Numerical investigation of heat transfer augmentation in curved channel using hybrid nanofluids

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Convective heat transfer can be enhanced by changing flow geometry and/or by enhancing thermal conductivity of the fluid. In this work, CFD modelling of horizontal straight and curved channel with square cross section were presented to investigate the effect of hybrid nanofluids on turbulent forced convective heat transfer. This study proposes simultaneous passive heat transfer enhancement by combining the geometry effect using 0.1% graphene nanoplatelets-silver hybrid nanofluids (GNP–Ag) inflow in straight and curved channel. The results showed that the average Nusselt number is generally higher for curved channel with hybrid nanofluid when compared with straight square channel. Moreover, for 0.1% of GNP–Ag hybrid nanofluid improvement is 22.61% and 34.78% for straight channel and 27.43% and 39.52 for curved channel at the Reynolds number of 5,000 and 17,500, respectively.

Keywords: Heat transfer; turbulent flow; hybrid nanofluid; curved channel; straight channel.

1. INTRODUCTION

According to the importance of energy in the world, so far, many attempts have been made to increase energy efficiency [1, 2]. One way is the use of fluids with higher heat transfer coefficient, by the addition of metal, non-metal and metal oxide particles with higher thermal conductivity into conventional fluids. Development of fluids thermal properties leads to more energy efficient, smaller size, lighter weight and lower operational costs for thermal systems like heat exchangers. The particles added to the base fluid should be in nanometer size, because the larger particles and cause problems such as erosion, sedimentation, clogging and higher
fluid resistance. Masuda et al. [3] and Choi et al. [4] were the first to raise the idea of using nanofluids. Bergman [5] investigated the effects of increasing thermal conductivity and reducing the specific heat of the nanofluid relative to the base fluid and quantified heat transfer enhancement. They show that using nanofluid instead of pure liquids can either enhance or degrade thermal performance.

In the recent years, significant investigations on the use of carbon-based nanomaterials such as, single-wall carbon nanotube, multi-wall carbon nanotube, graphene oxide and graphene nanoplatelets (GNP) to make nanofluids were reported in the literature [6-8]. New research indicates that graphene nanofluids could provide higher thermal conductivity enhancement in comparison to other tested nanofluids. Graphene particles have better thermal conductivity and also higher mechanical strength, and electrical conductivity. Favourable thermo-physical properties of graphene have made it an excellent candidate for use in nanofluids [9]. In addition, synthesizing graphene nano articles is relatively easy and cost effective. Small variation in properties of graphene has been reported due to different methods used to manufacture one layer or multi-layer graphene such as, exfoliation of graphene oxide layer, deposition with chemical vapor and mechanical cleavage, etc. [9-11].

Channels with non-circular geometry are usually excluded from many applications. For one reason, this kind of ducts has very low rate of heat transfer. On the other hand, the pressure drop in non-circular cross sections is much less than that compared to circular cross sections. It should be stressed that the friction factors in rectangular and circular tubes equal to 56.92/Re and 64/Re, respectively. Therefore, heat transfer enhancement of the channels with non-circular ducts can result in its wide applications in different industries. Furthermore, they have other advantages such as high compaction in comparison with other kind of channels, high mechanical resistivity, easy forming using thin metal, and low-pressure drop, triangular and square ducts which make them beneficial to be utilized in compact heat exchangers, combustion engines, boilers, nuclear reactor and energy recovery equipment, furnaces, rockets, medical and electronics industries. Due to the importance of low-pressure drop in these applications, heat transfer enhancement can open up great opportunists [17].

Considering the literature review about nanofluids, the aim of this study is to investigate and compare the heat transfer enhancement of graphene nanoplatelets–silver hybrid nanofluids (GNP–Ag) through the straight and curved channel with square cross-section in the turbulent flow regimes under constant heat flux boundary condition for the wall.

2. NUMERICAL MODEL

The computational domains were created in Free CAD as shown in Fig.1; the length of the copper channel is 500mm and the height and width are 2mm. The commercial pre-processor software GAMBIT 2.3.16 was used for meshing, labelling boundary conditions and determines the computational domain. Three different meshes, $1 \times 10^5$, $2 \times 10^5$, and $4 \times 10^5$, were tested and compared in terms of the local pressure, velocities, and temperature to ensure a mesh independent solution. It is found that mesh number of around $2 \times 10^5$ gives about 1% deviation compared to mesh size of $4 \times 10^5$; whereas the results from mesh number of $1 \times 10^5$ deviate by up to 8% compared to those from the finest one. Therefore, a mesh of around $2 \times 10^5$ ($20 \times 20 \times 500$) elements was considered sufficient for the numerical investigation purposes; a fine
structured mesh near the wall to resolve the boundary layer and an increasingly coarser mesh in the middle of the channel to reduce the computational cost.

![Diagram of straight and curved channels](image)

**Fig. 1** Shapes of straight and curved channel

### 2.1 Governing equations

The realizable k-ε turbulence model with wall heat treatment is used for turbulent flow simulation. The Realizable turbulence model by Shih et al.[12] is the most sophisticated model newly of the three k-ε differences and characteristics two main variations from the standard k-ε model. It utilizes a new equation for the turbulent viscosity equation and derived the dissipation rate transport equation from the mean-square vorticity fluctuation equation. Turbulent kinetic energy, k, and turbulent dissipation rate, ε, are combined to the governing equations using the relation of the turbulent viscosity $\mu = \rho C_{\mu} K^2/\epsilon$, where $C_{\mu}=0.09$ and the following values have been assigned as an empirical constant: $C_2=1.9$, $\sigma_r=0.85$, $\sigma_c=1.0$, and $\sigma_\epsilon=1.2$. 
\[ k = \frac{3}{2} (u_I)^2, \varnothing = C_{\mu}^{3/4} \frac{k^{3/2}}{L} \]  

(1)

Furthermore, the character L. in Eq. 6 refer to the turbulent characteristic length scale, which is set to be 0.07(d/2) in the current study. As well as the factor of 0.07 been adopted based on the maximum value of the mixing length in fully developed turbulent pipe flow. For an initial guess of turbulent quantities (k and \( \varnothing \)), the turbulent intensity (I) was specified. Where the turbulent intensity for each case can be calculated based on the Eq. 2. [13].

\[ I = 0.16 \times \text{Re}^{-1/8} \]  

(2)

ith regards to the nanofluid, infinitesimal (less than 100 nm) solid particles assumed to be able using single phase approach, so single phase approach adopted for nanofluid modelling. For all these assumptions, the dimensional conservation equations for steady state mean conditions are as follows: continuity, momentum and energy equations.[14].

\[ \frac{\partial u}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} (r \rho_{nf} u) = 0 \]  

(3)

\[ u \frac{\partial u}{\partial x} + v \frac{\partial}{\partial r} (r \rho_{nf} u) = - \frac{\partial p}{\partial x} + \frac{1}{r} \frac{\partial}{\partial r} \left[ r (\nu + \varnothing_H) \frac{\partial u}{\partial r} \right] \]  

(4)

\[ \frac{1}{r} \frac{\partial}{\partial r} (\rho u T) = \frac{1}{r} \frac{\partial}{\partial r} \left[ r (\alpha + \varnothing_H) \frac{\partial T}{\partial r} \right] + \frac{1}{r^2} \frac{\partial}{\partial x} \left[ \frac{k_{nf}}{C_p} \frac{\partial T}{\partial x} \right] \]  

(5)

3. THERMO-PHYSICAL PROPERTIES OF HYBRID NANOFLUIDS

The thermo-physical properties of graphene nanoplatelets–silver hybrid nanofluids (GNP–Ag) in this study such as thermal conductivity (\( k_{nf} \)) and viscosity (\( \varnothing_{nf} \)) have been obtained from the experimental study of [15] as shown in Fig. 2 and Fig. 3. Meanwhile, the density (\( \rho_{nf} \)) and specific heat capacity (\( C_{nf} \)), of nanofluid have been obtained by the relation [16].

\[ \rho_{nf} = \left( \frac{\phi}{100} \right) \rho_p + \left( 1 - \frac{\phi}{100} \right) \rho_f \]  

(6)

\[ C_{nf} = \frac{\phi}{100} (\rho C)_p + \left( 1 - \frac{\phi}{100} \right) (\rho C)_f \]  

(7)

Because the single-phase fluid Nusselt number correlations underestimate the heat transfer of nanofluids, the researchers have developed new Nusselt number correlations for nanofluids. Some of the available Nusselt number correlations are outline here:
Forced convection heat transfer coefficient under turbulent flow could be estimated by Dittus-Boelter [17] Eq. 8.

\[ Nu = \frac{h_f}{D} D = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \]  

Maiga et al. [18] presented equation for evaluation of Nusselt number for nanofluids as a function of Re and Pr:

\[ Nu = 0.085 \text{Re}^{0.71} \text{Pr}^{0.35} \]  

The available friction factor expression for water and nanofluids are represented by Eq. (10) Blasius [19] presented equation for evaluation of friction factor for water flow:

\[ f = 0.316 \text{Re}^{0.25} \]  

![Fig. 2 Thermal conductivity of the GNP-Ag nanofluid.](image-url)
4. RESULTS AND DISCUSSION

One of the key factors that determine the heat transfer performance is the cross-sectional tube geometry. This study examines straight and curved channel with square cross section. In order to validate the numerical procedure, a set of data was obtained with water as the working fluid. Comparison of the numerically measured Nusselt number for water with correlations of Dittus and Boelter [17] are presented in Fig. 4. This figure shows that the numerical results are in good agreement with the empirical correlations for turbulent flows. The maximum deviation between the present data and the existing correlations for Nusselt number is about ±5.3%, which validates the numerical procedure. Nanofluids with 0.1% weight concentrations of functionalized GNP–Ag are then tested in straight and curved channel. The results reveal that the Nusselt number enhances with increase of Reynolds number at 0.1% nanoparticles concentration as shown in Fig. 5. This is because the nanofluid contains suspended nanoparticles, which have higher conductivity compared to the base fluid. The Nusselt number enhancement for GNP–Ag nanofluid is also attributed to thermophysical properties of the nanoparticles as well as particle Brownian motion. Moreover, for 0.1% of GNP–Ag hybrid nanofluid improvement is 22.61% and 34.78% for straight channel and 27.43% and 39.52 for curved channel at the Reynolds number of 5,000 and 17,500, respectively.
Fig. 4 Nusselt number for water in straight and curved channel.

Fig. 5 Nusselt number for nanofluid in straight and curved channel.

Fig. 6 shows the numerical friction factor for the base fluid in straight and curved channel comparing to the experimental result of a circular tube by [15] and thermotical data of Blaisus equation (10) [19]. A maximum deviation of 5% is obtained between theoretical data and numerical data. Moreover, Fig. 7 shows the numerical friction factor of GNP–Ag nanofluids in straight and curved channel. Nevertheless, Blaisus equation (10) [19]. is used for estimating the friction factor of GNP–Ag nanofluids at 0.1% weight concentration and the result is illustrated in Fig. 7. The improvement of friction factor for 0.1% weight concentration of GNP–Ag nanofluid is 9.2 % for curved channel at the Reynolds number of 17,500. The enhancement of
friction factor due to the suspended of GNP–Ag nanoparticles in the base fluid is not significant in comparison to the heat transfer enhancement.

Fig. 6 Friction factor for water in straight and curved channel.

Fig. 7 Friction factor for nanofluid in straight and curved channel comments and response.

5. CONCLUSIONS
A computational study was conducted to investigate the turbulent flow heat transfer performance of straight and curved channel with square cross section with water and GNP–Ag hybrid nanofluids. It is found that adding 0.1% nanoparticle volumetric concentration improves heat transfer performance for straight and curved channel. However, higher amounts of nanoparticles are not recommended. In- curved channel gives better performance than straight channel for nanofluids. The Nusselt number is enhanced in comparison to the base fluid. For 0.1% of GNP–Ag hybrid nanofluid improvement is 22.61% and 34.78% for straight channel and 27.43% and 39.52 for curved channel at the Reynolds number of 5,000 and 17,500, respectively. The increase of friction factor is negligible when compare to the advantages of heat transfer enhancement. The developed Nusselt number and friction factor correlations are proposed. Future study will evaluate various modeling approaches for nanofluid heat transfer, e.g., two-phase mixture, Euler-Euler, and Euler-Lagrange models, in coils with respect to the effect of secondary flow to the nanoparticle concentration.

Reference


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