
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2s^{-1})
ρ	Density (kg m^{-3})
σ	electric conductivity $[s^3\ A^2\ m^{-2}\ kg^{-1}]$
φ	nanoparticle volume fraction
ψ	streamline function $\left(= r_o(\nu_f u_\infty x)^{1/2} f(\xi,\eta)\right)$
	Subscripts
BF	Base fluid
dr	Drift
f	Fluid
i	Inlet conditions

Condensation of R-22 inside a horizontal twisted tape inserted tube. Hejazi et al. [10] studied the condensation of R-134a in horizontal tubes equipped with twisted tapes and developed a new correlation for prediction of pressure drop. Salimpour and Yarmohammadi [11, 12] reported both enhanced heat transfer and increased pressure drop of twisted tape inserted tubes during condensation of R-404A, experimentally. They observed that the insertion of twisted tape inside horizontal tubes increases the condensing pressure drop up to 239% compared to plain tubes on a nominal area basis. Agrawal et al. [13] used coiled wires to augment heat transfer coefficient in condensation of R-22 vapor. Akhavan-Behabadi et al. [14, 15] performed two experimental studies on heat transfer enhancement and pressure drop increase of R-134a condensation inside horizontal tubes with spring inserts. They observed that the insertion of helically coiled wires inside horizontal tubes augments the pressure loss from 260% to 1600% compared to the plain tube values.

Eiamsa-ard and Kiatkittipong [16] performed an experimental and numerical study to investigate the effect of using multiple twisted tapes with different configuration on the heat transfer and fluid flow of TiO_2-water nanofluid. Despite the large amount of research devoted to the effect of tube inserts on the nanofluid flow and two-phase flow (boiling and condensation), it is noted that there is not a research which investigate the details of fluid flow and heat transfer performance of nanofluids in coiled wire inserted tubes using CFD study. In the present study, numerical study of Al_2O_3-water nanofluid flow in different coiled wire inserted tubes are performed to investigate the effects of inserting coiled wires in tubes on the fluid dynamic and heat transfer performance of nanofluids.

Mathematical modelling

Geometry

The geometry of present simulations contains different coiled wire inserted tubes with different coil and pitch diameter. The schematic of a coiled wire inserted tube is shown in Figure 1.

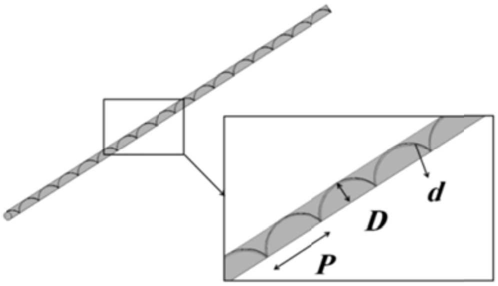


Fig. 1. The schematic geometry of considered problem

Mixture model

In the present study, numerical study of nanofluid flow is performed using mixture model which is a single fluid two phase approach. This method investigates equilibrium over spatial length scales. In this method each phase has its own velocity field, and in a given control volume there is a certain fraction of base fluid and nanoparticles. Instead of utilizing the governing equations of each phase separately, it solves the continuity, momentum and energy equations for the mixture, and the volume fraction equation for nanoparticles.

The equations for the steady state conditions and mean flow are:

- Continuity:

$$\nabla.(\rho_m V_m)=0 \tag{1}$$

- Momentum:

$$\nabla.(\rho_m V_m V_m)=-\nabla P+\nabla.(\mu_m \nabla V_m)+\nabla.\left(\sum_{k=1}^{n}\varphi_k \rho_k V_{dr,k} V_{dr,k}\right)-\rho_{m,i}\beta_m g(T-T_i) \tag{2}$$

- Energy:

$$\nabla.\left(\sum_{k=1}^{n}\phi_k V_k(\rho_k H_k+P)\right)=\nabla.(k_m \nabla T) \tag{3}$$

- Volume fraction:

$$\nabla.(\phi_P \rho_P V_m)=-\nabla.(\phi_P \rho_P V_{dr,P}) \tag{4}$$

Where V_m is the mass average velocity:

$$V_m=\frac{\sum_{k=1}^{n}\phi_k \rho_k V_k}{\rho_m} \tag{5}$$

In equation 2, $V_{dr,k}$ is the drift velocity for nanoparticles:

$$V_{dr,k}=V_k-V_m \tag{6}$$

The slip velocity (relative velocity) is calculated as the velocity of nanoparticles relative to the velocity of base fluid:

$$V_{pf}=V_p-V_f \tag{7}$$

The relation between drift velocity and relative velocity is as follows:

$$V_{dr,p}=V_{pf}-\sum_{k=1}^{n}\frac{\phi_k \rho_k}{\rho_m}V_{fk} \tag{8}$$

The relative velocity and drag function are calculated using Manninen et al. [17] and Schiller and Naumann [18] relations respectively, as follows:

$$V_{pf}=\frac{\rho_P d_P^2}{18\mu_f f_{drag}}\frac{(\rho_P-\rho_m)}{\rho_P}a \tag{9}$$

$$f_{drag}=\begin{cases}1+0.15\,Re_P^{0.687} & for \quad Re_P\le 1000\\ 0.0183\,Re_P & for \quad Re_P>1000\end{cases} \tag{10}$$

The acceleration (a) in equation 9 is

$$a=g-(V_m.\nabla)V_m \tag{11}$$

Nanofluid mixture properties

The mixture properties for Al_2O_3-water nanofluid are calculated based on following expressions:

- Density [19]:

$$\rho_m=\phi\rho_p+(1-\phi)\rho_f \tag{12}$$

- Specific heat capacity [20]:

$$(\rho C_p)_m=\phi(\rho C_p)_p+(1-\phi)(\rho C_p)_f \tag{13}$$

- Dynamic viscosity [21]:

$$\mu_m=\mu_f+\frac{\rho_p V_B d_p^2}{72C\delta} \tag{14}$$

Where V_B and δ are the Brownian motion of nanoparticles and the distance between nanoparticles respectively and is calculated from:

$$V_B=\frac{1}{d_p}\sqrt{\frac{18k_B T}{\pi\rho_p d_p}} \tag{15}$$

$$\delta=\sqrt[3]{\frac{\pi}{6\phi}}d_p \tag{16}$$

C in equation 14 is defined as:

$$C=\frac{(C_1 d_p+C_2)\phi+(C_3 d_p+C_4)}{\mu_f} \tag{17}$$

Where C_1, C_2, C_3 and C_4 are given as:

$$\begin{aligned}&C_1=-0.000001133\ ,\ C_2=-0.000002771\\&C_3=0.00000009\ ,\ C_4=-0.000000393\end{aligned} \tag{18}$$

- Thermal conductivity [22]:

$$\frac{k_m}{k_f}=1+64.7\varphi^{0.7460}\left(\frac{d_f}{d_p}\right)^{0.3690}\left(\frac{k_p}{k_f}\right)^{0.7476}\Pr_f^{0.9955}\,\mathrm{Re}_f^{1.2321} \tag{19}$$

Where Re_f and Pr_f can be expressed as:

$$Re_f = \frac{\rho k_B T}{3\pi\eta^2 \lambda_f} \tag{20}$$

$$Pr_f = \frac{\eta}{\rho_f \alpha_f} \tag{21}$$

Where λ_f is the MFP (mean free path) of water molecular (λ_f= 0.17 nm), k_B is Boltzmann constant (k_B= 1.3807 × 10^{-23} J/K) and η can be defined by the following equation:

$$\eta = A.10^{\frac{B}{T-C}}, A = 2.414\times10^{-5}, \\ B = 247.8, C = 140 \tag{22}$$

- Thermal expansion coefficient [23]:

$$\beta_m = \left[\frac{1}{1+\frac{(1-\phi)\rho_f}{\phi\rho_p}} \frac{\beta_p}{\beta_f} + \frac{1}{1+\frac{\phi}{1-\phi}\frac{\rho_p}{\rho_f}} \right] \beta_f \tag{23}$$

Boundary conditions

For numerical simulation, the equations of previous sections should be solved subject to the following boundary conditions:

- Tubes inlet:

$$V_{m,z} = V_i,\ V_{m,x} = V_{m,y} = 0 \tag{24a}$$

$$T = T_i \tag{24b}$$

$$\phi = \phi_i \tag{24c}$$

- Fluid-wall interface:

$$V_{m,x} = V_{m,y} = V_{m,z} = 0 \tag{25a}$$

$$q''_w = -k_m \left.\frac{\partial T}{\partial n}\right|_w \tag{25b}$$

- Tubes outlet: Zero gradient is applied to hydrodynamic variables and constant gradient is applied to temperature [4-5, 24]:

Numerical methods

The numerical study is performed using the finite volume method. A second order upwind method is used for the convective and diffusive terms and the SIMPLE algorithm is employed to solve the coupling between the velocity and pressure fields.

To make sure that the obtained results are independent of the size and the number of generated grids, several grids with different sizes along the axial, radial and angular directions has been tested for each coiled wire inserted tube; and it has been attempted to consider for each tube the best grid, with the highest accuracy and the lowest computation cost.

The investigated tubes contain between 2 and 3 million elements. Figure 2 shows a sample of grid generation for coiled wire inserted tubes.

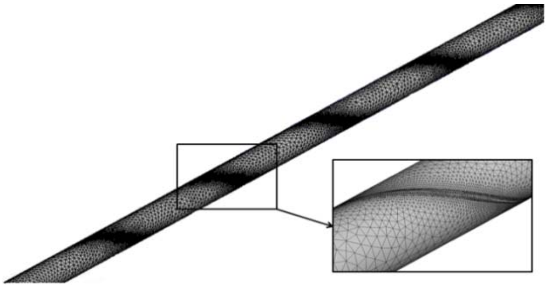


Fig. 2. The schematic geometry of considered problem

Validations

To attain the confidence about the numerical study, it is necessary to compare the results with the available data. Figure 3 compares the local heat transfer coefficient (h) and local friction factor (C_f) for a plain tube without coiled wire of present study with the available data of Mirmasoumi and Behzadmehr [25] and Shariat et al. [26]. As is evident from this figure the present simulations agree well with the available data.

RESULTS

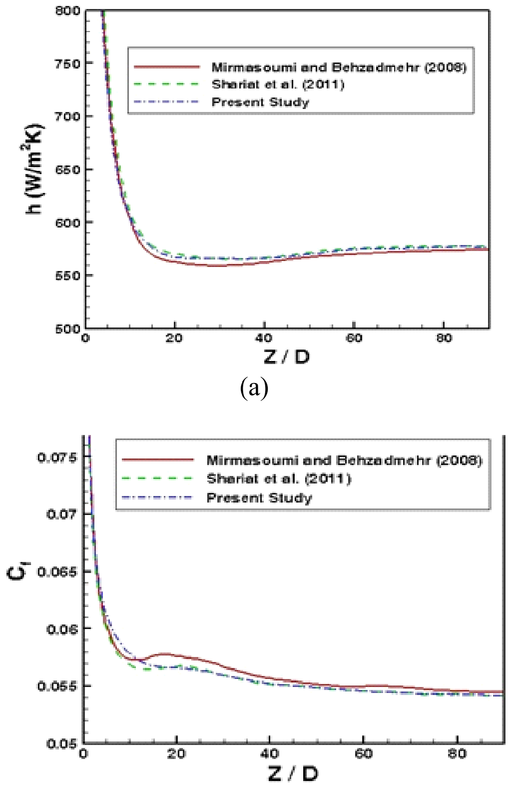
Numerical simulations of Al_2O_3-water nanofluid flow are performed in different coiled wire inserted tubes to investigate the effects of inserting coiled wires in tubes on the fluid dynamic and heat transfer performance of nanofluids.

Effect of different enhancement mechanism

In heat exchangers the heat transfer coefficient and pressure drop are two important parameters and should be investigated simultaneously [5].

Therefore in the result section, heat transfer coefficient and pressure drop values of two different heat transfer enhancement mechanisms namely using nanofluid and using coiled wire in tubes are presented and compared with each other.

As shown in Table 1, using coiled wire in tubes leading to increase in $\bar{h}$ about 13.44% but increase the Δp about 14.66% with respect to the flow without nanofluid and coiled wire (a plain tube working with base fluid). Similarly, using nanofluid leading to increase in $\bar{h}$ about 5.52% but increase the Δp about 8.92%.



(a)

(b)

Fig. 3. Comparison of (a) h and (b) C_f of the present numerical simulation with the available data for a plain tube (Re=300, Gr=90000, d_p=10nm,Φ=2%)

Table 1
Thermophysical properties of the working fluid and the nano particle.

Physical properties	Fluid phase (water)	Nano particle (Cu)
C_p(J/kg K)	4179	385
ρ(kg/m^3)	997.1	8933
κ(W/m K)	0.613	400
$\alpha \times 10^7$(m^2/s)	1.47	1163.1
$\beta \times 10^5$(K^{-1})	21	1.67

Finally, using both of the mentioned mechanisms leading to increase in $\bar{h}$ about 17.51% but increase the value of Δp about 22.86% with respect to the flow without nanofluid and coiled wire. It is obvious from the mentioned data that increase of heat transfer value due to using coiled wire is more than that of using nanofluid and similarly increase of pressure drop due to using nanofluid is less than that of using coiled wire. The reason of this problem is greater mixing of fluid inside tubes due to using coiled wire in tubes.

Effect of coil diameter

Effect of changing $\frac{d}{D}$ on the $\bar{h}$ and Δp, are shown in the first row of Table 2 (definitions of *d*, *D* and *p* are presented in Figure 1). Moreover the detailed effects of changing $\frac{d}{D}$ on the temperature and velocity distributions at the outlet section are shown in Figures 4 and 5 respectively.

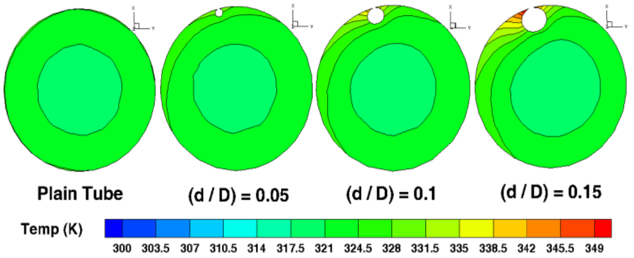


Fig. 4. Effect of changing coil diameter on temperature distribution in nanofluid flow

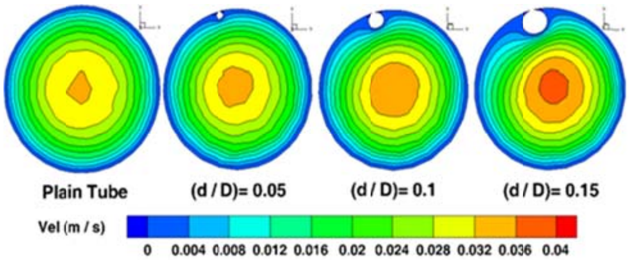


Fig. 5. Effect of changing coil diameter on velocity distribution in nanofluid flow

As shown in the first row of Table 2, increase in $\frac{d}{D}$ from 0.05 to 0.015 leading to increase in $\bar{h}$ about 3.02% but increase the Δp about 7.16%.

It seems that using coiled wire with higher $\frac{d}{D}$ is a good idea for increasing the heat transfer value and the higher pressure drop value of this idea can be compensated with a pressure compensation device such as pump. Moreover it is obvious from Figures 4 and 5 that the maximum value of fluid temperature and fluid velocity is strengthened using greater $\frac{d}{D}$.

Secondary flows or secondary velocity vectors inside a tube play an effective role in the amount of heat transfer in tubes.

The secondary flows are created as a result of the difference between nanofluid densities in the upper and lower regions of the tube [26]. Figure 6 illustrates the effect of changing $\frac{d}{D}$ on the secondary vectors of the nanofluid at the outlet sections of different coiled wire inserted tubes. As it is obvious from this figure, the secondary vectors are strengthened due to using coiled wires with greater $\frac{d}{D}$.

Effect of coil pitch

Effect of changing $\frac{p}{D}$ on the $\bar{h}$ and Δp are shown in the second row of Table 2. Moreover the detailed effects of changing $\frac{p}{D}$ on the temperature and velocity distributions at the outlet section are shown in Figures 7 and 8 respectively.

Table 2
Effect of different parameters on the average heat transfer coefficient and pressure drop.

Effect of Variable	Value	$\bar{h}$(w/m^{2}k)	Changes in $\bar{h}$ (%)	Δp(pa)	Changes in Δp(%)
$\frac{d}{D}$	0.05	544.06	0.00	9.91	0.00
	0.10	550.11	1.11	10.05	1.41
	0.15	560.50	3.02	10.62	7.16
$\frac{p}{D}$	5	550.11	0.00	10.05	0.00
	10	541.25	-1.61	9.83	-2.18
	13	523.78	-4.78	9.51	-5.37
Re	100	477.57	0.00	8.94	0.00
	300	550.11	15.18	10.05	12.41
	500	614.78	28.73	11.35	26.95
$\phi(\%)$	0	489.42	0.00	9.84	0.00
	1.5	550.11	12.40	10.05	2.11
	3	591.32	20.82	10.19	3.52
$d_p(nm)$	20	561.48	0.00	10.09	0.00
	40	550.11	-2.02	10.05	-0.39
	100	525.94	-6.32	10.08	-0.09
Gr	45000	476.25	0.00	10.01	0.00
	90000	550.11	15.50	10.05	0.39
	135000	648.29	36.12	10.11	0.99

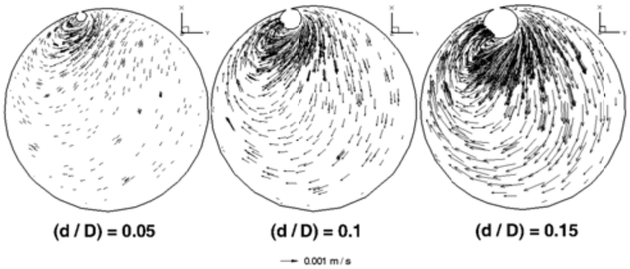


Fig. 6. Effect of changing coil diameter on secondary velocity vectors in nanofluid flow

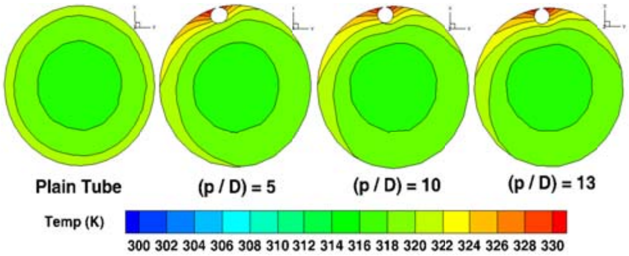


Fig. 7. Effect of changing coil pitch on temperature distribution in nanofluid flow

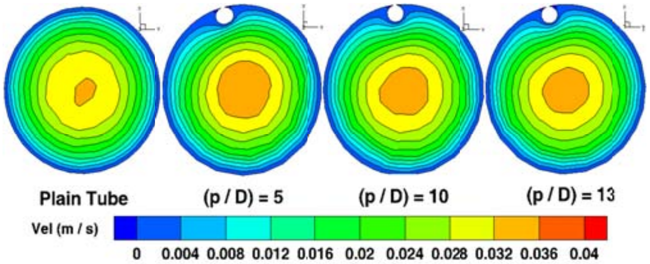


Fig. 8. Effect of changing coil pitch on velocity distribution in nanofluid flow

As shown in the second row of Table 2, increase in $\frac{p}{D}$ from 5 to 13 leading to decrease in $\bar{h}$ about 4.78% but decrease the Δp about 5.37%. It seems that using coiled wire with smaller $\frac{p}{D}$ is a good idea for increasing the heat transfer and the higher pressure drop value of this idea can be compensated with a device such as pump. Moreover it is obvious from Figures 7 and 8 that the maximum value of fluid temperature and fluid velocity does not change due to using coiled wires with different $\frac{p}{D}$. However as shown in Figure 9, the secondary vectors are weakened due to using coiled wires with greater $\frac{p}{D}$. The reason of this problem is smaller mixing of fluid due to using coiled wires with greater $\frac{p}{D}$.

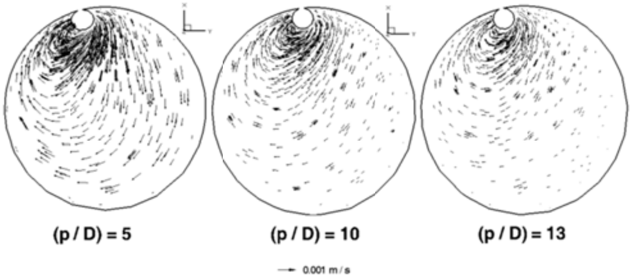


Fig. 9. Effect of changing coil pitch on secondary velocity vectors in nanofluid flow

Conclusion

Al_2O_3-water nanofluid flow in different coiled wire inserted tubes has been numerically studied to investigate the effects of inserting coiled wires in tubes on the fluid dynamic and heat transfer performance of nanofluids. The two phase mixture model and constant heat flux wall boundary condition have been employed in the laminar regime.

The results showed that using coiled wire in tubes leading to increase in $\bar{h}$ about 13.44% but increase the Δp about 14.66% with respect to the flow without nanofluid and coiled wire.

Similarly, using nanofluid leading to increase in $\bar{h}$ about 5.52% but increase the Δp about 8.92%. Finally, using both of the mentioned heat transfer enhancement mechanisms leading to increase in $\bar{h}$ about 17.51% but increase the value of Δp about 22.86%.

Increase of heat transfer value due to using coiled wire is more than that of using nanofluid and similarly increase of pressure drop due to using nanofluid is less than that of using coiled wire. Increasing $\frac{d}{D}$ from 0.05 to 0.015 leading to increase in $\bar{h}$ about 3.02% but increase the Δp about 7.16%.

Increasing $\frac{P}{D}$ from 5 to 13 leading to decrease in $\bar{h}$ about 4.78% but decrease the Δp about 5.37%. Using coiled wire with greater $\frac{d}{D}$ and smaller $\frac{P}{D}$ is a good idea for increasing the heat transfer value and the higher pressure drop value of this idea can be compensated with a pressure compensation device such as pump. The secondary vectors of nanofluid are strengthened due to using coiled wires with greater $\frac{P}{D}$ and smaller $\frac{P}{D}$.

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