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Numerical Comparison of Turbulent Heat Transfer and Flow Characteristics of SiO_2/Water Nanofluid within Helically Corrugated Tubes and Plain Tube

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ABSTRACT

Turbulent heat transfer in Helically Corrugated tubes (HCT) was numerically investigated for pure water and SiO_2 nanofluid using Computational fluid dynamics (CFD). This study was carried out for different corrugating pitches (5, 7, 8 mm) and heights (0.5, 0.75, 1.25 mm) at various Reynolds numbers ranging from 5000 to 13300. The effect of nanoparticles on heat transfer augmentation for plain tube and HCT was considered and the relative Nusselt numbers were also compared. However, the heat transfer extremely increased with increasing the volume fraction of nanoparticles in the plain tube but, the effect of helical corrugation on the heat transfer increment was much more than that of the nanoparticles enhancement in the HCT. It was concluded that the corrugated height increment and the corrugated pitch reduction increase the heat transfer process. The maximum heat transfer was obtained at Reynolds number of 13300, HTC with p=5 mm and e=1.25 mm, and SiO_2 volume fraction of 1%.

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1. INTRODUCTION

Ultrahigh performance cooling is one of the most vital needs of many industrial technologies. Modern nanotechnology can produce metallic or nonmetallic particles of nanometer dimensions. Nanomaterials have unique mechanical, optical, electrical, magnetic, and thermal properties. Hong et al. showed a new class of nanotechnology-based heat transfer fluids with fantastic thermal properties [1]. The goal of nanofluids was to achieve the highest possible thermal properties in the lowest possible concentrations (preferably<1% by volume) by uniform dispersion and stable suspension of nanoparticles (preferably<10 nm) in the host fluids [2].

One of the best techniques for enhancing heat transfer was based on the surface roughness. In fact, it promotes the turbulence near surfaces. Among several roughened tubes, the helical corrugated geometries have been paid much attention. Helical corrugation creates the chaotic flow mixing and reduces the thermal boundary layer thickness. It will increase the heat transfer [3, 4].

The viscosity and specific heat of silicon dioxide (SiO_2) nanoparticles with various diameters (20, 50 and 100 nm) and weight ratio of 60:40 ethylene glycol and water mixture were experimentally investigated by Namburu et al. [5]. They showed a new correlation based on the viscosity with particle volume percentage and nanofluid temperature. They also investigated specific heat of SiO_2 nanofluid for various particle volume concentrations.

Naphon et al. experimentally studied the heat transfer and friction factor in horizontal double pipes using helical ribbed tube [6]. They considered the effects of height and pitch of corrugations on the heat transfer and pressure drop. It concluded that height of corrugation had more significant effect on the heat transfer and pressure drop.

Forced convection of nanofluid in a double-tube counter flow heat exchanger was simulated by Demir et al. [7].

Laohalertdecha and Wongwises studied the effect of corrugation pitch on the condensation heat transfer coefficient and pressure drop of R-134a inside a

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horizontal HCT [8]. According to this research, the corrugation pitch had significant effect on the heat transfer. In fact, it increases with increasing the pitch to diameter ratio. Furthermore, a double-tube coaxial heat exchanger (heated by solar energy) with aluminum oxide nanofluid was experimentally and numerically studied by Luciu et al. [9]. They showed that nanofluids had higher performance of heat transfer than that of the base fluid. Rabienataj Darzi et al. experimentally investigated the effect of nanofluid on turbulent heat transfer and pressure drop inside the concentric tubes [10]. According to that research, the corrugation pitch had a significant effect on the heat transfer. In fact, it increased with increasing the pitch to diameter ratio. Moreover, specified amount of nanoparticles to pure fluid enhanced the heat transfer with a slight pressure drop. In the current research, the effect of various volume concentrations of nanoparticles on the heat transfer in a Helically Corrugated Tube (HCT) was numerically considered. Furthermore, the effect of various helix pitches and heights was investigated. The numerical results were compared and validated with the experimental data obtained from literature [10].

2. MODELING EQUATIONS

The average Nusselt number and friction factor basis of inner diameter of tube can be expressed by:

$$Nu = \frac{\mathrm{hd_i}}{\mathrm{k}} \tag{1}$$

$$f = \frac{\Delta P}{\frac{1}{2}\rho u^2 (\frac{l}{d_i})} \tag{2}$$

where, ρ is density of working fluid, k is thermal conductivity of fluid, Δp is pressure drop along inner tube, l is test section length and h is convective heat transfer coefficient.

The Newton’s law of cooling is given by:

$$Q = hA(T_w - T_f) \tag{3}$$

here, Q is the amount of heat transfer between the wall and the fluid, A is the solid–liquid interface area, T_w is the wall temperature, and T_f is the bulk fluid temperature. h (convective heat transfer coefficient) is defined by:

$$h = \frac{Q_{ave}}{\mathrm{A}\,(T_w - T_b)} \tag{4}$$

where, T_w is the wall temperature and T_b is the bulk temperature (fluid). The average heat flux is calculated as:

$$Q_{ave} = \frac{1}{2}(Q_c + Q_h) \tag{5}$$

Q_c is the heat transferred to cold fluid in inner tube which is calculated as:

$$Q_c = \dot{m}_c C_{cp}(T_{c,out} - T_{c,in}) \tag{6}$$

where, m_c, C_{cp}, $T_{c,in}$ and $T_{c,out}$ are the mass flow rate of cold fluid, specific heat of cold fluid, inlet and outlet cold fluid temperatures, respectively. Q_h is the heat transferred from hot fluid in outer tube:

$$Q_h = \dot{m}_h C_{hp}(T_{h,in} - T_{h,out}) \tag{7}$$

where, m_h, $T_{h,in}$ and $T_{h,out}$ are the hot water mass flow rate, inlet and outlet hot fluid temperatures, respectively. For dilute suspensions (φ<2%), the famous Stokes–Einstein formula for viscosity can be approximated by [11]:

$$\mu_{nf} = \mu_f(1 + 2.5\,\varphi) \tag{8}$$

The density of nanofluid is evaluated using the general formula for the mixtures:

$$\rho_{eff} = (1 - \varphi)\rho_f + \varphi\rho_p \tag{9}$$

and C_p is calculated by Xuan and Roetzel's equation [12]:

$$(\rho C_p)_{eff} = (1 - \varphi))(\rho \mathrm{Cp})_f + \varphi(\rho \mathrm{Cp})_p \tag{10}$$

Maxwell model [13] is applied for the thermal conductivity calculation [Equation (11)]. It was recommended for homogeneous and low volume concentration liquid-solid suspensions with randomly dispersed, uniformly sized and non-interacting spherical particles [14].

$$\frac{K_{nf}}{K_f} = \frac{K_f + K_p + 2\varphi\,(K_p - K_f)}{K_f + K_p - 2\varphi\,(K_p - K_f)} \tag{11}$$

Naphon et al. investigated the effect of height and pitch of corrugation on the Nusselt number and friction factor in various tubes with small diameter [6]. They found a correlation for Nusselt number based on the Reynolds number, Prandtl number, and pitch and height of corrugation as:

$$Nu_a = 44.269({}^{e}/_{d})^{0.89}({}^{p}/_{d})^{-0.96}(Re - 1500)^{0.27}Pr^{-0.26} \tag{12}$$

Nu_a is Nusselt number for HCT. e, p and d are rib-height, helix pitch and internal diameter of tube, respectively. They also found a correlation for Nusselt number in a plain tube as:

$$Nu_f = 1.84(Re - 1500)^{0.32}Pr^{0.07} \tag{13}$$

The friction factor versus Reynolds number in a plain tube and HCT with different pitches and heights of corrugation in nanofluids can be estimated by Equation (2) and would be compared by [12]:

$$f_s = 0.66Re^{-0.33} \tag{14}$$

$$f_a = 7.85(\frac{e}{d})^{1.68}(\frac{p}{d})^{-0.54}Re^{-0.21} \tag{15}$$

where, f_s and f_a are friction factor for the plain tube and HCT, respectively. As the authors mentioned, Equation (15) is not valid for e=0.5 mm and e=0.75 mm.

3. NUMERICAL PROCEDURE AND VALIDATION

The geometry of the case study was drawn in three-dimensional modeling software (version 2012) and then imported in the Gambit (2.4.6). In this case, Tetrahedral /Tgrid mesh was applied and 1265000 meshes were obtained. Figure 1 shows this case geometry. Table 1 shows the geometric specification of tubes.

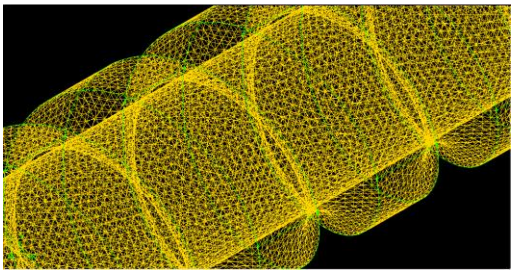


Figure 1. The geometry of helically corrugated tube

TABLE 1. The geometric specification of tubes

	d (mm)	e (mm)	p (mm)	e/d	p/d
1. Plain tube	8.1	-	-	-	-
2. Corrugated tube	8.1	0.5	5	0.0617	0.617
3. Corrugated tube	8.1	0.75	5	0.0926	0.617
4. Corrugated tube	8.1	1.25	5	0.1570	0.617
5. Corrugated tube	8.1	1.25	7	0.1570	0.862
6. Corrugated tube	8.1	1.25	8	0.1570	0.988

The volume concentrations of nanofluids were 0, 0.5 and 1.0% at 25 °C as base temperature. Water was employed as the working fluid. Simulation was carried out with uniform velocity profile at the inlet. Moreover, uniform outlet pressure was assumed at the outlet. A constant heat flux on the wall was chosen. Reynolds number varied from 5000 to 13300 at each step of iterations (as input data). The friction factor and Nu were known as output data. k- Epsilon model was used for turbulence. The main advantages of this simulation are rapid, stable and reasonable results for many flows in especial in high Reynolds numbers [15].

FLUENT software (version 6.3.26) with solver strategy was applied in this research. Gambit software was used to analyze problems. The single phase conservation equations were solved by control volume approach. CFD modeling region can be classified into few major steps including preprocess stage and the geometry of problem constructed as flat narrow and computational mesh generation in Gambit software. It is followed by the physical model which boundary conditions and other parameters were appropriately defined. All scalar data and velocity components were calculated at the center of control volume interfaces where the grid schemes were intensively used. All solutions were converged when their residuals for all governing equations were less than 10^{-6}. The final results were obtained when FLUENT iterations led to the converged data defined by a set of converged criteria.

4. RESULTS AND DISCUSSION

The effect of nanoparticles on heat transfer in a HCT with different pitches of corrugation was investigated. As shown in Figure 2, Nusselt numbers versus various Reynolds numbers were compared with the experimental data illustrated in the literature for a plain tube and HTC (with e=1.25 mm & p=0.5 mm) for pure fluid [10]. Maximum error was 12.1% at Reynolds number of 13300 for HTC while the results for plain tube were in good agreement with the experimental ones. It seems that the heat transfer does not considerably change in the laminar flow while it intensively changes in the turbulent flow. In fact, the helical corrugation (as roughened surfaces) increases the turbulency in special near the wall [16, 17].

Figure 3 shows the effect of nanoparticles on heat transfer in a plain tube. Nanoparticles generally increase the heat transfer. It is due to increasing the thermal conductivity of nanofluid compared to the pure fluid and its effect on the heat transfer coefficient [18]. As shown in this figure, nanoparticle concentrations of 0.5 and 1% do not have a sharp effect on the heat transfer in comparison with each other. Therefore, nanoparticles addition more than 1% has no significant effect on the heat transfer.

Figure 4 to 6 show the effect of nanoparticles on Nusselt number for different concentrations of nanoparticles inside HCT (e=1.25 mm and p=5, 7 & 8 mm). It can be seen that heat transfer increases by increasing the nanoparticles concentration in corrugated tube with small corrugation pitch augments although it has no considerable effect on heat transfer for high pitch of corrugation. Furthermore, different compositions of nanoparticles did not have significant effect on Nu number in large corrugation pitch augments (e.g. p=8 mm). Rabienataj Darzi et al. found that the Nusselt number increases from 65 to 120 for SiO_2 volume fraction of 1% and e=1.25 mm when corrugation pitch decreases from 8 to 5. Furthermore, nanoparticles addition does not considerably change the Nusselt number at p=8 mm [10].

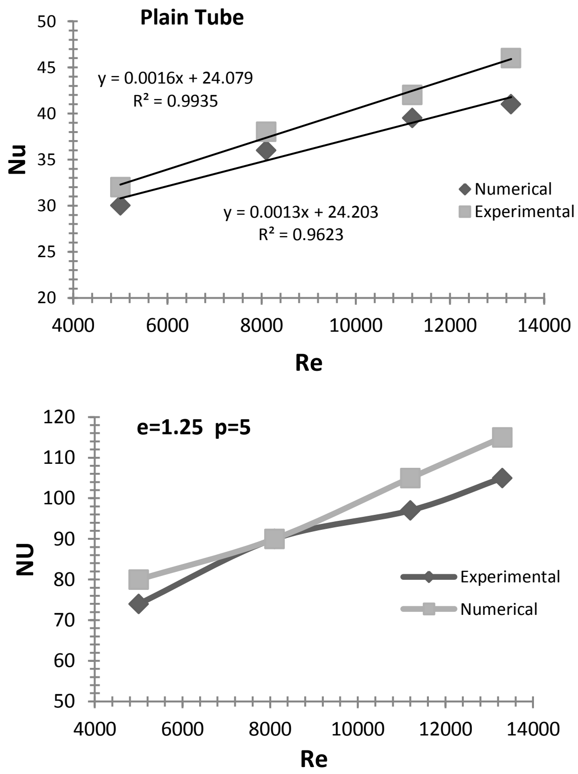


Figure 2. Verification of present modeling result for pure fluid

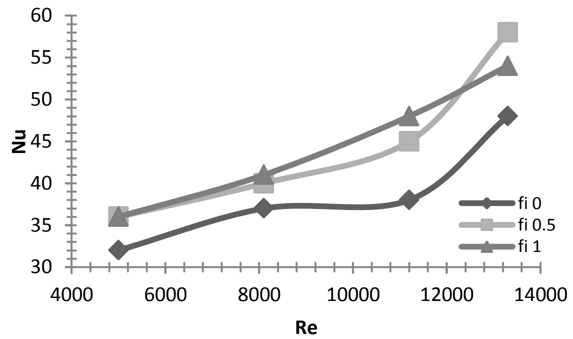


Figure 3. Nusselt number vs. Reynolds number for various concentrations of nanoparticles inside the plain tube

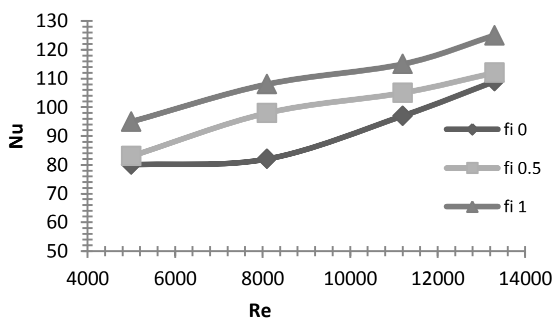


Figure 4. Nusselt number vs. Reynolds number for various concentrations of nanoparticles inside the HCT with e=1.25 mm and p=5 mm

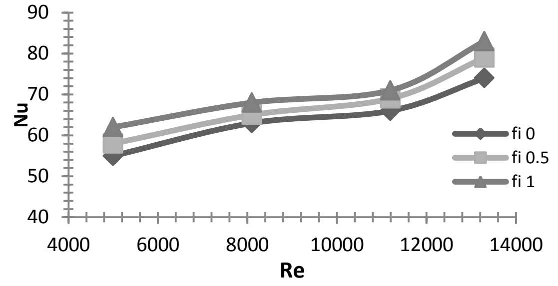


Figure 5. Nusselt number vs. Reynolds number for various concentrations of nanoparticles inside the HCT with e=1.25 mm and p=7 mm

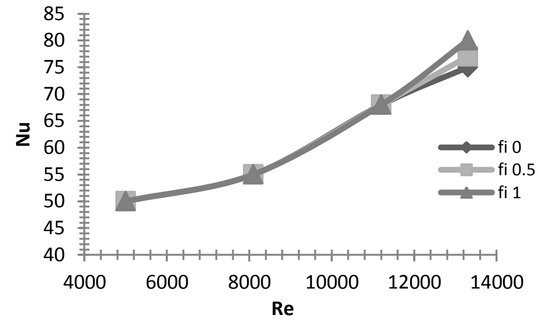


Figure 6. Nusselt number vs. Reynolds number for various concentrations of nanoparticles inside the HCT with e=1.25 mm and p=8 mm

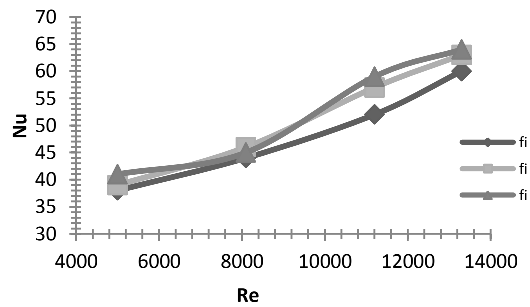


Figure 7. Nusselt number vs. Reynolds number for various concentrations of nanoparticles inside the HCT with e=0. 5 mm and p=5 mm

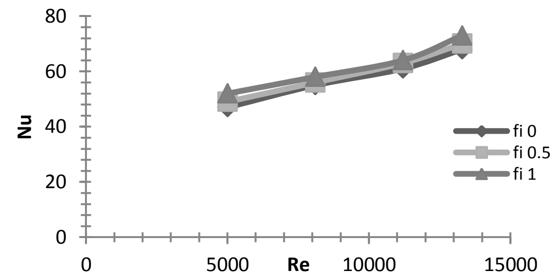


Figure 8. Nusselt number vs. Reynolds number for various concentrations of nanoparticles inside the HCT with e=0.75 mm and p=5 mm

Figures 7 to 9 show effects of nanoparticles on the heat transfer in a HCT with different corrugation heights. Tube with higher height and smaller pitch of corrugation increases the heat transfer compared with the plain tube. Furthermore, nanoparticles in HCT with high height and small pitch of corrugation extremely increase the heat transfer compared with the plain tubes. Naphon et al. investigated that the height of corrugation has more effect on the heat transfer and pressure drop in a horizontal double-pipe helical ribbed tube with diameter less than 10 mm [12], while it seems that the corrugation height and pitch almost have the similar effect on the heat transfer and friction factor (Figure 10) in our case.

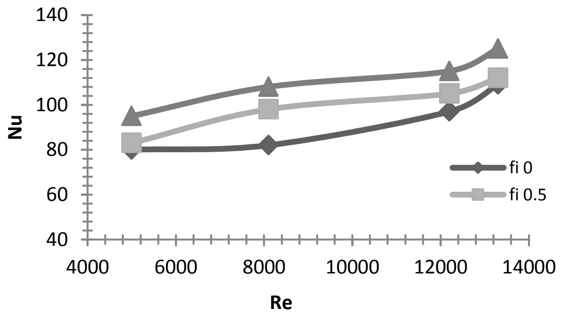
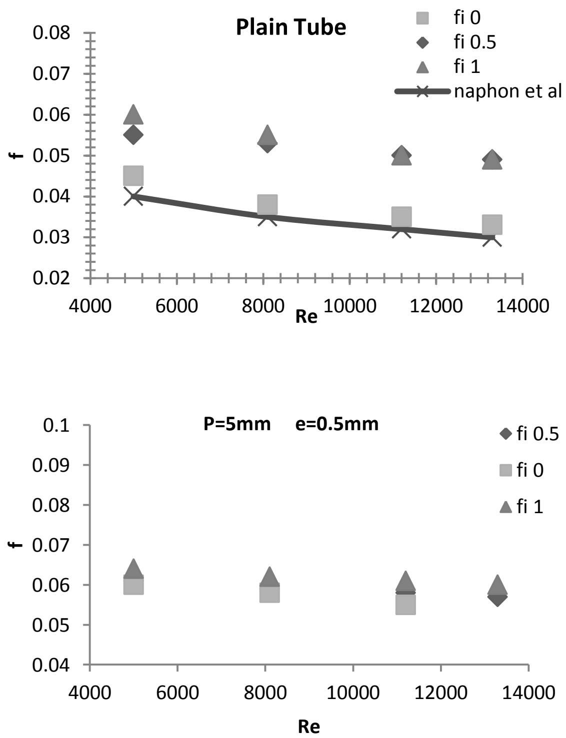


Figure 9. Nusselt number vs. Reynolds number for various concentrations of nanoparticles inside the HCT with e=1.25 mm and p=5 mm



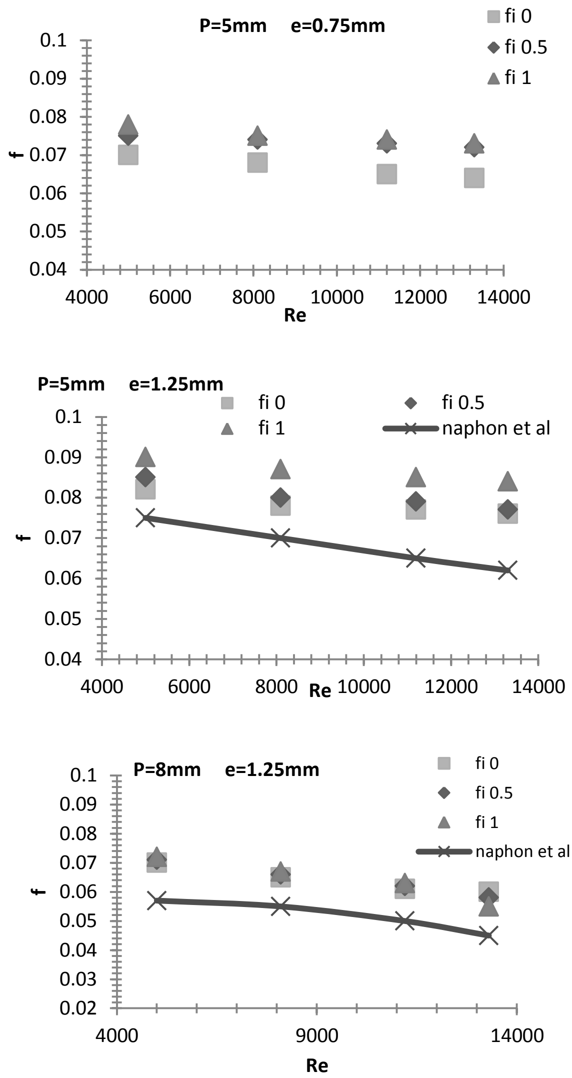


Figure 10. Friction factor vs. Reynolds number for the various tubes

Figure 10 shows friction factor verses Reynolds number. As shown in this figure, a good agreement between the simulated data and correlated ones obtained for plain and corrugated tubes. The friction factor increased with increasing the corrugation height and decreasing the corrugation pitch. It was also found that the effect of Reynolds number on the friction factor for corrugated tube was less than that of the plain tube. In the plain tube, the laminar sub layer thickness and friction factor decreased when the Reynolds number increased. In the corrugated tubes, the corrugation performed similar to the artificial roughness. In fact, a part of corrugated roughness situates out of laminar sub layer (under the main flow) when Reynolds number increased. In this region the normal stress increased with increasing the Reynolds number while shear stress near wall surface decreased. Interaction between these two stresses causes the friction factor reduction against Reynolds number for the HCT in comparison with the plain tube.

5. CONCLUSIONS

In the current research, the effect of various volume concentrations of SiO_2 nanoparticle on heat transfer in a HCT was simulated. The effect of various helix pitches in different rib-heights was also investigated. The numerical data for pure fluid were validated and compared with the experimental ones obtained from the literature [10]. It was concluded that higher height and lower pitch of corrugation intensify the flow mixing and reduce the boundary layer thickness where the nanoparticles ejection from laminar sub layer to main flow enhances. It seems that the corrugated height increment and the corrugated pitch reduction intensify the effect of nanoparticles on the heat transfer process. Moreover, nanoparticles addition in a HCT causes an extra augmentation in the heat transfer compared with the plain tubes. Although, the effect of helical corrugation on the heat transfer increment is much more than that of the nanoparticles enhancement. Furthermore, the friction factor increased with increasing the corrugated height and the corrugated pitch. It was also found that the effect of Reynolds number on the friction factor for the corrugated tube was less than that of the plain tube. Finally, the maximum Nusselt number was obtained at p=5 mm, e=1.25 mm, Re=13300 and SiO_2 volume fraction of 1% although the friction factor amount was minimum in these conditions.

6. NOMENCLATURE

A	Tube area,	m^2
C_p	Specific heat,	J/kg
d	Tube diameter,	m
e	Corrugation height,	m
f	Friction factor	
h	Heat transfer coefficient,	W/m^2K
k	Thermal conductivity,	W/mK
l	Tube length,	m
m	Mass flow rate,	kg/s
Nu	Nusselt number	
p	Corrugation pitch,	m
P	Pressure,	Pa
Pr	Prandtl number	
Re	Reynolds number	
T	Temperature,	K
U	Velocity,	m/s

Greece symbols

ρ	Density,	kg/m^3
μ	Viscosity,	kg m/s
φ	concentration (volume fraction) of nanoparticles	

Subscripts

ave	average
b	bulk
c	cold
h	hot
f	fluid
i	inner
in	inlet
nf	nanofluid
out	outlet
p	Nanoparticles
w	Tube wall

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Numerical Comparison of Turbulent Heat Transfer and Flow Characteristics of SiO_2/Water Nanofluid within Helically Corrugated Tubes and Plain Tube

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چکیده

مدل سازی عددی انتقال حرارت جریان آشفته در لوله های چین دار حلزونی با استفاده از نرم افزار فلوینت، برای آب خالص و نانو ذره اکسید سیلسیم انجام شد. مطالعه صورت گرفته بر روی گام های مارپیچ مختلف (۵،۷،۸ میلی متر) و ضخامت های مارپیچ (۰,۵،۰,۷۵،۱,۲۵ میلی متر) در اعداد رینولدز بین ۵۰۰۰ تا ۱۳۳۰۰ در نظر گرفته شد. تاثیر افزودن نانو ذره بر روی انتقال حرارت برای لوله ساده و پیچ دار در نظر گرفته شد و اعداد ناسلت مربوطه اندازه گیری شد. در لوله ساده انتقال حرارت با افزایش میزان نانو ذره به شدت افزایش یافت. این درحالی است که تاثیر گام مارپیچ و ضخامت مارپیچ در لوله پیچ دار، بیش از افزودن نانو ذره است. افزایش ضخامت و کاهش گام باعث افزایش انتقال حرارت در لوله های پیچ دار شد. بیشترین عدد ناسلت در رینولدز ۱۳۳۰۰، گام ۵ میلی متر،ضخامت ۱,۲۵ میلی متر و یک درصد حجمی از نانو ذره اکسید سیلسیم به دست آمد.

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