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Performance Evaluation of Nanofluid for Heat Transfer Enhancement and Pumping Power Reduction through a Semicircular Corrugated Pipe

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Abstract

Implementing nanofluid in heat transfer enhancement application is a modern and accessible method. In this present investigation Al_2O_3-water and CuO –water nanofluid with 1 % - 5 % volume fraction was chosen to study forced convective heat transfer enhancement through a semicircular corrugated pipe. 5000 W/m^2 constant heat flux was considered as subjected to the pipe wall. The improvement was observed in both heat transfer rate and required pumping power with increased volume fraction of nanofluid comparing with base fluid water. The numerical simulation was analyzed in the range of Reynolds number 10,000 to 20,000. Effect of using nanofluid on total wall shear stress was also studied. 2% Al_2O_3-water and 1% CuO-water nanofluid were selected as they exhibit superior performances in enhanced heat transfer with optimum pumping power than water. Finally, the power advantage for both nanofluid was performed under prescribed flow condition.

Keywords

Heat transfer enhancement; Heat flux; Corrugation; Nanofluid; Pumping power; Total wall shear stress.

1. Introduction

Nanotechnology for many industrial and engineering applications is an advanced technique and it permits the best way in sustainable energy management. 'Nanofluid' is a suspension containing metal particles in nano scale (10^{-9} meter) with base fluid like water, oil, ethelyn glycol of preferred volume fraction. Normally water has lower thermal conductivity than any metal and when it is mixed with metal particles, the thermal conductivity will be higher than water. The performance of heat transfer depends on the thermal conductivity of the base fluid. Metal particles which is mixed in the water can clog into the piping system or it may require more pumping power. The problem is solved by taking the metal particles in nano scale. Nanofluid has opened the new opportunity for designing more efficient and compact thermal equipment. Enormous studies have been performed for enhancing the heat transfer performances implementing nanofluid as cooling or heating medium.

In forced convection of heat transfer, the discontinuous fluid domain helps to break down the flow pattern of the flowing fluid through the domain that intends to increase the heat transfer rate. Ramgadia et al. [1], investigated on the performances of heat transfer through wavy passage for both steady and unsteady flow with the range of Reynolds number (Re=25 to Re=1,000). For steady flow, the change was very low but for unsteady condition, the improvement was better. G. Fabbari [2], analyzed finite element model to predict the thermos-physical behavior in both corrugated and smooth wall under laminar flow condition and found an improved result to maximize heat transfer performance using corrugation. Y.Sui et al. [3], carried out a numerical simulation in 3-D microchannel for laminar flow condition. Results showed that, for the generation of secondary flow through wavy channel which leads to enhance convective flow mixing and increase heat transfer performance. Experimental study was conducted by B.Sunden and I. Karlsson [4], to find out the heat transfer and pressure drop in trapezoidal channel under constant wall temperature. Significant improvement in heat transfer but very large increase in pressure drop. For turbulent flow condition, many investigations were performed experimentally and numerically for finding out the effect of corrugation in thermos-physical behavior of working fluid. Results showed improved performances through different corrugated passage with increased amount of pressure drop due to flowing through different corrugations. [5-8]

Maiga et al. [9], studied on forced convection by the flow of water-γ Al_2O_3 and ethylene glycol-γ Al_2O_3 nanofluids through a uniformly heated wall. The investigation indicated that with the increase of nanofluid volume concentration, the heat transfer rate increases and it had an adverse effect on wall friction due to higher volume concentration of nanofluid. Santra et al. [10], investigated on the effect of using copper-water nanofluid (10 nm diameter) in heat transfer improvement having 0.05 % to 5 % volume fraction through different heated square cavity with Rayleigh number 10^4 to 10^7. A study was done both in experimentally and numerically on the effect of using Al_2O_3 nanofluid through mini channel in laminar flow regime for heat transfer and pressure drop variations [11]. Farajollahi et al. [12], investigated on heat transfer performance using γ-Al_2O_3 and TiO_2-water nanofluid through shell and tube heat exchanger and found the perfect nanofluid between them on the basis of maximum enhancement in heat transfer. Natural convection heat transfer enhancement in horizontal concentric annuli using Cu, Ag, Al_2O_3, and TiO_2 nanofluid was observed by Abu-Nada et al. [13], for Rayleigh number 10^3 to 10^5.

Al- Shamni et al. [14], studied on heat transfer in turbulent flow regime with Re= 10,000 to Re= 40,000 of Al_2O_3, CuO, SiO_2 and ZnO nanofluids (having particle size of 25 nano meter to 70 nano meter) through different rib groove channel and selected the best nanofluid for specific shape on the basis of higher heat transfer rate in terms of Nusselt number. Effect of increasing the amplitude of the corrugation was also studied. Manavi et al. [15], investigated on the improvement of turbulent convective heat transfer using Al_2O_3-water nanofluid considering two phase modeling system through a wavy channel under constant wall heat flux. Noor et al. [16], compared various nanofluids including Al_2O_3-water, TiO_2-water and CuO-water nanofluids through trapezoidal channel on the basis of convective heat transfer improvement and Optimized pumping power is determined for desired heat transfer rate compared with base fluid water. The effect of changing the ratio of amplitude and wave length of corrugation was also studied numerically in terms of heat transfer and pumping power.

From the literature review, most of the works were focused on the improvement of heat transfer performance and change in pressure drop using nanofluid through plain or corrugated fluid domain. There are a very few numbers of investigation on determining the best nanofluid for heat transfer improvement considering optimized pumping power, wall shear stress, mass flow rate and power advantages for specific geometry. So the scope of the present study is to find out the best nanofluid among Al_2O_3-water and CuO-water nanofluid having volume concentration range of 1 % to 5 % on the basis of improved heat transfer rate with optimum pumping power and power advatnage from Reynolds number 10,000 to 20,000 through semicircular corrugated pipe.

2. Governing equations

The Reynolds number for the nanofluid flow is expressed as

$$Re = \frac{\rho_{nf}\, u_{av}\, D}{\mu_{nf}}$$

The rate of heat transfer Q_{nf} to pipe wall is considered to be diminished to nanofluid flowing through the semicircular pipe, in this period the temperature rise from the inlet bulk temperature T_{bi} to outlet bulk temperature T_{bo}. [18]

$$Q_{nf} = \dot{m}_{nf} C_{p_{nf}} (T_{bo} - T_{bi})_{nf} \qquad (1)$$

Where $\dot{m}_{nf}$ is the mass flow rate of the flowing nanofluid through the pipe, $C_{p_{nf}}$ is the specific heat of the nanofluid at constant pressure. The bulk temperature T_b is taken as

$$T_b = \frac{\int_0^{A_c} uT\,dA_c}{\int_0^{A_c} u\,dA_c} \tag{2}$$

The average heat transfer coefficient, h_c is termed as [18]

$$h_c = \frac{Q_{nf}}{A_W\,(\Delta T_m)} \tag{3}$$

Where A_w is the surface area of the circular pipe and ΔT_m is the temperature difference between the wall and the average bulk temperature of the fluid.

$$\Delta T_m = T_w - T_b$$

The average wall temperature T_w is given by

$$T_w = \frac{1}{\sigma}\int_0^{\sigma} T_{w,x}\,dx$$

So the average Nusselt number is expressed as

$$Nu = \frac{h_c D}{k_{nf}} \tag{4}$$

Hydraulic diameter D_h for the semicircular pipe is

$$D_h = \frac{S_{max} + S_{min}}{2}$$

Where S_{max} and S_{min} are taken as the maximum and minimum height in the semicircular pipe.

The pumping power per unit length in turbulent flow is calculated by [19]

$$\dot{W} = \frac{\frac{\pi}{4} {D_h}^2 U_{av}\,\Delta P}{L} \tag{5}$$

Where ΔP is pressure difference termed as

$$\Delta P = \frac{f L \rho {U_{av}}^2}{2D}$$

Total shear stress at corrugated pipe wall is expressed as [17]

$$\tau_o = \frac{f \rho {U_{av}}^2}{8} \tag{6}$$

3. Thermo-physical properties of nanofluid

The density and specific heat of the nanofluid are calculated using following equation [20].

Density, $\rho_{nf} = (1-\phi)\rho_w + \phi\,\rho_p$ (7)

Specific heat, $C_{nf} = (1-\phi)C_w + \phi C_p$ (8)

The viscosity of Al_2O_3-water is calculated using the following equations which have been derived from the experimental works of Pak and Cho [20]

For Al_2O_3-water nanofluid,

$$\mu_{nf} = \mu_w(1 + 39.11\phi + 533.9\,\phi^2) \tag{9}$$

Since there are no experimental results available in the literature for the viscosity of CuO-water nanofluid at different volume fraction where base fluid is pure water, the correlation developed by Corcione [21] has been used.

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{1-34.87\left(\frac{d_p}{d_{bf}}\right)^{-0.3}\phi^{1.03}} \tag{10}$$

Where d_{bf} is the equivalent diameter of the base fluid molecule,

$$d_{bf} = \left[\frac{6M}{N\pi\rho_{fo}}\right]^{1/3}$$

In which M is the molecular weight of the base fluid, N is the Avogadro number, and ρ_{bf} is the mass density of the base fluid. The thermal conductivity of Al_2O_3 – water is calculated by [20]

For Al_2O_3 – water,

$$K_{nf} = K_{bf}\,(1.0021 + 7.3349\phi) \tag{11}$$

The thermal conductivity of CuO-water nanofluid has been calculated using the Maxwell [22] model. The thermal conductivity of the nanofluid is given by,

$$k_{nf} = \frac{k_p+2k_{bf}+2(k_p-k_{bf})\phi}{k_p+2k_{bf}-(k_p-k_{bf})\phi}\,k_{bf} \tag{12}$$

4. Physical model

The Fluid domain is taken for numerical analysis with finite volume method (FVM) in both circular plain pipe and the semicircular corrugated pipe having 12 millimeter diameter. 2-D axisymmetric model is taken for better computation. The plain circular pipe length is chosen 1 meter long and the thermos-physical as well hydrodynamic behaviors are calculated between 800 millimeter and 900 millimeter distance from the inlet to ensure all the measured parameters are in the fully developed flow region. For the semicircular corrugated pipe, 300 millimeter length is taken and 1 millimeter circle radius with 12 millimeter wave length of the corrugation. In semicircular corrugated pipe, first 30 millimeter is called the entry region, next 200 millimeter is corrugated section and rest 70mm is exit region.

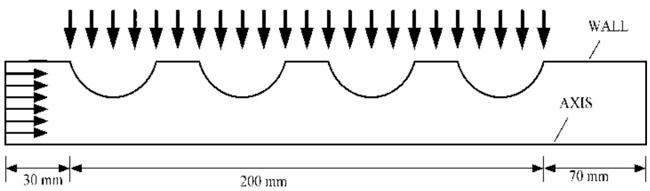

Fig. 1. Physical model of semi circular corrugated fluid domain(not up to scale).

5. Boundary conditions

The fluid domain has been characterized with velocity inlet and pressure outlet.5000 W/m^2 constant heat flux is applied on the corrugated wall, the entry and the exit region of semicircular pipe have no heat flux. Fluid is allowed to flow with uniform velocity through inlet having constant temperature 300 K. k-ε turbulent model with realizable enhanced wall treatment is selected for fluid dynamics behavior analysis through the corrugated domain. The fluid particles are allowed to move freely with no slip condition and 5% turbulent intensity has been used. Reynolds numbers have been implemented in terms of velocity of the fluid. Convective heat transfer coefficient and the pressure difference are calculated through plain and corrugated pipe with the increase of Reynolds number taking water and 1 %-5 % volume fraction of Al_2O_3-water and CuO-water nanofluid as base fluid by using their different thermo-physical properties. In this pressure velocity coupling, for pressure PRESTO, second order upwind for momentum, turbulent kinetic energy, and turbulent dissipation rate have been applied in spatial discretization. The test section for corrugated pipe is taken at 70 millimeter and 237 millimeter from inlet. In this section the wall temperature, bulk temperature and the pressure at two test points are calculated using user defined functions(UDF) in 'CFD-post processing'.

6. Code validation & grid independence test

In order to investigate the thermophysical and hydrodynamic behavior for both plain and corrugated pipe using Al_2O_3-water and CuO-water nanofluid commercial software 'ANSYS-fluent 12.0' has been employed. Water is taken as the working fluid through the plain circular pipe in order to numerically calculate the Nusselt number for the Reynolds number ranging from 10,000 to 20,000. Numerically found results of the present investigation show similarity with the correlation for Nusselt number given by Notter and Sleicher[17].

The correlation given by Notter and Sleicher is:

$$Nu = 5 + 0.016\, Re^{a} Pr^{b} \tag{7}$$

Where, $a = 0.88 - \frac{0.24}{4+Pr}$ and $b = 0.33+0.5e^{(-0.6Pr)}$

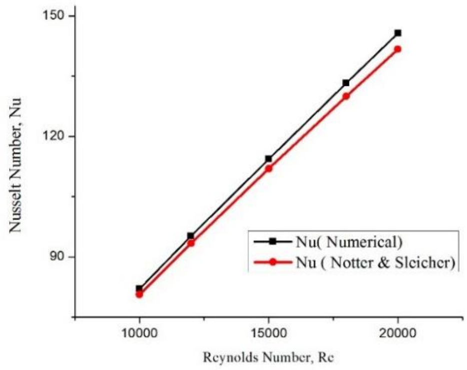

Fig. 2. Code validation

Figure 2 shows good agreement between proposed code and the empirical correlation given by ‘Notter and Sleicher.’

Grid independence test is conducted for the accuracy of the numerical simulations applied in corrugated pipe. A fixed Reynolds number (Re=15,000) and water as base fluid are taken to carry out the grid independence test. Diffreent element sizes has been applied to change the number of elements and Nusselt number is calculated for particular grid number. Number of elements are tested 14,228 , 28,138 , 32,803 , 43,568 , 48,574 and calculated Nusselt number is observed decreasing at first but beyond 32,803 elements, the Nusselt numbers become almost constant with the increase of elements.Therefore, 32,803 has been taken as the optimum grid for the semicircular corrugated pipe. Figure 3 represents the grid independency for the semicircular corrugated geometry.

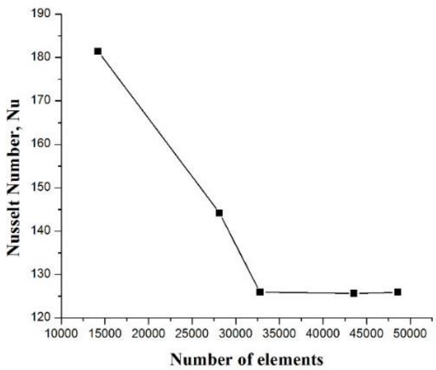

Fig. 3. Grid independence test

7. Result & discussion

7.1 Effect of corrugation on heat transfer performance

For water, taken as base fluid through both circular and semicircular corrugated pipe the effect of corrugation on heat transfer performance is analyzed. It shows improvement in heat transfer rate due to corrugation as the flow pattern and mixing behavior changes. Figure 3 shows improvement on heat transfer performance comparing with plain circular pipe due to the turbulence at the near wall behavior. 34.81 % increase in heat transfer is obtained from the corrugation shape at Reynolds number 18,000.

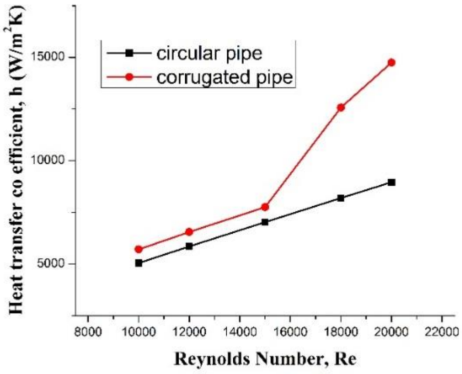

Fig. 4. Comparison of heat transfer enhancement for corrugation

7.2 Effect of corrugation on pumping power

Due to corrugation, pressure drops and frictional loss increases in corrugated pipe. The required pumping power is expected to be increased in the corrugated pipe than plain pipe. Pumping power requirement become higher in the semicircular pipe. Figure 5 represents pumping power variations with Reynolds number for water as working substance through plain and corrugated shape geometry. At Reynolds number 18,000 semicircular corrugated pipe requires 99.125 % of extra pumping power than plain pipe for flowing water through the fluid domain.

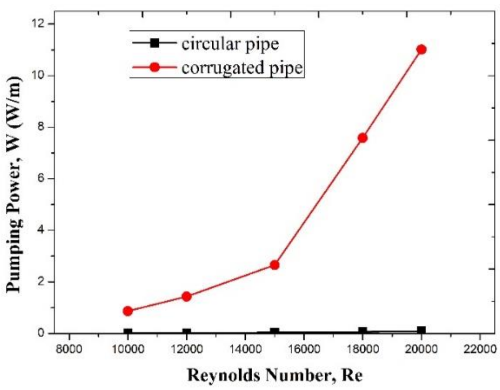

Fig. 5. Variation of pumping power due to corrugation

7.3 Effect of using nanofluid in heat transfer

In this present study, Al_2O_3-water and CuO-water nanofluid are used with 1 % - 5 % volume fraction as the working fluid through the semicircular domain. As the volume concentration of nanofluid increases, the thermal conductivity of the base fluid improves, Figure 6(A) & 6(B) represents significant improvement in heat transfer performance due to nanofluid. The improvement also occurs for a fixed volume fraction nanofluid with the increase of Reynolds number. At Reynolds number of 20,000 the improvement occurs 26.39 % and 24.27 % at highest volume concentration of Al_2O_3 and CuO than water.

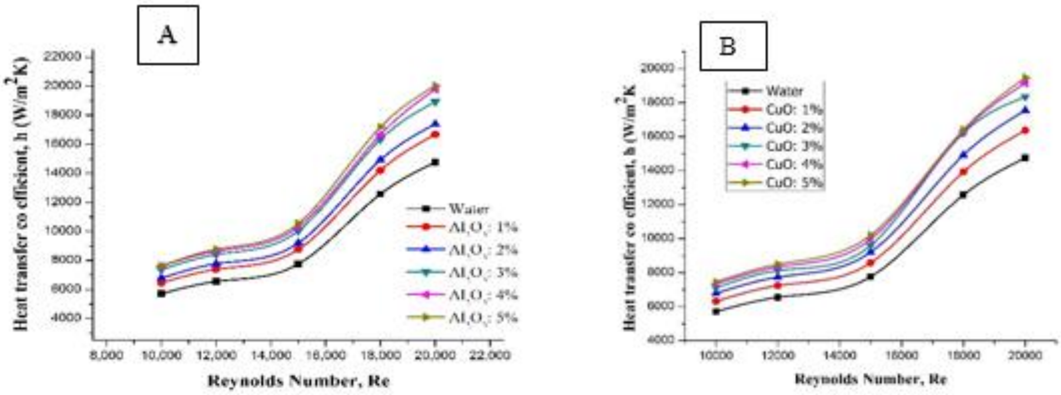

Fig. 6. Heat transfer improvement for (A) Al_2O_3 ,(B)CuO nanofluid with Reynolds number.

7.4 Effect on pumping power using nanofluid

As the volume fraction of nanofluid increases, the requirement of pumping power increases due to higer viscosity of the working fluid. Figure 7 and Figure 8 indicate that pumping power for Al_2O_3 and CuO nanofluid have been increased with the volume fraction of nanofluid is increased from 1 % to 5 %. Higher the volume fraction, higher the pumping power. At 5 % volume fraction of both Al_2O_3-water and CuO-water nanofluid, the pumping power requires 60.49 % and 42.90 % more power in comparison with water through the semicircular corrugated pipe in turbulent regime having Reynolds number 20,000.

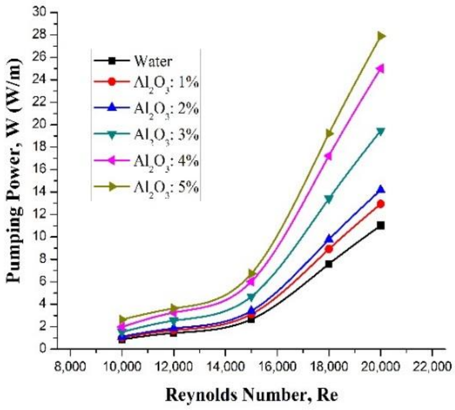

Fig. 7. Pumping Power behavior on increasing Al_2O_3 nanofluid volume fraction.

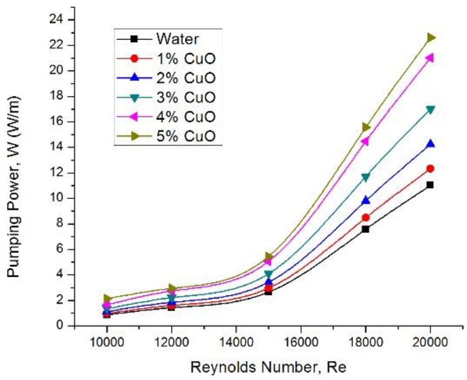

Fig. 8. Pumping Power behavior on increasing CuO nanofluid volume fraction.

7.5 Effect on total wall shear stress for nanofluid

Frictional loss and pressure drop increase for the implementation of nanofluid in increased volume fraction and Reynolds number. More frictional loss increases the total wall shear stress. The total wall shear stress is calculated for two different nanofluid as well as for water. Figure 8 shows variation of total wall shear stress for semicircular corrugated pipe with Reynolds number for 1 % to 5 % volume fraction. Higher total wall shear stress is expected from higher volume fraction of nanofluid due to change in fluid flow behavior in terms of circulation, vortex generation and turbulence. Figure 10 shows nonconventional behavior due to material property. Al_2O_3-water nanofluid is exposed to more wall shear stress than CuO-water nanofluid except 2 % volume fraction.

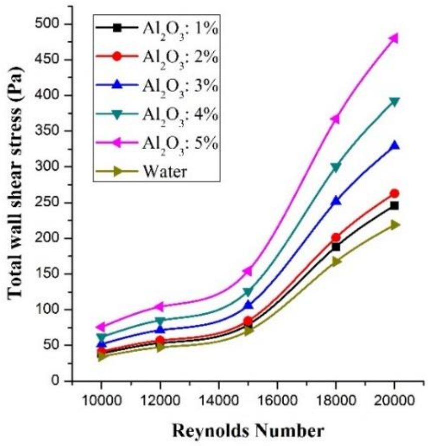

Fig. 9. Variation of total wall shear stress with Reynolds number in semicircular corrugated pipe.

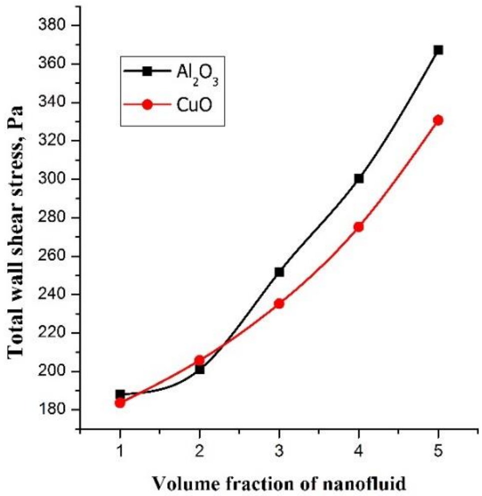

Fig. 10. Effect on total wall shear stress with increasing volume fraction of nanofluid

7.6 Justification on pumping power for specific heat transfer performance

The present investigation is lead to find out the optimum pumping power for specific heat transfer rate. Though heat transfer rate increases at higher volume fraction of nanofluid but adversely it requires higher pumping power due to higher wall shear stress, pressure drop. Figure 11 refers to find out the optimum pumping power on specific heat transfer rate for 1 % - 5 % volume fraction of CuO-water nanofluid comparing with water. 1 % volume fraction of CuO-water nanofluid requires lower pumping power than water through semicircular corrugated pipe at same increased heat transfer rate. For Al_2O_3-water nanofluid, 2 % volume fraction offers lowest pumping power than water for the same fluid domain.

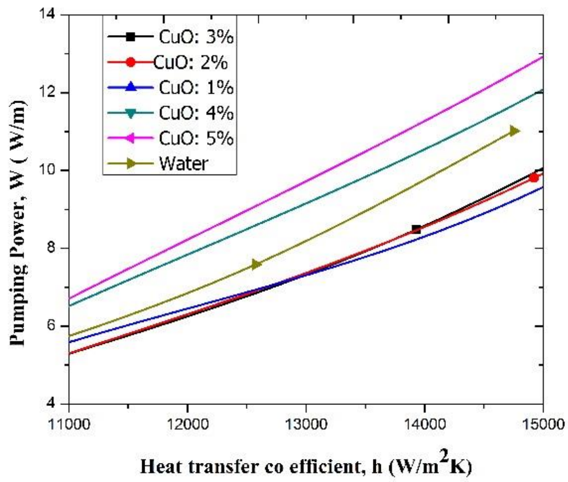

Fig. 11. Pumping Power optimization for CuO nanofluid (Tested range of heat transfer co efficient 11000 W/m^{2}K to 15000 W/m^{2}K)

Both nanofluid have the ability to improve the heat transfer performance than water through the semicircular corrugated pipe. Selecting the perfect nanofluid among two of them for this type of corrugated pipe can be justified from Table 1 based on power advantage, mass flow and other parameters.

Table 1. Comparison of two nanofluid performance with water through semicircular pipe

Working condition	Working Fluid		
	Water	2 % Al_2O_3	1 % CuO
Density (kg/m^3)	996	1040.61	1051.04
Viscosity (kg/m-s)	7.98e-04	8.99e-04	8.58e-04
Specific heat (J/kg-K)	4178	4126.955	4141.47
Requirement of heat transfer coefficient (W/m^{2}K)	14000	14000	14000
Reynolds number (Re)	19000	18000	18000
Velocity (m/s)	1.522	1.546	1.470
Pressure drop (KPa/m)	13	13.5	12.49
Pumping Power(W/m)	9.84	8.62	8.54
Power advantage (W/m)	_	1.22	1.3
Power advantage (%)	_	12.39 %	13.21 %
Mass flow (kg/s)	0.11913	0.1264	0.12143

8. Conclusions

Semicircular corrugated pipe and nanofluid have been used to enhance the heat transfer performance in this investigation. Corrugation in the pipe offers more pumping power due to increased viscosity for flowing fluid through it. Nanofluid compensates the increased pumping power in optimum level comparing with water. Al_2O_3-water and CuO-water nanofluid with 1 % - 5 % volume fraction are used to enhance the heat transfer rate as well as for finding out optimum pumping power than water through the corrugated pipe. 2 % Al_2O_3-water and 1 % CuO-water offer comparatively low pumping power to accomplish same heat transfer rate. Based on power advantage, 1 % CuO- water nanofluid shows superior performance for enhanced heat transfer and reduced pumping power than 2 % Al_2O_3-water through semicircular corrugated pipe. So 1 % CuO may be the suitable solution for enhancing the forced convective heat transfer rate.

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Nomenclature

A_c	Cross-sectional area of pipe, m^2
A_w	Sufrace area of pipe, m^2
C_p	Specific heat, J. kg^{-1}. K^{-1}
D_h	Hydraulic diameter, m
D	Diameter, m
k	Thermal conductivity, W. m^{-1}. K^{-1}
Q	Heat transfer, W
q	Heat flux, W.m^{-2}
T	Temperature, K
U	Velocity at inlet, m. s^{-1}
L	Length of the test section, m

Dimensionless parameter

Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
	friction factor

Greek symbols

ρ	Density, Kg. m^{-3}
τ_0	Total wall shear stress, Pa
ϕ	Solid volume fraction
ν	Kinematic viscosity, m^2. s^{-1}
μ	Dynamic viscosity, Kg. m^{-1}. s^{-1}

Subscripts

av	average value
i	value at inlet
o	value at outlet
bf	base fluid
nf	nanofluid
max	maximun value
min	minimum value
w	water
p	nano

(metal)

particle

f