ICMIEE18-147

Numerical Study of Pumping Power and Volumetric Flow Rate Advantage of SiC-Water Nanofluid through a Channel

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ABSTRACT

The numerical analysis of laminar heat convective heat transfer of Silicon Carbide (SiC) - water Nanofluid for the developed region through two parallel plates is presented in this present work. The second order single phase energy equation, mass and momentum equation are solved by using finite volume method with the ANSYS FLUENT 16 software. The distances between two parallel plates are 4mm and length 600mm respectively. Silicon Carbide (SiC) is used as nanoparticle and water is used as the base/working fluid for the investigation. At the time of simulation 1% to 5% volume concentration of the SiC nanoparticles are used for mixing with water to produce Nanofluid. A wide range of interval of Reynolds number from 500 to 1100 at constant heat flux 500 W/m^2 at the channel wall has been also introduced. The result revels that for increasing the Reynolds number the Nusselt number and heat transfer coefficient are increased linearly in the developed region for both water and SiC-H_2O nanofluid. At constant Reynolds number by increasing the volume fraction of SiC-H_2O nanofluid from 1% to 5% the value of Nusselt number and heat transfer coefficient has been increased compared to pure water. And at constant heat transfer coefficient SiC-water nanofluid required 10% to 80% less pumping power and 4% to 25% less volumetric flow rate compared to pure water.

Keywords: Volume concentration, constant heat flux, pumping power, volumetric flow rate.

1. Introduction

From the last few decades the importance and research on nanotechnology is the most fundamental and effective topics of thermal engineering. At present to improve heat transfer efficiency and heat transfer rate nanoparticles are used with base fluids. Beside this the utilization of pumping power to get this enhancement is also less and this is the most advantage thing to using nanoparticles in working fluids. Basically by adding small amount of solid particles with the base or working fluid, the thermal conductivity of the fluid can be increased noticeably. And by using these concept researchers has been made nanofluid which is the combination of base fluid (water ,engine oil or ethylene glycol) and very small amount of solid particles at Nano scale size (1nm to100nm). Al_2O_3 CuO, TiO_2, SiC, SiO_2, Fe_2O_3, MgO etc. particles are used as nanoparticles to mix with base fluids. Different researchers carried out their investigation on nanofluids. In 1995-1996 Choi and Eastman [1] reinvestigated with their Nano scale metallic particle and carbon nanotube suspensions in Argonne National Laboratory. Choi and Eastman have tried to suspend various metal and metal oxides nanoparticles in several different fluids (Choi (1998) [2]; Choi et al. (2001) [3]; Choi et al. (2005); Choi et al. (2006)[4]; Eastman et al. (2001); Eastman et al. (1999); Eastman et al. (2004)) and their result are promising. From their investigation they also observed that many things remain vacuous about these suspensions of Nano-structured materials, Choi and Eastman have been termed these as “Nano fluid” Xuan and Li, 2003[5] examined the convective heat exchange and the stream highlights of Cu– water Nano fluids in a 10-mm inward distance across tube. The trial comes about because of their investigation, in the turbulent area showed that the friction factors of the Nano fluids, between 1 and 2 vol. % fractions are generally the same as those of water flow. Williams et al., 2008 [6] experimentally explored the turbulent stream of alumina–water and zirconium– water Nano fluids in tubes. They found that current connections for single-stage stream can enough anticipate Nano fluid stream convective heat exchange and weight drop. Rea et al., 2009[7] led an investigation on the laminar convective warmth exchange and weight drop of alumina– water and zirconium– water Nano fluids in a tube with 4.5-mm inward width. Their discoveries demonstrated that, with appropriately measured Nano fluid properties, there is no deviation in convective heat exchange and weight drop of Nano fluid spill out of customary single-stage stream hypothesis. Heris et al.,2013 [8] played out an exploratory investigation to decide the pressure drop and heat exchange qualities of Al_2O_3/water and CuO/water nanofluids in a triangular conduit under consistent heat flux where the flow was laminar. Their outcomes demonstrated that, at similar estimations of nanoparticle volume division and Reynolds number, utilizing Al_2O_3 nanoparticles is more beneficial than CuO nanoparticles. Wen and Ding, 2004[9] also investigated with laminar convective heat transfer using Al_2O_3 nanofluid. Hwang and Choi, 2009[10] also worked on it and showed that 3% volume concentration of Al_2O_3 nanofluid gives 8% enhancement of heat transfer coefficient. M. Monjur and A.K.M [11] investigated on energy savings of heat exchanger and they showed that for constant heat transfer coefficient Al_2O_3-water, CuO-water and TiO_2-water required less pumping power and volumetric flow rate compare to pure water. P.A. Ingole, S.M. Shinde and P.A. Patil [12] investigated on pumping power of car radiator

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by using Al_2O_3 -water nanofluid and they find that 2% volume concentration Al_2O_3-water need 23.81% less pumping power compared to pure water.
From the above literature review it is clear that almost all the researches are on heat transfer enchantment argumentation of nanofluid but the justification of implementing nanofluid in terms of increased pumping power due to the improvement of thermo-physical properties has not been studied elaborately. And so the present work focus on how SiC-water nanofluid influences the pumping power and volumetric flow rate of 2 dimensional single phase laminar convective channel flow.

2. Physical Model and Boundary Conditions:

A 2D Parallel plate with a steady heat flux connected on its surface can be considered as the least difficult case to investigate heat transfer rate and corresponding pumping power requirement. In order to investigate the performance of Nanofluid in a channel, a numerical study has been carried out by employing commercial computational fluid dynamics software ANSYS Fluent. Laminar flows through a channel the distance between two horizontal plates are 4mm and 600 mm length is presented. A constant uniform heat flux of 500 W/m^2 is applied at the wall boundary of the parallel plates and fluid is permitted to stream with a fitting speed and uniform temperature of 303 K at the inlet of the parallel plates with a presumption of no slip condition on the parallel plate's wall. All the fluid dynamic and heat exchange parameters are extricated after the hydrodynamic and thermal improvement of the fluid stream and in this case the entrance length is x/D=60 beyond which all the measurements are taken. For calculating the heat transfer enhancement and friction factor the temperatures are taken at line which is drawn 590mm distance from inlet and pressures are taken at 565mm and 555mm from the inlet.

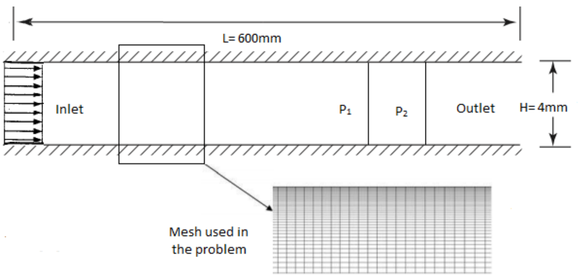

Fig.1 Physical model of the numerical problem and the corresponding mesh of the domain.

3. Numerical Method and Methodology:

A commercial computational fluid dynamics software ANSYS (Fluent) for this numerical analysis has been used. All the governing equations for mass, momentum, energy, and laminar quantities are solved using a control volume technique. At inlet laminar inlet velocity and at the outlet boundary pressure outlet is considered. Under relaxation factors 0.4 for pressure, 0.76 for momentum equation, 1 for energy equation, and 0.9 for density equation are considered for parallel plate. SiC-water nanofluids with different particle volume fractions (1, 2, 3, 4, and 5%) are tested with a wide range of Reynolds number (400-1100 for parallel plate) and then results are compared with base fluid water.

3.1 Governing Equation:

The governing equation for continuity, momentum and energy for forced convection under laminar flow and steady-state conditions are expressed as follows. Beside this equation for Reynolds number, Nusselt number, heat transfer rate, average heat transfer coefficient, friction factor, pressure difference, pumping power and thermophysical properties equation (density, specific heat, viscosity, thermal conductivity etc) of nanofluids also expressed here.

Continuity Equation:
In steady flow, the amount of mass within the control volume under remains constant, and thus the conversation of mass can be expressed as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Momentum Equation:
For laminar flow, the momentum equation can be expressed as:

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

Energy Equation:
Energy can be transferred by heat, work, and mass only, the energy balance for a steady-flow control volume can be write explicitly as

$$(E_{in}- E_{out}) = -\rho c_p\left(u\frac{\partial T}{\partial x}+T\frac{\partial u}{\partial x}\right)dx.dy -\rho cp\left(v\frac{\partial T}{\partial y}+T\frac{\partial u}{\partial y}\right)dx.dy$$

$$= -\rho c_p\left(u\frac{\partial T}{\partial x}+T\frac{\partial T}{\partial y}\right)dx.dy \tag{3}$$

The Reynolds number for the flow of Nanofluid is expressed as: $Re=\frac{\rho_{nf}U_{av}D_h}{\mu_{nf}}$ (4)

The rate of heat transfer Q_{nf} to the tube wall is assumed to be totally dissipated to Nanofluid flowing through a channel, raising its temperature from inlet fluid bulk temperature T_{bi} to exit fluid bulk temperature T_{bo}. Thus,

$$Q_{nf}=m_{nf}C_{P_{nf}}(T_{bo}-T_{bi}) \tag{5}$$

Where m_{nf} the mass flow rate of nanofluid is, $C_{p_{nf}}$is the specific heat of Nano fluid at constant pressure.
The average heat transfer coefficient h_c is given by:

$$h_c=\frac{Q_{nf}}{A_w(\Delta T)} \tag{6}$$

Where A_w is the surface area of circular tube and the temperature difference between the wall and calculated as:

$$T = \frac{(T_w - T_o) - (T_w - T_i)}{\ln\left(\frac{T_w - T_o}{T_w - T_i}\right)} \quad (7)$$

So the expression of average Nusselt number is defined as follows:

$$Nu = \frac{h_c D_h}{K_{nf}} \quad (8)$$

Pressure difference: $\Delta P = \frac{f L \rho U^2}{2 D_h}$ (9)

Then, the Darcy friction factor, for laminar flow is:

$$f = \frac{64}{Re} \quad (10)$$

The pumping power per unit length in laminar flow is given by:

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

Thermal and fluid dynamic Properties of Nanofluid:

Dynamic Viscosity:

In 2007, Chen et al. showed a relation for finding the viscosity of nanofluids up to the volume fraction 10% Chen et al. eq^n [13]:

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

Thermal Conductivity:
A wide range of experimental and theoretical studies were conducted in the literature to model thermal conductivity of nanofluids. The existing results were generally based on the definition of the effective thermal conductivity of a two-component mixture. . There are several thermal conductivity equations among them for SiC we use Maxwell mode equation [14]

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

Density:
Using classical formulas derived for a two-phase mixture density (Xuan and Roetzel, 2000) of the nanofluid as a function of the particle volume concentration and individual properties can be computed using following equation [15]:

$$\rho_{nf} = \rho_p \emptyset + \rho_{bf}(1 - \emptyset) \quad (13)$$

Specific Heat:
Using classical formulas derived for a two-phase mixture, the specific heat capacity (Pak and Cho, 1998) of the nanofluid as a function of the particle volume concentration and individual properties can be computed using following equation [16]:

$$C_{nf} = (1 - \emptyset)C_w + \emptyset C_p \quad (14)$$

4. Code Validation Test

For laminar channel flow at uniform velocity and constant heat flux water has been passed through the channel and a range of Reynolds number 400-1100 has been considered for calculating Nusselt numbers. At fully developed zone the obtaining Nusselt number is compared with the constant value of Nusselt number 8.23 (at constant heat flux for parallel plate) and with the Pahor and Turton [17] theoretical equation which is shown in Figure 2.
Pahor and Turton equation at constant heat flux as follows:

$$Nu = 8.24\left(1 + \frac{3.79}{Pe^2} + \cdots\right), \quad Pe \gg 1 \quad (15)$$

$$Nu = 8.118(1 - 0.031Pe), \quad Pe \ll 1 \quad (16)$$

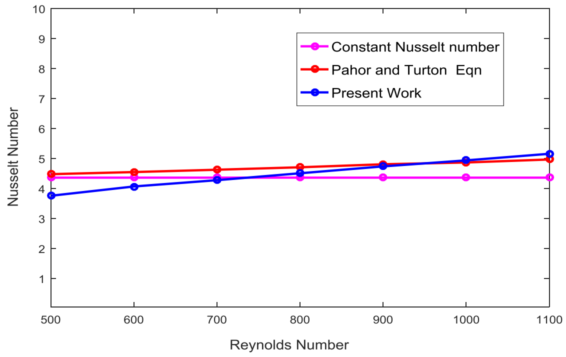

Fig. 2: Comparison of Nusselt number between Pahor and Turton equation, constant Nusselt number at constant heat flux and present work

5. Result and discussion:

The figure 3 shows the effect of volume fraction and Reynolds number on the nusselt number of SiC-water, from the figure it has been obtained that the Nusselt number of the nanofluid used in the present work increases with the increase in Reynolds number and Volume fraction of the nanofluids. 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. S. Zeinali Heris, 2006 [8] worked with laminar convective heat transfer of circular tube by using Al_2O_3-water and CuO-water nanofluids and investigated that the nusselt number is increased for both nanofluids respectively with increasing the volume fraction of the nanofluids and with the increment of Peclet number that indicates the increment of Reynolds number and this trend is observed in figure 4. Pak and Cho et el [16] also investigated that the Nusselt number for fully developed turbulent flow increased correspondingly to the increasing volume fraction as well as Reynolds number for γ-Al_2O_3 –water and TiO_2-water nanofluids which trend is also similar to the present work.

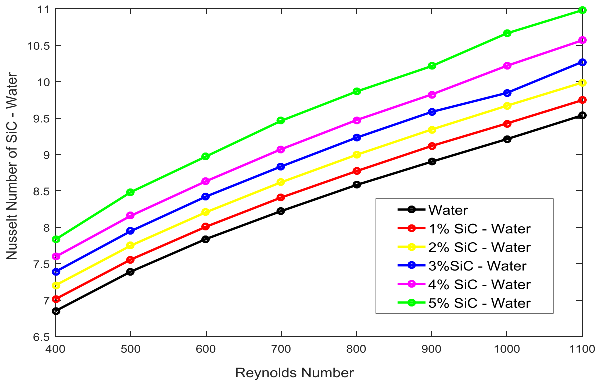

Fig. 3 Comparison of Nusselt number with Reynolds number of different volume fraction of SiC-water Nano fluid

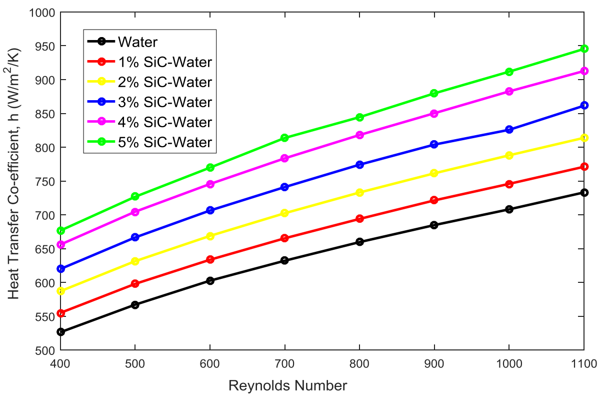

Fig. 4: Comparison of Heat transfer coefficient with Reynolds number of different volume fraction of SiC-water Nano fluid

The figure 5 represents the effect of volume fraction of nanofluids on heat transfer co-efficient for different Reynolds number. From the figures it is observed that the value of heat transfer coefficient increases rapidly with the increase of volume concentration and Reynolds number. This is due to the increases of the thermal conductivity and decreases of the specific heat capacity of the Nano fluid which increases the Nusselt number with higher velocity and temperature gradient and this phenomenon increases the heat transfer coefficient gradually. According to Wen and Ding, 2006[9] the numerical study of the particles migration due to viscosity gradient and a non-uniform shear rates leads to higher heat transfer coefficient of nanofluids. From the figures the increment of heat transfer coefficient compared to pure water is 7.2% to 31.5% for Al_2O_3-water with respect to 1% to 5% volume concentration for Reynolds number 500 to 1400. S. Zeinali Heris and Esfahany, 2006[8] investigated convective heat transfer of circular tube by using Al_2O_3-water nanofluid and observed that the heat transfer coefficient increases rapidly with the increases of Reynolds number with respect to increase of volume concentration that satisfied the present work. Another same investigation was carried by Lin-wen Hu , 2000[18] with Al_2O_3-water and Zirconia-water and reported that at fully developed region the heat transfer coefficient increases 27% for Al_2O_3-water and 3% for zirconia-water nanofluid that also almost similar to the present work. Sezer Ozerinc, 2010 [19] also proposed that for Al_2O_3-water nanofluid the heat transfer coefficient increases rapidly compare to pure water with the increment of Reynolds number and volume fraction. Figure 5 represent the effect of volume fraction on pumping power for different Reynolds number and the figure shows us that with the increase in Reynolds number with respect to volume concentration the required pumping power is also increasing both for water and four nanofluids. And it is also observed from the figures that the Nanofluid required more pumping power compared to pure water. At relatively lower Reynolds number the difference among the values of pumping power per unit length for different volume fraction is comparatively smaller. The figure 6 shows the variation of changing pumping power per unit length of nanofluids with different values of heat transfer coefficient and volume concentration. From graphs it is seen that by increasing the values of heat transfer coefficient, the pumping power becomes higher. The pumping power for SiC-water nanofluids is reduced 11% to 83% for ϕ = 1% to 5% compared to pure water for same heat transfer rate. A similar trend is also analyzed by M. Monjurul Ehsan [11] for turbulent convective heat transfer of pipe flow by using Al_2O_3-water, CuO-water and TiO_2-water nanofluids.

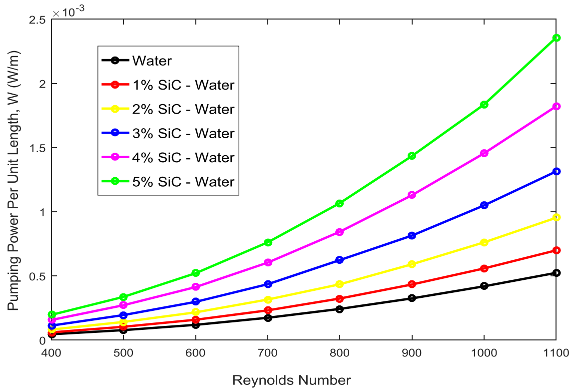

Fig. 5: Comparison of Pumping power with Reynolds number of different volume fraction of CuO-water Nano fluid

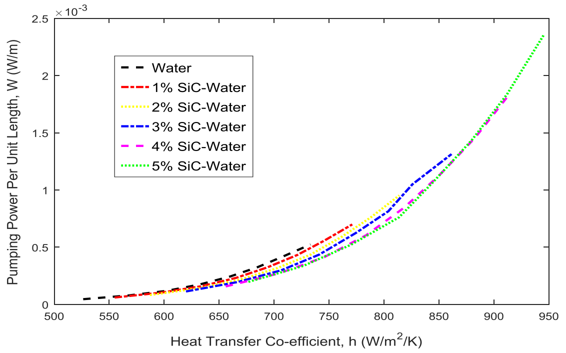

Fig. 6: Comparison of Pumping power with Reynolds number of different volume fraction of CuO-water nanofluid

The table1 shows the performance comparison pumping power advantage and reduction of volumetric flow rate of different volume fraction of SiC-water nanofluid with base fluid. From the table it is clear that at constant heat transfer coefficient the Reynolds number, velocity pumping power and volumetric flow rate of nanofluid has been reduced compared to pure water and the reduction is increased by increasing the volume concentration of the nanofluid. And so to get same heat transfer coefficient nanofluid needs lower pumping power and volumetric flow rate compared to pure water. This reduction is 11% to 83% for pumping power and 8% to 24.2% for volumetric flow rate compared to pure water.

Table 1: Comparison of the performance of different volume concentration of SiC-water nanoparticles with base fluid.

Type of fluid parameters	Water	1% SiC	2% SiC	3% SiC	5% SiC
Heat Transfer coefficient $W/m^2.K$	700	700	700	700	700
Reynolds number	967	810	695	585	450
Velocity m/s	0.09685	0.044323723	0.041872801	0.038946054	0.036705767
Thermal conductivity	0.633	0.652	0.671	0.691	0.711
Pumping power per unit length W/m	0.000387	0.000341	0.000230	0.000150	0.0000655
Power advantage (%)	-	11.88%	40.56%	61.24%	83%
volumetric flow rate, m^3/s	4.868E-06	4.45E-06	4.20952E-06	3.9159E-06	3.69007E-06
Reduction in volumetric flow rate	-	8.47%	13.5%	19.6%	24.2%

8. Conclusion

In the present work SiC-water nanofluid have been analyzed through a typical channel to investigate the heat transfer enhancement and pumping power and volumetric flow rate reduction. The heat transfer coefficient and Nusselt Number drop increase with the increase in volume fraction for the nanofluid as well as with the Reynolds number compared to pure water. And to get same heat transfer coefficient SiC-water required less pumping power and volumetric flow rate compared to pure water.

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Nomenclature

C_p: Specific heat at constant pressure
D_h: Hydraulic diameter
f: Friction factor
h: Average heat transfer coefficient
k: Thermal conductivity
m: Mass flow rate _
v: Volumetric flow rate
Δp: Differential pressure loss
Q: Heat transfer
T: Temperature
T_0: Reference temperature, 273 K
u: Velocity of flow at inlet