CONVECTIVE HEAT TRANSFER AND POWER SAVING APPLICATION OF Si BASED NANOPARTICLES IN A CIRCULAR PIPE

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***Abstract*— A numerical study of laminar forced convection heat transfer for the fully developed region inside a pipe filled with Si based nanoparticle is presented for investigating the parameters of heat transfer such as pumping power, Nusselt number, and convective heat transfer coefficient at the presence of various nanoparticle concentrations in base fluid. Four Si based nanoparticles Si, SiC, SiO_2, Si3N4 with 1-5% volume fraction have been mixed with water to prepare nanofluids, which is used for working fluid to flow over a pipe with 5 mm diameter, and 700mm length. Heat transfer characteristics, and pumping power have been calculated at fully developed region with constant heat flux condition on pipe wall to identify the heat transfer enhancement ratio, and pumping power reduction ratio among base fluid water, and each nanofluids. It is worth mentioning that utilizing SiC nanoparticle shows not only the highest increment of Nusselt number, and convective heat transfer coefficient but also the highest decrement of pumping power requirement, and FOM in comparison to the base fluid.**

***Keywords*— Nusselt number; pumping power; convective heat transfer coefficient; figure of merit.**

I. INTRODUCTION

Nanofluid is one of the novel innovations of the modern world. Nanofluid is basically a mixture of high thermal conductive solid nanoparticles with low thermal conductive base fluid, and so mixing the nanoparticles into the base fluid changes some thermophysical properties, i.e. thermal conductivity, specific heat, density, and viscosity of the base fluid. Because of its high heat transfer properties compared to base fluid, Nanofluid provides better efficiency in the heat exchanger. Moreover, for getting the same amount of heat transfer, nanofluid requires comparatively less energy due to its lower pumping power requirement. So, utilizing nanofluids in place of conventional fluid can increase efficiency.

Nanofluid was first projected by Choi and Eastman (1995), and they noticed a significant increment of thermal conductivity by utilizing nanofluid. Agarwal *et al.* (2013) investigated the stability of nanofluid and discovered very higher stability of nanofluid at comparatively low volume fraction. Ehsan *et al.* (2016) explored the capability of heat exchangers to save energy, and identified that not only minimum volumetric flow rate but also a small amount of pumping power was needed for CuO-water, TiO_2-water, and Al_2O_3-water than pure water whenever heat transfer coefficient was fixed. Ingole *et al.* (2017) utilized Al_2O_3-water nanofluid in order to identify car radiator's requirement of pumping power, and found that just a minor amount of pumping power was required whenever Al_2O_3-water was used in place of pure water. Karimzadehkhouei *et al.* (2019) analyzed the impact of inlet temperature for alumina-water nanofluid for thermally developing, and hydro-dynamically developed zone of laminar fluid flow and identified significant effects of inlet temperature for thermally developing region. Using a trapezoidal enclosure, Ahmed *et al.* (2018) identified that the rsing of mean Nusselt number with the decrement, and increment of Richardson number and volume fraction respectively. In addition, heat exchangers related application of nanofluids was reviewed by Pordanjani *et al.* (2019), and a significant enhancement of heat transfer was noticed in almost all cases, which reduced heat exchanger volume, and saved energy.

Moreover, Hussein *et al*. (2017) noticed that the utilization of nanofluid has a significant impact in the case of efficiency improvement of solar collectors. Mohammed *et al*. (2014) examined buoyancy-opposing laminar mixed convection in a vertical duct, and found that SiO_2 nanofluid has the highest Nusselt number at the highest buoyancy level. Chand *et al*. (2015) identified destabilizing effects by using Darcy, as well as Prandtl numbers and stabilizing effects by utilizing modified diffusivity ratio, as well as Lewis number. Meanwhile, Kamel *et al*. (2019) and Al-Rashed *et al*. (2018) also found a significant improvement of heat transfer characteristics by the utilization of nanofluid. Furthermore, the enhancement of heat transfer of Al_2O_3-water based nanofluid in an oval channel was examined by Mashayekhi *et al.* (2020), and the highest heat transfer coefficient in CCI-inward was identified. Qi *et al.* (2019) conducted an experiment utilizing triangle tubes and identified heat transfer enhancement in twisted tape tubes compared to smooth tube. By reviewing recent heat transfer applications.

Sajid and Ali (2019) noticed that the presence of nanoparticles noticeably reduced both boundary layer thickness, and particle clustering and as a result, the heat transfer characteristics of the system significantly improved. Mahian *et al.* (2019) reviewed nanofluids' heat transfer characteristics and discovered the two-phase mixture model as a comparatively easier approach, which usually gives results that are closer to experimental data. Cardona-Castro *et al.* (2016) carried out their study by utilizing Si nanocrystal based nanofluid and found that Si-NCs PL peak shifts are influenced by both interfacial states, and bandgap changes because of temperature effects. Zhao *et al.* (2015) utilized water-based SiC nanofluid inside mini-channel, and noticed the increment of Nusselt number at the beginning stage but it dropped later with the rising of volume concentration. Maouassi *et al.* (2017) worked on SiO_2 nanofluid utilizing a solar flat plate collector, and found a significant heat transfer enhancement whenever Reynolds number, as well as nanoparticles concentration increased. Huminic *et al.* (2017) noticed that not only temperature but also weight concentration increased whenever thermal conductivity of SiC nanoparticles rose.

Hussein *et al.* (2019) noticed that with the growth of Richardson number, and solid volume fractions, average Nusselt numbers rise. Moreover, Kolsi *et al.* (2014) identified a notable growth of the rate of entropy generation, particularly near the warm left sidewall due to the rising of Rayleigh number. Kasmani *et al.* (2017) found that with the increase of the Soret parameter, both the Dufour parameter and the rate of heat transfer are decreased. Mallikarjuna *et al.* (2016) noticed that the flow properties, heat, and mass transfer rate for different transpiration parameter values were significantly affected. Li *et al.* (2017) examined the enhanced oil recovery utilized silica-based nanofluid and identified the application of it as a promising method. Chun *et al.* (2011) investigated the heat transfer characteristics of Si, and SiC nanofluids but they didn't notice any notable variations among the boiling curves' behavior. Li *et al.* (2014) found the increment of thermal conductivity and stability of graphene nanofluid by utilizing SiO_2-coating. Additionally, Ekiciler *et al.* (2019), Kaya *et al.* (2019), Kapıcıoğlu and Esen (2020), He *et al.* (2020), Rabby *et al.* (2019), Iyahraja *et al.* (2019), Singh *et al.* (2019), Rabby *et al.* (2020), Kasmani *et al.* (2017), Belhadj *et al.* (2018) also investigated the impact of nanofluids on laminar convective heat transfer, and their results also identified the improvement and enhancement of heat transfer characteristics by the utilization of nanofluids.

Though there are a number of papers in the literature related to nanofluid, the majority of them analyzed only heat transfer characteristics of few nanoparticles such as Al_2O_3, CuO, TiO_2, Cu, ZnO. Heat transfer characteristics of other types of nanofluid are still under investigation. In addition, until now, no study has been found, which investigated different kinds of Si-based nanoparticles altogether for identifying heat transfer characteristics. Apart from heat transfer characteristics, the requirement of pumping power for flowing fluid is very rare in the literature. Therefore, this study aims to identify both heat transfer, and power-saving applications of various kinds of Si-based nanoparticles (Si, SiC, SiO_2, Si_3N_4) all together in a circular pipe numerically by using a single-phase, 2D axisymmetric control volume method, and Ansys Fluent 19 software. Therefore, it fulfills the gaps, and helps researchers to do further research in the future. The present study can be applied in the industrial field.

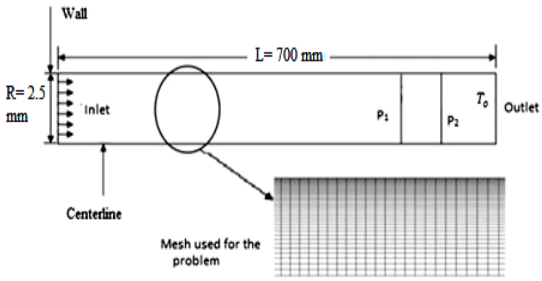


Figure 1: Computational geometry of the circular tube and mesh.

II. METHODS

A. Computational Model and Boundary Conditions

For investigating the "heat transfer rate" as well as the corresponding "pumping power", fixed heat flux is considered on both surfaces of a two-dimensional tube. The flow is considered laminar, and a two-dimensional pipe with 5 mm diameter, and 700 mm length has been presented. At the tube wall boundary, a uniform constant 500 W/m^2 heat flux is exerted, and the tube wall is considered to be in no-slip condition. At the tube inlet, inlet velocity, and constant temperature are set as boundary conditions for allowing the fluids to flow at a uniform temperature of 303 K. At the tube outlet, pressure outlet is considered as boundary condition. The parameters of heat exchange and fluid dynamics are released after making thermal, and hydro dynamic enhancement of the fluid stream. Measurements are computed beyond the entrance length of $x/D = 60$. To determine the heat transfer characteristics as well as pumping power, the surface, and bulk temperatures were examined at a distance of 700 mm from the inlet to outlet. Furthermore, pressures were measured at lines which were situated around 675 mm, and 665 mm from the inlet in order to calculate the pressure drop, and the friction factor. As the region has been considered fully developed, therefore, neither pressure drop, nor friction factor depends on the distance.

B. Numerical Method

For the computational analysis, "ANSYS (Fluent)" has been utilized. Utilizing a control volume method, solution of all governing equations has been done. Moreover, laminar inlet velocity and boundary pressure outlet has been considered at the inlet and outlet respectively. The relaxation factors for density, energy, momentum and pressure have been set to be 0.8, 1, 0.78, and 0.4, respectively. Si-water, SiC-water, SiO_2-water, and Si_3N_4-water nanofluids with different particle volume fractions (1-5%) are tested with a Re= 500 and constant h= 1100 W/m^2-K, and then results are compared with every used nanofluid.

C. Assumptions

Nanofluids has been assumed to be thermally and hydrodynamically stable. In addition, flow has been considered incompressible, single phase, and slip less.

D. Governing Equations

The governing equations are expressed as follows:
Continuity equation: For steady flow, the conservation of mass for nanoparticles can be written as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \tag{1}$$

Here, u and v are the velocity of the fluid at x and y directions respectively.
Momentum equation: For laminar flow, the X-momentum, and Y-momentum equations are:
X-momentum equation,

$$\rho_{nf}\left(u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{dx} + \mu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

Y-momentum equation,

$$\rho_{nf}\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{dy} + \mu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

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

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

Here, C_p is the specific heat at constant pressure, k is the thermal conductivity, and T is the temperature of fluids.

E. Thermal and Fluid Dynamics Properties

The Reynolds number for the flow of nanofluid is expressed as:

$$Re = \frac{\rho_{nf} U_{av} D_h}{\mu_{nf}} \tag{5}$$

The rate of heat transfer,

$$Qnf = m_{nf} C_{P_{nf}} \Delta T \tag{6}$$

Here, m_{nf} is the mass flow rate of nanofluid and $C_{p_{nf}}$ is the specific heat of nanofluid at constant pressure.

The average heat transfer coefficient h_c is given by:

$$h = \frac{Q_{nf}}{A_w(\Delta T)} \tag{7}$$

Here, A_w is the surface area of the circular tube.

The temperature difference between the wall, and the tube is calculated as:

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

The average Nusselt number is defined as follows:

$$Nu = \frac{hD_h}{K_{nf}} \tag{9}$$

Friction factor Darcy-Weisbach equation:

$$f = \frac{64}{Re} \tag{10}$$

The pumping power per unit length is given by:

$$P = \frac{(\pi/4) D^2 U_{av} \Delta P}{L} \tag{11}$$

Here, differential pressure difference:

Table1. Thermophysical properties of nanofluids (Cengel 2014).

Nanofluids	α_{nf} (m^{2}s^{-1})	ρ_{nf} (kgm^{-3})	C_{nf} (Jkg^{-1}K^{-1})	K_{nf} (Wm^{-1}K^{-1})
Si	89.2×10^6	2330	712	148
SiC	230×10^6	3160	675	490
SiO_2	8.34×10^5	2220	745	1.38
Si_3N_4	9.65×10^6	2400	691	16.0

$$\Delta P = \frac{fL\rho U^2}{2D_h} \tag{12}$$

Nusselt number enhancement ratio: $\frac{Nu_{nf}}{Nu_{bf}}$

Overall heat transfer coefficient enhancement ratio: $\frac{h_{nf}}{h_{bf}}$

Figure of Merit:

$$FOM = \left(\frac{h_{nf}}{h_{bf}}\right)\left(\frac{P_{bf}}{P_{nf}}\right) \tag{13}$$

F. Thermo-Physical Properties of Nanofluid

Dynamic Viscosity: There are several equations for dynamic viscosity; among them, we utilize Brinkman (1952) equation. The equation can be expressed as:

$$\mu_{nf} = (1 + 2.5\emptyset)\mu_f \tag{14}$$

Kinematic Viscosity:

$$\alpha_{nf} = \mu_{nf}/\rho_{nf} \tag{15}$$

Thermal Conductivity: Among several equations, we use Maxwell (1873) equation.

$$K_{nf} = \frac{K_p + 2K_{bf} + 2(K_p - K_{bf})\emptyset}{K_p + 2K_{bf} - (K_p - K_{bf})\emptyset} \times K_{bf} \tag{16}$$

Density: Xuan and Roetzel (2000) equation of density for nanofluids is used here. The equation is given below:

$$\rho_{nf} = \rho_p\emptyset + \rho_{bf}(1 - \emptyset) \tag{17}$$

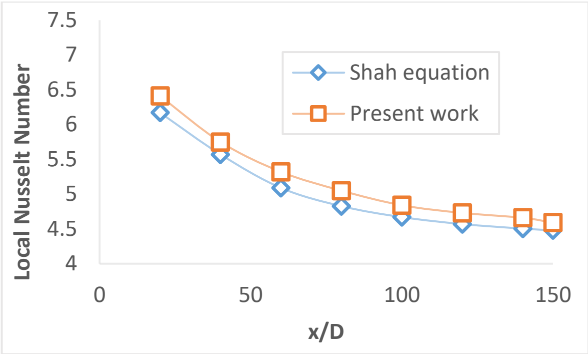
Specific Heat: Pak and Cho (2013) equation is used for specific heat capacity. The equation is given below:

$$C_{nf} = (1 - \emptyset)C_w + \emptyset C_p \tag{18}$$

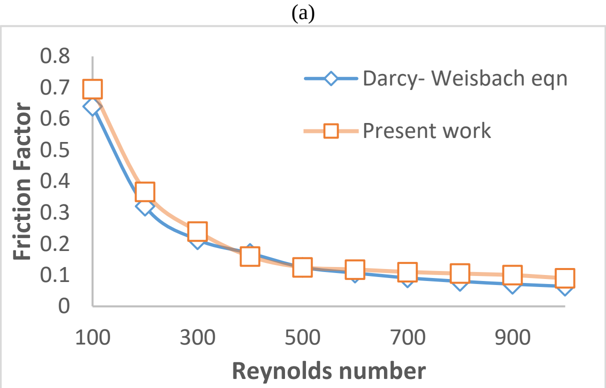
Thermophysical properties of nanofluids are shown in Table 1.

G. Validation of Simulation Model

In the case of laminar tube flow, the movement of water has been done through the tube at a uniform speed and fixed heat flux. For calculating Nu, a range of Re from 300 to 1000 is considered to compare the Nu for the present study with standard Nu for laminar flow at constant heat flux, which is presented in Table 2. Results showed almost close value of Nu for all considered Reynolds numbers with a standard value of Nu. As all the Reynolds numbers almost provided similar value for Nu, therefore for this study we choose only one Reynolds number (500) for further calculation. At the same time, a range of Re (100-1000) has been examined to measure f. At the fully developed zone, comparison of local Nu of present work with Shah equation (Shah and London, 1978) has been conducted, which is shown in Fig. 2(a). It gives a good agreement with only a 2% error for Nusselt number, which is a constant. Additionally, a comparison has been made with the friction factor obtained at the fully developed zone with the Darcy-Weisbach equation, which is shown in Fig. 2(b), and it gives a small amount of error, which is acceptable. The



(a)



(b)

Figure 2: Comparison of Local Nusselt number, and friction factor of present work with (a) Shah equation for Local Nusselt Number, and (b) Darcy-Weisbach equation for friction factor of different Reynolds number.

Table 2. Variation of Nu for present study with standard Nu for different Reynolds Number.

Reynolds Number	Nu for present study	Standard Nu for laminar flow at constant heat flux for pipe
300	4.23	
500	4.48	
700	4.52	4.36
900	4.55	
1000	4.6	

correlation developed by Shah Equation for laminar tube as follows:

$$Nu = 1.302\left(\frac{x^*}{2}\right)^{-\left(\frac{1}{3}\right)} - 0.5, x^* \leq 0.003 \quad (19)$$

$$Nu = 4.364 + 0.263\left(\frac{x^*}{2}\right)^{-0.506} e^{-41\left(\frac{x^*}{2}\right)}, x^* > 0.03 \quad (20)$$

Here, $x^* = \frac{2(x/D)}{Re\ Pr}$

H. Grid Independence Test

Water has been selected as the working substance, and the simulation has been run at a Reynolds number 500 for grid independence investigation. The test has been carried out for discovering the optimum grid size of the current study. In order to establish the impact on the Nu at 700 mm distance, calculated on 700 mm, five diffident grid sizes (500 ×20, 800×25, 900×30, 1000×35, and 1200×40) have been tested, which is shown in Fig. 3.

III. RESULTS AND DISCUSSION

The Nusselt number enhancement ratio of various Si based nanoparticles has been illustrated in Fig. 4 with a

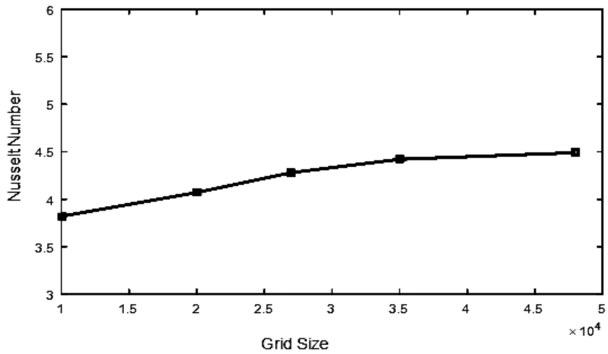


Figure 3: Variation of Nusselt Number for different grid sizes.

constant Re=500. It has been observed that for all Si based nanoparticles, Nu_{nf}/Nu_{bf} increases significantly with the rising of nanoparticles' volume fraction. This is occurred because of the increment of the effective thermal conductivity and an increase of energy exchange rate resulting from the irregular and chaotic motion of ultrafine particles of the nanofluids with the increases of the volume. Moreover, higher enhancement of Nusselt number ratio between nanofluids and base fluid has been noticed with the presence of nanoparticles' volume concentration in water whereas this ratio of SiC nanoparticles is the highest in comparison to others, and the ratio of SiO_2 nanoparticles is the lowest compared to others. Nu_{nf}/Nu_{bf} increases from 4.55% to 20.45% in comparison to pure water by utilizing SiC nanoparticles. In Fig. 5, the comparison of h_{nf}/h_{bf} for Si based nanoparticles is presented. It has been noticed that h_{nf}/h_{bf} increases significantly with the increment of nanoparticles' volume fraction for all Si based nanoparticles. From the results, it is clear that SiC-water provides more enhancements, and SiO_2-water shows less enhancement ratio at constant Reynolds number 500 in comparison to others. Moreover, h_{nf}/h_{bf} increases from 5.5% to 21.5% in comparison to pure water by utilizing SiC nanoparticles. The comparison of h_{nf}/h_{bf} for SiC-water nanofluid is demonstrated in Fig. 6 for various Re, and the increment of h_{nf}/h_{bf} has been noticed with the rising of SiC-water nanofluid's volume fraction, and Re. Re=1000 gives a comparatively higher enhancement ratio, and Re=500 gives a comparatively lower enhancement ratio. Additionally, h_{nf}/h_{bf} increases from 6.5% to 22.5% in comparison to pure water by utilizing SiC-water nanofluid at Re=1000.

The results from Fig. 7 show that at constant Reynolds number 500, pumping power requirements are enhanced whenever nanoparticles' volume fraction increases, and SiC-water, as well as SiO_2-water, required the highest, and the lowest power respectively. Furthermore, P_{nf}/P_{bf} increases from 8.2% to 55.2% in comparison to pure water by utilizing SiC nanoparticles. On the other hand, at a constant value of h= 1100 W/m^2-K, whenever nanoparticles' volume fraction increases, the pumping power requirement dropped significantly, which is shown in Fig. 8. Therefore, for achieving the same heat transfer rate, the more we add nanoparticles,

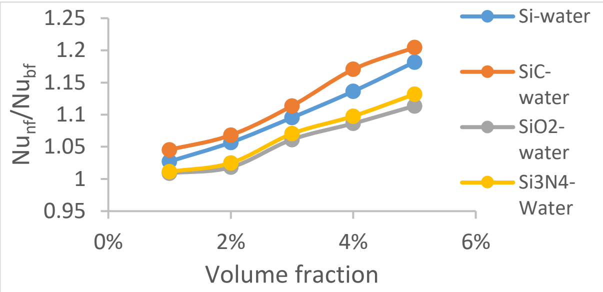


Figure 4: Variation of Nu_{nf}/Nu_{bf} with volume fraction of different types of Si based nanoparticles at Re= 500.

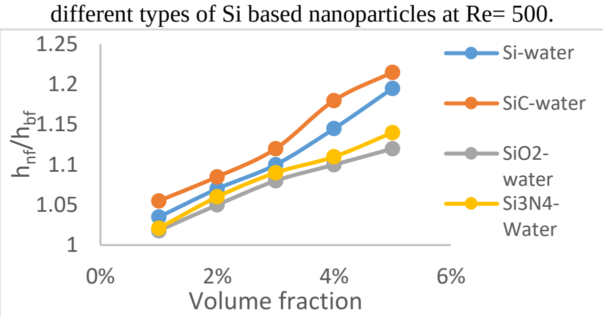


Figure 5: Variation of h_{nf}/h_{bf} with volume fraction of different types of Si based nanoparticles at Re= 500.

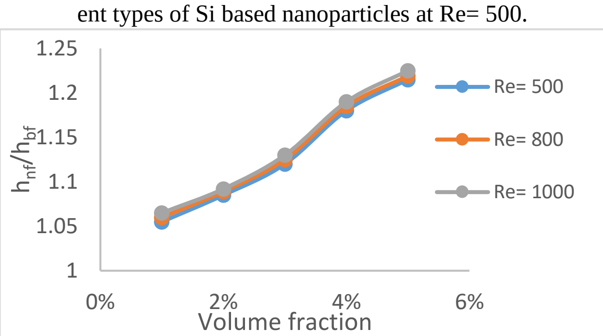


Figure 6: Variation of h_{nf}/h_{bf} with volume fraction of SiC-water nanofluid for different Reynolds number.

the more pumping power requirement will be decreased, and this is the big advantage of using nanofluid. In this case, among all the nanofluids, SiC-water required the lowest power, and SiO_2-water required the highest power. Additionally, P_{nf}/P_{bf} decreases from 11% to 47% in comparison to pure water by utilizing SiC nanoparticles at a constant heat transfer condition. For evaluating the performance of the utilized nanoparticles in terms of pumping power, another performance parameter FOM has been calculated at constant h= 1100 W/m^2-K, which is exhibited in Fig. 9. FOM is the ratio of heat transfer rate and required pumping power. A lower value of FOM indicates better performance of nanoparticle. SiO_2-water nanofluid shows the highest value, and SiC-water provides the lowest value of FOM at constant h=1100 W/m^2-K. This behavior is occurred due to the highest and the lowest density of SiC and SiO_2 nanoparticles respectively, which affect the fluid's velocity and flow behavior. Moreover, FOM decreases from 6.11% to 35.61% in comparison to pure water by utilizing SiC nanoparticles.

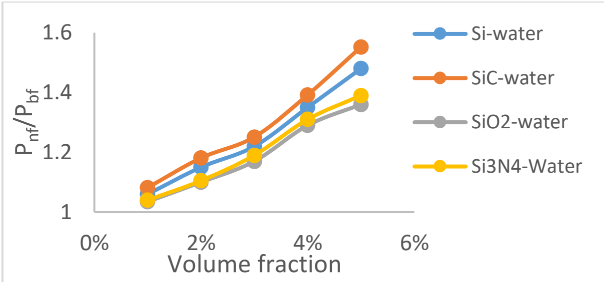


Figure 7: Variation of P_{nf}/P_{bf} with volume fraction of different types of Si based nanoparticles at Re= 500.

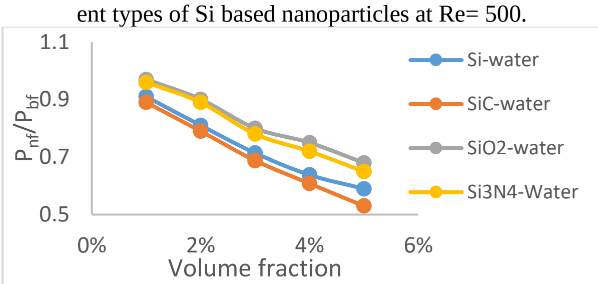


Figure 8: Variation of P_{nf}/P_{bf} with volume fraction of different types of Si based nanoparticles at h= 1100 W/m^2-K.

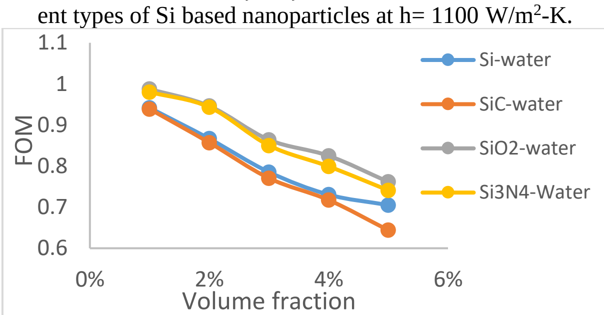


Figure 9: Variation of FOM with volume fraction of different types of Si based nanoparticles.

IV. CONCLUSION

In this study, four Si-based nanoparticles were computationally investigated after mixing up with base fluid to calculate h_{nf}/h_{bf}, and P_{nf}/P_{bf} in a pipe. Single-phase laminar flow with the control volume method for 2D axisymmetric pipe was considered for this numerical analysis by using Ansys fluent software. 1-5% volume fraction of Si, SiC, SiO_2, and Si_3N_4 was considered to prepare nanofluids. However, the results understandably illustrate that the presence of nanoparticles' volume fraction in the base fluid enhances Nusselt number up to 20.45%, heat transfer coefficient up to 21.5% wherein SiC, and SiO_2 nanoparticles show the highest, and the lowest enhancement respectively. On the contrary, the presence of nanoparticles volume fraction in the base fluid increases pumping power requirements up to 55.2% for constant Re, while it is reduced up to 47% for constant h. Furthermore, SiC, and SiO_2 nanoparticles show the highest and the lowest growth respectively for constant Re but in terms of constant h, SiC, and SiO_2 nanoparticles show the highest, and the lowest reduction respectively. Additionally, the presence of nanoparticles' volume fraction in base fluid reduces FOM. The reduction is up to 35.61% at constant heat transfer coefficient wherein SiC, and SiO_2 nanoparticles show the lowest and the highest reduction respectively.

NOMENCLATURE

$\emptyset$	Volume concentration
T	Temperature (°C or K)
ρ	Density (kgm^{-3})
U_{av}	Average inlet velocity (m/s)
D_h	Hydraulic diameter (m)
m	Mass flow rate (kg/s)
Q	Heat transfer rate (J/s)
K	Thermal conductivity ($Wm^{-1}.K^{-1}$)
μ	Dynamic Viscosity ($kg\cdot m^{-1}\cdot s^{-1}$)
h	Average heat transfer coefficient ($Wm^{-2}K^{-1}$)
ΔT	Temperature difference (°C or K)
C_p	Specific heat at constant pressure ($J.mol^{-1}.K^{-1}$)
Δp	Pressure difference (Pa or N/m^2)
f	Friction factor
P	Pumping power (KW)
Re	Reynolds number
Nu	Nusselt number
Pr	Prandlt number
Subscripts	
i	Inlet
o	Outlet
w	Wall
nf	Nanofluid
bf	Basefluid
p	Particle size

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