HEAT TRANSFER THROUGH TRIANGULAR CORRUGATED PIPE FOR LAMINAR FLOW REGION BY USING NANOFLUIDS: A NUMERICAL STUDY

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A triangular corrugated pipe was studied numerically along with Al_2O_3-water, CuO-water, and SiC-water nanofluids, to identify the thermal capacity for laminar flow. Ansys fluent software and steady-state control volume method were applied for simulation purposes. Hence, different volume fractions (1% - 5%) of CuO, Al_2O_3, and SiC nanoparticles were considered to mix with water to suspend nanofluids. 400 to 1200 Reynolds number with a constant wall heat flux of 1000 W/m^2 were considered to calculate the heat transfer rate. In addition, the required pumping power for such enhancements was determined as well. The simulation results highlighted that corrugated pipe provided highest improvement in heat transfer with increase in Reynolds number compared to straight pipe. Consequently, the mixing of nanoparticles in the working fluid showed more enhancement. For the corrugated pipe, at Re =1200, CuO-water, Al_2O_3-water, and SiC-water nanofluids showed a maximum 11.94%, 8.96%, and 9.15% enhancement respectively of Nusselt number compared to water. Furthermore, CuO-water, Al_2O_3-water, and SiC-water nanofluids showed enhancement in pumping power compared to water. Additionally, a correlation to predict the Nusselt number for nanofluid and triangular corrugated pipe was also developed by using Buckingham π Theorem, which showed good agreement with numerical results. However, it can be concluded that corrugated pipe, along with nanofluids, provide enhancement in heat transfer for the laminar developed region of a pipe.

Keywords: *Nusselt number; nanofluids, volume concentration, Buckingham π Theorem, pumping power*

1. Introduction

The straight pipe surface and working fluids that are usually utilized in different heat transfer apparatus often provided poor heat transfer efficacy. Therefore, studies in different heat transfer techniques are necessary. Mixing of small amount of oxide or metal-based nanoparticles with working fluids named nanofluid undoubtedly helps to enhance heat transfer. Applying corrugation or roughness on the wall surface of the pipe is another potential passive technique to improve heat transfer. Moreover, the combined use of both techniques by flowing the nanofluid through corrugated pipe is considered more efficient to improve thermal efficacy.

In heat transfer, utilization of corrugated channels has been investigated broadly in the last few decades. Several numerical and experimental work have conducted on corrugated pipe. Over the years, study on nanoparticles also gain popularity to enhance heat transfer. Smaisim [1] investigated thermal efficacy for a corrugated pipe applying a four-start spiral wall and identified precise proportional relationship between the heat transfer and severity index. Additionally, a higher heat transfer was observed compared to the pressure loss at a specific Reynolds threshold. Ehsan et al. [2] evaluated the enhancement of convective heat transfer through a rough circular pipe using Al_2O_3-water nanofluid. Improvement in heat transfer was examined in this study by applying nanofluid and rough pipe.

Navickaite et al. [3] analyzed elliptical double corrugated pipes for improving the thermal performance. The analysis showed that the fluid flow was affected by the double corrugated pipes' novel geometry, which disturbed thermal boundary layers and modified the flow profile in comparison to the plain pipe. This study also found that the Nusselt number's rise was around 20% for the elliptical corrugated pipes. Omer [4] found that nanofluids' enhancement of heat transfer has a little effect on nanoparticle material, and more enhancements were observed in metals rather than metal oxides. His analysis also showed that the increase of inlet Reynolds number resulted in enhancement of convective heat transfer performance and a rise in pumping power requirement with a small penalty. Abbas and Dhaidan [5] examined that the pressure loss and heat transfer rate changed greatly with nanoparticle concentration. Yang et al. [6] found that in the corrugated pipe the rise of pulsating amplitude resulted in an increased average pressure drop compared to the steady-state. In contrast, the pulsating flow initiation made the mean Nusselt number lower in the corrugated pipe than the steady-state. Ahmed et al. [7] identified improvement in heat transfer with the increase in volume fraction of nanoparticles in base fluid. Additionally, maximum heat transfer was identified in trapezoidal corrugated channel in the study. Kamel et al. [8] also observed a significant enhancement in the heat transfer by utilizing nanofluids.

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Hassanzadeh and Tokgoz [9] analyzed hydraulic and thermal behavior of Nano fluids for circular corrugated ducts. This study discovered that turbulent flow generated throughout the ducts due to periodic corrugations, resulting in higher thermal performance and fluid mixing than the plain duct. Navaei et al. [10] observed that the nanofluid containing SiO_2 had the maximum Nusselt number in comparison to other varieties. Mohammed et al. [11] studied on vertical duct for laminar mixed convection and examined that SiO_2 nanofluid provided the maximum Nusselt number at the highest buoyancy level. To achieve the boundary conditions more realistic, Chand et al. [12] investigated a linear evaluation of thermal instability for a nanofluid layer in the presence of suspended particles. The stability of the fluid layer has been demonstrated to be impacted by the suspended particles.

Ajeel et al. [13] compared the thermal efficacy of a semicircle trapezoidal corrugated channel. The Nusselt number and pressure drop were 1-4 times larger than the straight corrugated profile when using ZnO nanofluid in a house-shaped corrugated channel. To be more precise, the semicircle, trapezoidal, and house-shaped corrugated profiles increased their thermal performance by 7.4%, 8.7%, and 4.86%, respectively, over the straight one. Andrade et al. [14] observed that internal flow in corrugated pipes was used to characterize heat transfer and pressure drop. It was observed that corrugated pipes' efficacy for maximal heat transfer augmentation was in the transitional flow regime, with a Reynold number around 2000. The experimental pipes had a Nusselt number of up to 4.7.Karimzadehkhouei et al. [15] investigated the impact of inlet temperature on the thermally rising and hydrodynamically evolved zone of laminar fluid flow in an alumina-water nanofluid. The findings also showed that inlet temperature impacts for thermally developing zones were more meaningful and resulted.

Even though several studies worked on a corrugated pipe using nanofluids, the majority of them only demonstrated the heat transfer increase of nanofluids. Only a minority of them mentioned the pumping power requirement, which significantly influences hydraulic performance. Moreover, to predict the heat transfer of different nanofluids for triangular corrugated pipe there is no proper correlation in literature. Therefore, to obtain a better understanding of this research, a triangular corrugated pipe was used in combination with Al_2O_3-water, CuO-water, and SiC-water nanofluids, which are introduced as working fluids, to study improvements in laminar convective heat transfer in terms of Nusselt number and the appropriate pumping power demand for such enhancements. In addition a correlation for Nusselt number to predict heat transfer is also proposed.

2. Numerical Method

2.1 Computational Model

ANSYS Fluent software has been used for the CFD analysis to investigate the thermal and hydraulic performance of nanofluids through a corrugated pipe. Nanofluids were considered to flow through axisymmetric two-dimensional triangular corrugated pipe presented in Figure 1. A uniform heat flux 500 W/m^2 applied at corrugated surface of the pipe with no-slip condition. At inlet, constant velocity was applied to allow the fluids to flow at a constant temperature of 303 K while at outlet, pressure outlet condition was applied. Laminar convective simple control volume second order upwind method was applied for simulation purpose.

2.2 Assumptions

Nanofluids were considered as hydrodynamically and thermally stable. Moreover, the flow were assumed single-phase, incompressible, and slip less.

3. Mathematical Model

3.1 Governing Equations

The Navier-Stokes governing equations for laminar cylindrical axisymmetric stady flow can be address as follow:

Continuity equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

Momentum equation:

X-momentum equation,

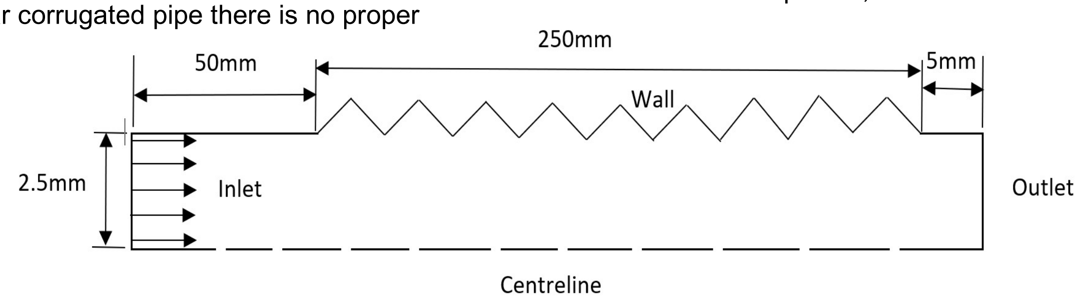


Fig. 1- Computational model of the saw type corrugated pipe

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{dx}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \quad (2)$$

Y-momentum equation,

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{dy}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \quad (3)$$

Here, ρ is the density, and μ is the viscosity of fluids.
Energy Equation:

$$\rho_{nf}\,C_{P_{nf}}(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y})=k_{nf}(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}) \quad (4)$$

The equation for Reynolds number can be address as,

$$Re=\frac{\rho_{nf}U_{av}D_h}{\mu_{nf}} \quad (5)$$

The equation for the heat transfer rate of nanofluid,

$$Q_{nf}=m_{nf}C_{P_{nf}}\Delta T \quad (6)$$

The average heat transfer coefficient h_c is given by,

$$h_c=\frac{Q_{nf}}{A_w(\Delta T)} \quad (7)$$

The temperature difference between the pipe and surface wall is express as,

$$\Delta T=\frac{(T_w-T_o)-(T_w-T_i)}{\ln\left(\frac{T_w-T_o}{T_w-T_i}\right)} \quad (8)$$

The average Nusselt number is as follows,

$$Nu=\frac{h_cD_h}{K_{nf}} \quad (9)$$

The pumping power per unit length,

$$W=\frac{(\pi/4)^2U_{av}\Delta P}{L} \quad (10)$$

3.2 Thermo Physical Properties of Nanofluids

Dynamic Viscosity: For this study, Maiga et al. [16] equation for Al_2O_3 and Chen et al. [17] equation for CuO-water and SiC-water were utilized to calculated dynamic viscosity. The equations can be expressed as:

Maiga et al. equation:

$$\mu_{nf}=(1+7.3\emptyset+123\emptyset^2)\mu_p \quad (11)$$

Chen et al. equation:

$$\mu_{nf}=\mu_{bf}[1+10.6\emptyset+(10.6\emptyset)^2]\mu_p \quad (12)$$

Thermal Conductivity: To calculate thermal conductivity the Maxwell [18] equation for all nanofluids was applied, which is given by:

$$K_{nf}=\frac{K_p+2K_{bf}+2(K_p-K_{bf})\emptyset}{K_p+2K_{bf}-(K_p-K_{bf})\emptyset}\times K_{bf} \quad (13)$$

Density: For calculating the density of all nanofluids, Xuan and Roetzel [19] equation has been used, which is given by:

$$\rho_{nf}=\rho_p\emptyset+\rho_{bf}(1-\emptyset) \quad (14)$$

Specific Heat: For calculating specific neat of all nanofluids, Pak and Cho [20] equation has been used, which is given by:

$$C_{nf}=(1-\emptyset)C_w+\emptyset C_p \quad (15)$$

4. Validation and Grid Refinement Test

4.1 Validation Test

The theoretical equation of Shah and London [21] for local Nusselt number of straight pipe is applied for validation purpose. Moreover, the validation was also done for friction factor of straight pipe by using Darcy weisbach equation. 500 W/m^2 heat flux and 100-1000 range of Reynolds number were used or analysis. The results present in Figure 2 showed a good agreement between present work and theoretical results in terms of friction factor and Nusselt number.

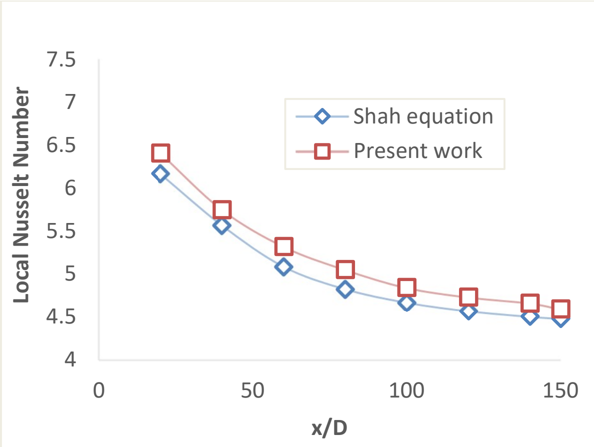
$$Nu=1.302\left(\frac{x^*}{2}\right)^{-\left(\frac{1}{3}\right)}-0.5,x^*\leq\ 0.003 \quad (16)$$

$$Nu=4.364+0.263\left(\frac{x^*}{2}\right)^{-0.506}\ e^{-41\left(\frac{x^*}{2}\right)},x^*>0.03 \quad (17)$$

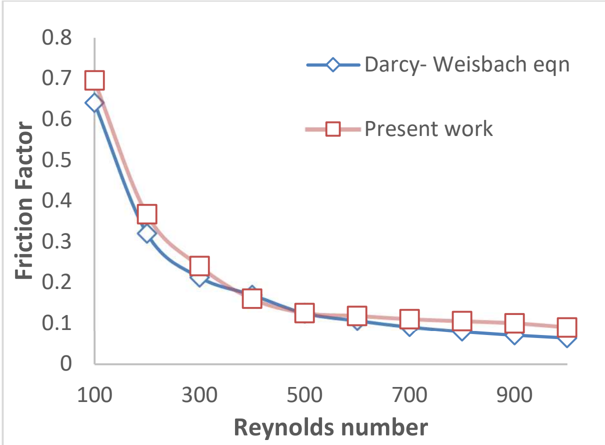
$$Where,\qquad x^*=\frac{2(x/D)}{Re\ Pr} \quad (18)$$

4.2 Grid Refinement Test

The grid refinement test was performed for corrugated pipe for different element numbers by generating quadrilateral dominant mesh in Ansys Fluent. The grids, which showed the relative differences of average Nusselt number less than 1%, are finalized for simulations purposes. The results for grid refinement test is presented in Table 1.



a



b

Fig. 2 - Comparison of (a) Local Nusselt number and (b) friction factor of the present study with theory.

Table 1

Grid independency analysis

Elements	Nu	Deviation (%)
50000	4.25	-
70000	4.4	3.35
80000	4.48	1.81
90000	4.53	1.11
100000	4.55	0.44

5. Results and Discussion

5.1 Impact of corrugation on heat transfer

The influence of corrugation surface on heat transfer is presented in Figure 3 for water as base fluid. The Figure demonstrates that with the increase in Reynolds number Nusselt number is also increased for both plain and corrugated pipe while corrugated pipe showed highest enhancement in Nusselt number compared to plain pipe. It was observed that the Nusselt number enhance up to 10.75% as a result of utilizing the corrugated pipe. The heat transfer area in corrugated pipe is more compared to the plain pipe due to the corrugated surface, which made the Nusselt number in corrugated pipe is the highest.

5.2 Effect of corrugation on pumping power

Figure 4 represents the variations in the pumping power of water as a working fluid for both corrugated and plain type geometry as a Reynolds number function. It has been identified that the pumping power requirement can be increased by up to 98.75% when using a corrugated pipe. Due to the higher-pressure drop in corrugated pipe, the pumping power needed in the corrugated pipe rather than the flat pipe is expected to be increased.

5.3 Effect of nanofluids as working fluid in heat transfer performances

Al_2O_3-water, CuO-water, and SiC-water nanofluids were considered as working fluids to flow over the corrugated passage. 1-5% volume concentrations of the nanoparticles were mixed with water to prepared nanofluids. By increasing the presence of nanoparticles, the thermal conductivity was also increasing, which enhanced the Nusselt number for nanofluid. Figures 5, 6, and 7 demonstrate variations of Nusselt number for Al_2O_3-water, CuO-water, and SiC-water nanofluids, respectively. The change also occurred with the

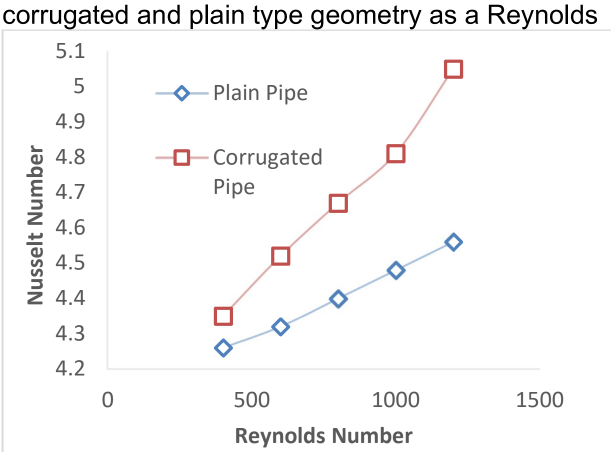


Fig.3 - Variation in Nu with Reynolds number for water as base fluid

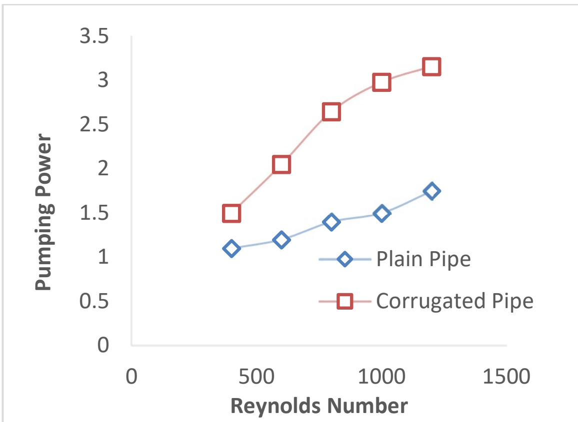


Fig. 4 - Changes in pumping power (W) requirement between corrugated and plain pipe with water as base fluid

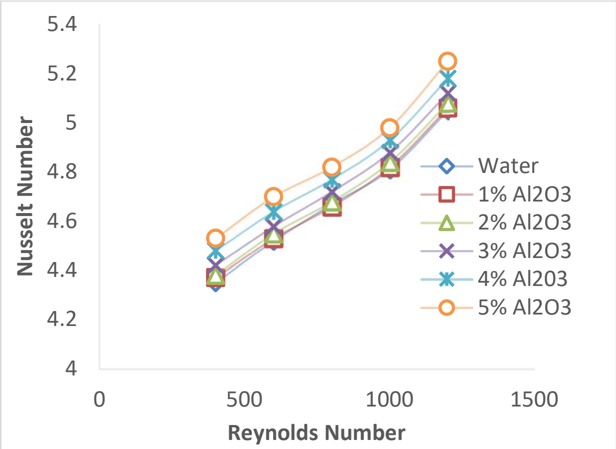


Fig. 5 - Variation of Nusselt Number with Reynolds Number for Al_2O_3-water nanofluid

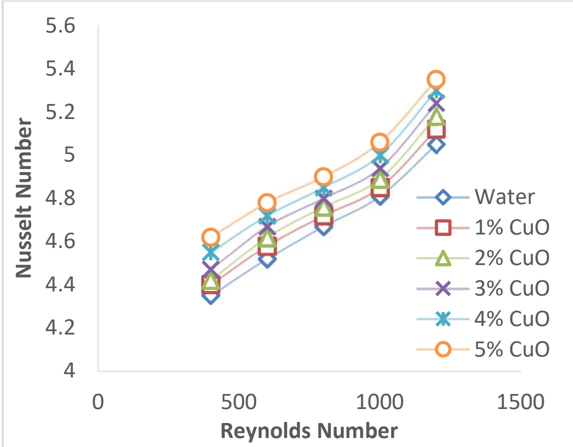


Fig. 6 - Variation of Nusselt Number with Reynolds Number for CuO-water nanofluid

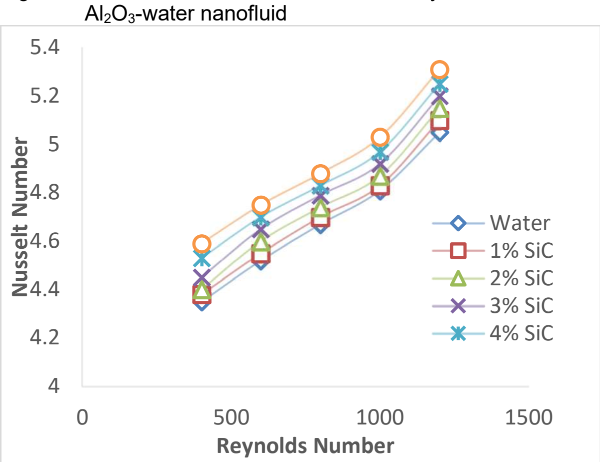


Fig. 7 - Variation of Nusselt Number with Reynolds Number for SiC-water nanofluid

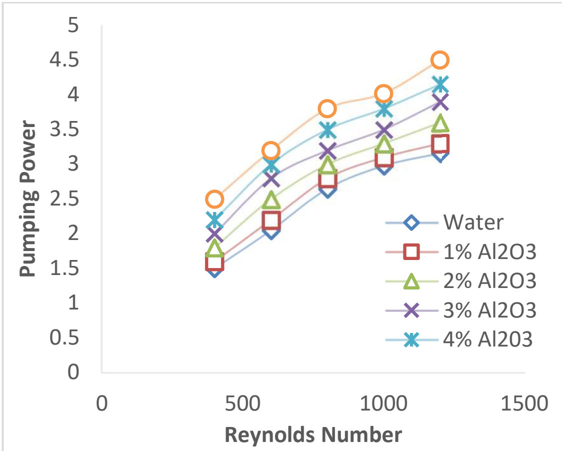


Fig. 8 - Required Pumping power (W) with different Reynolds number for Al_2O_3-water nanofluid

Reynolds number for a constant volume concentration of the nanoparticles. At a Reynolds number of 1200, the maximum growth of Nusselt number were 8.96%, 11.94%, and 9.15% for 5% Al_2O_3-water, CuO-water, and SiC-water nanofluids, respectively.

5.4 Effect on pumping power using nanofluids

By adding volume concentration of nanoparticles, the pumping power requirement has increased due to the higher viscosity of the working fluid. Figures 8, 9, and 10 represent the variation of pumping power requirement with Reynolds number for Al_2O_3-water, CuO-water, and SiC-water nanofluids, respectively. At a Reynolds number of 1200, the enhancement of pumping power requirement was 41.33%, 49.26%, and 44.97% for 5% volume fraction of Al_2O_3-water, CuO-water, and SiC-water nanofluids, respectively.

5.6 Correlation of nanofluid's Nusselt number for corrugated pipe

To calculate the Nusselt number of nanofluids, a correlation was developed and presented in equation (20) using numerical results for the corrugated pipe from Ansys showed in Figures 7, 8, and 9. The developed correlation of nanofluid's Nusselt number is a function of Nusselt number of base fluid water, volume concentration of nanoparticles, pipe geometry, Reynolds number and density of nanofluids. The calculated Nusselt number of nanofluid from the developed correlation was compared with the Nusselt number of nanofluid from current numerical results to validate the developed correlation with numerical results. The comparison between the Nusselt number of nanofluids for developed correlation and current numerical results was presented in Figures 11-16 for Reynolds numbers 400 and 600 of Al_2O_3-water, CuO-water, and SiC-water nanofluids, respectively. The figures showed that results from correlation showed good agreement only maximum 2% deviation with current numerical results which refers that currently developed correlation has potential to calculate Nusselt number for different nanofluids under steady-state laminar convective heat transfer condition for saw type corrugated pipe and other assumptions mentioned in the numerical method section.

$$y = \emptyset\left[y, Nu_{bf}, Re, \varphi, D/L, \rho_{bf}/\rho_{nf}\right] \quad (19)$$

$$Nu_{nf} = Nu_{bf} \times e^{\varphi} + \left(\frac{D\rho_{bf}}{ReL\rho_{nf}}\right)^{0.75} \quad (20)$$

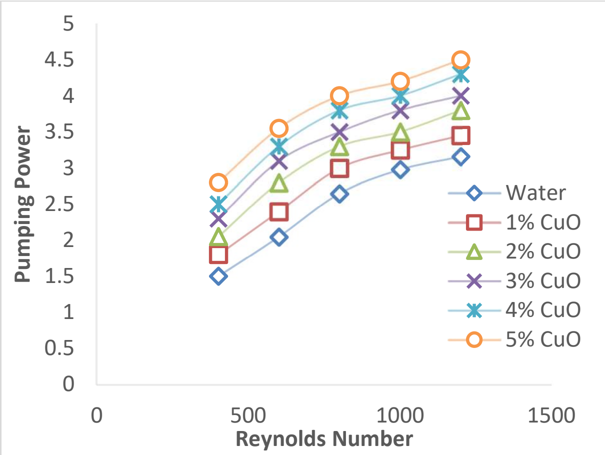


Fig. 9 - Required Pumping power (W) with different Reynolds number for CuO-water nanofluid

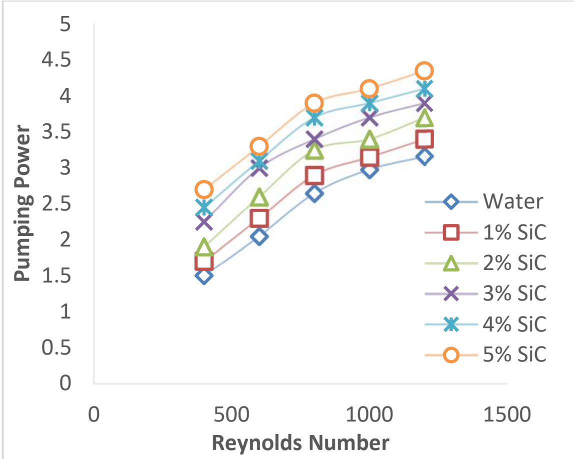


Fig. 10 - Required Pumping power (W) with different Reynolds number for SiC-water nanofluid

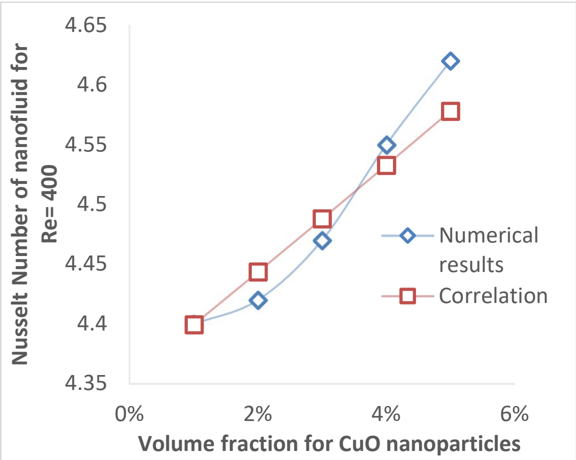


Fig. 11 - Comparison of Nu for CuO-water between developed correlation and current numerical results for Re = 400

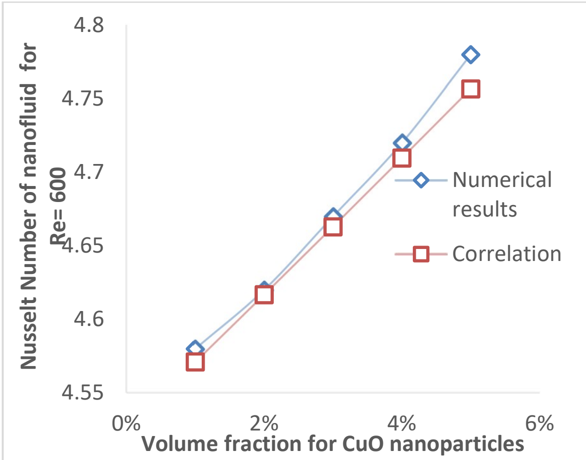


Fig. 12 - Comparison of Nu for CuO-water between developed correlation and current numerical results for Re = 600

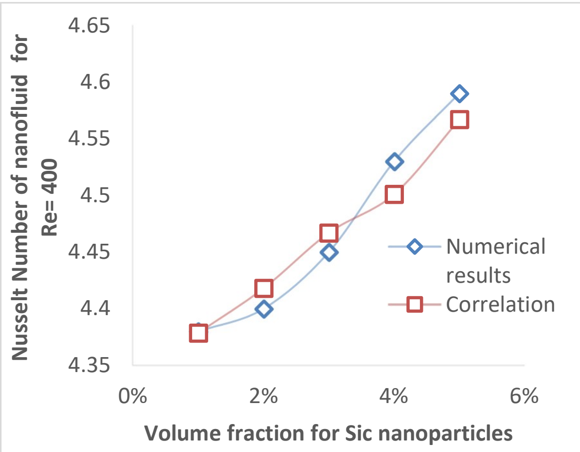


Fig. 13 - Comparison of Nu for SiC-water between developed correlation and current numerical results for Re = 400

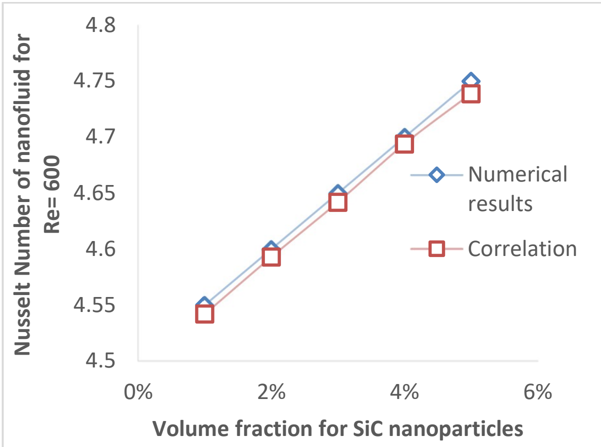


Fig. 14 - Comparison of Nu for SiC-water between developed correlation and current numerical results for Re = 600

The equation 20 was developed by using Buckingham π Theorem where Nusselt number of nanofluids is a function $Nu_{bf}, \varphi, Re, D, L, \rho_{nf}, \rho_{bf}$ therefore the Nusselt number of nanofluids,

$$y = f\left(Nu_{bf}, \varphi, Re, D, L, \rho_{nf}, \rho_{bf}\right); y = Nu_{nf}$$

where $y = Nu_{nf}$ is dependent variable and $Nu_{bf}, \varphi, Re, \rho_{nf}, \rho_{bf}$ are independent variables.

The functional relationship between dependent and independent variables can be written as:

$$f\left(Nu_{bf}, \varphi, Re, \rho_{nf}, \rho_{bf}\right) = 0$$

Here total number of variables are $n = 8$.
Dimensions of the variables:

$$y = M^0L^0 \qquad \rho_{nf} = \frac{kg}{m^3} = \frac{M}{L^3} = M^1L^{-3} \qquad D = m = L^1$$
$$Nu_{bf} = M^0L^0 \qquad \rho_{bf} = \frac{kg}{m^3} = \frac{M}{L^3} = M^1L^{-3} \qquad L = m = L^1$$
$$Re = M^0L^0 \qquad \varphi = M^0L^0$$

The number of π terms = $n - m = 6$
therefore,

$$f_1\ (\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8) = 0$$

now, π terms-

$\pi_1 = D^{a_1}\ \rho_{nf}^{\ b_1} y$	$M^0L^0 = (L^1)^{a_1}(M^1L^{-3})^{b_1}M^0L^0$	$b_1 = 0$; $a_1 = 0$	$\pi_1 = D^0\ \rho^0\ y = y$
$\pi_2 = D^{a_2}\ \rho_{nf}^{\ b_2}\ Nu_{bf}$	$M^0L^0 = (L^1)^{a_2}(M^1L^{-3})^{b_2}M^0L^0$	$b_2 = 0$; $a_2 = 0$	$\pi_2 = D^0\ \rho^0\ Nu_{bf} = Nu_{bf}$
$\pi_3 = D^{a_3}\ \rho_{nf}^{\ b_3}\ Re$	$M^0L^0 = (L^1)^{a_3}(M^1L^{-3})^{b_3}M^0L^0$	$b_3 = 0$; $a_3 = 0$	$\pi_3 = D^0\ \rho^0\ Re = Re$
$\pi_4 = D^{a_4}\ \rho_{nf}^{\ b_4}\ \varphi$	$M^0L^0 = (L^1)^{a_4}(M^1L^{-3})^{b_4}M^0L^0$	$b_4 = 0$; $a_4 = 0$	$\pi_4 = D^0\ \rho^0\ \varphi = \varphi$
$\pi_5 = L^{a_5}\ \rho_{nf}^{\ b_5}\ D$	$M^0L^0 = (L^1)^{a_5}(M^1L^{-3})^{b_5}L^1$	$b_5 = 0$; $a_5 = -1$	$\pi_5 = L^{-1}\ \rho_{nf}^{\ 0}\ D = D/L$
$\pi_6 = D^{a_6}\ \rho_{nf}^{\ b_6}\rho_{bf}$	$M^0L^0 = (L^1)^{a_6}(M^1L^{-3})^{b_6}L^1$	$b_6 = -1$; $a_6 = 0$	$\pi_6 = D^0\ \rho_{nf}^{\ -1}\rho_{bf} = \rho_{bf}/\rho_{nf}$

Now, now,

$$f_1(y, Nu_{bf}, Re, \varphi, D/L, \rho_{bf}/\rho_{nf}) = 0$$

therefore, the Nu_{nf} will be,

$$y = \emptyset\ [y, Nu_{bf}, Re, \varphi, D/L, \rho_{bf}/\rho_{nf}]$$

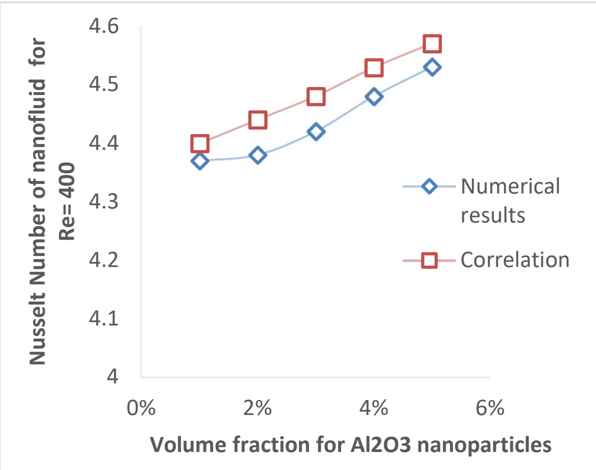


Fig. 15 - Comparison of Nu for Al_2O_3-water between developed correlation and current numerical results for Re = 400

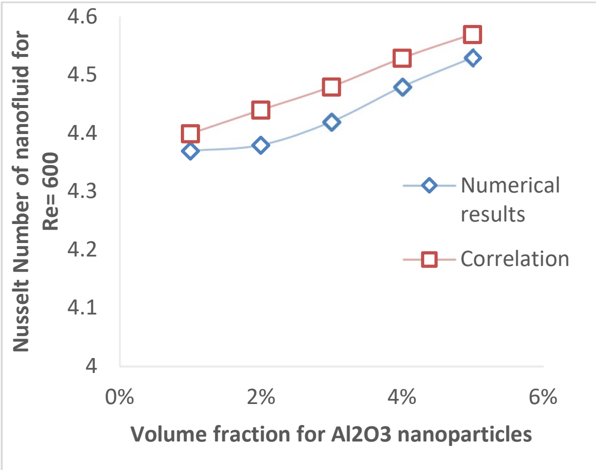


Fig.16 - Comparison of Nu for Al_2O_3-water between developed correlation and current numerical results for Re = 600

6. Conclusion

This study considered type corrugated pipe with nanofluids as the working fluids to improve heat transfer performances. Owing to the increased viscosity of a fluid through it, corrugation in the pipe provides more pumping capacity. In optimal comparability with water, nanofluid compensates for increased pumping capacity. Hence, 1% to 5% volume fraction of Al2O3-water, CuO-water, and SiC-water nanofluids were used to improve the heat transfer rate and identify the pumping power for the corrugated pipe. The key findings from the simulation of this study were:

1. Presented saw type corrugated pipe provides more heat transfer rate than the plain pipe due to the heat transfer area's extension. Hence, utilization of corrugated pipe, the Nusselt number, increased up to 10.75% and 6.85%, respectively, compared to the plain pipe.
2. The results from this study also showed

that Al_2O_3-water, CuO-water, and SiC-water nanofluids required more pumping power than water at constant Reynolds Number due to the pressure loss and friction factor of nanofluids. At Reynolds number 1200, the increment of pumping power requirement was 41.33%, 49.26%, and 44.97% for 5% volume fraction of Al_2O_3-water, CuO-water, and SiC-water nanofluids, respectively.

3. A correlation to calculate the Nusselt number of nanofluid was also developed by using numerical results from Ansys simulation and Buckingham π Theorem, which showed good agreement, maximum 2% deviation only from numerical results of Nusselt number for nanofluids.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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Nomenclature

Ø	Volume concentration
ρ	Density (kgm^{-3})
T	Temperature (°C or K)
U_{av}	Average inlet velocity (m/s)
m	Mass flow rate (kg/s)
D_h	Hydraulic diameter (m)
μ	Dynamic Viscosity (kg·m^{-1}·s^{-1})
Q	Heat transfer rate (J/s)
K	Thermal conductivity (Wm^{-1}.K^{-1})
ΔT	Temperature difference (°C or K)
h	Average heat transfer coefficient (Wm^{-2}K^{-1})
Δp	Pressure difference (Pa or N/m^2)
f	Friction factor
C_p	Specific heat at constant pressure (J.mol^{-1}.K^{-1})
Re	Reynolds number
W	Pumping power (KW)
Nu	Nusselt number

Subscripts

i	Inlet
o	Outlet
w	Wall
nf	Nano fluid
bf	Base fluid
p	Particle size

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