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Impacts of Corrugation Profiles on The Flow and Heat Transfer Characteristics in Trapezoidal Corrugated Channel Using Nanofluids

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ABSTRACT

In this paper, turbulent forced convection of nanofluids flow in different configurations of trapezoidal corrugated channels is numerically investigated over Reynolds number ranges of 10000–30000. This study evaluates the effects of four different types of nanofluids which are Al_2O_3, CuO, SiO_2 and ZnO–water under constant heat flux condition (10kw/m^2)· The governing equations of continuity, momentum and energy are solved using finite volume method (FVM). The study was carried out at 8% volume fraction of nanoparticles with 20nm particle diameters. Simulation results show that the corrugation profile has a significant impact on the thermal performance compare with straight profile. Furthermore, by adopting new channel geometry, the heat transfer enhancement can be improved more than two times that for straight channels. Among the nanofluid evaluated here, SiO2-water offers the highest enhancement of heat transfer. For all studied forms, the nozzle rib configuration of trapezoidal corrugated channel achieved maximum PEC and can lead to more compact heat exchangers.

Keywords:
Heat transfer enhancement, Turbulent flow, Corrugation profiles, Trapezoidal corrugated channel, Nanofluids

1. Introduction

Due to increasing global competition, a number of industries have a strong need to develop advanced heat transfer fluids with significantly higher thermal conductivities than are presently available. Corrugated surface geometry is one of the many suitable passive techniques to enhance the heat transfer in heat exchangers due to growing recirculation regions near the corrugated wall and hence, enhances the mixing of fluid as well as heat transfer. On the coolant side, the use of nanofluids, a liquid in which nanoparticles are added to a base fluid, can also enhance the heat transfer due to the improved thermal conductivity of the fluid. Many numerical and experimental

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investigations on the convective heat transfer in corrugated channels have been carried out using water or air as a working fluid [1-5].

Azwadi and Adamu [6] numerically studied the convective heat transfer over Reynolds numbers range of 10,000– 120,000 for hybrid nanofluid flow in a circular tube subjected to constant heat flux. In this study, a remarkable improvement was observed in using the hybrid nanofluid due to synergistic effect. At 1% volume fraction of Ag/HEG 34.34% and 38.72% enhancement was recorded at Reynolds number of 60,000 and 40,000 respectively.

Naphon [7–10] conducted numerical and experimental study of forced convection heat transfer and flow developments in a channel with V-corrugated upper and lower plates in which all configuration peaks lie in an in-phase arrangement. The results show that wavy angle and channel height have significant effect on the temperature distribution and flow development. It was found that the sharp edge of the wavy plate (V-shaped) has a significant effect on the enhancement of heat transfer. The turbulent flow of nanofluids with different volume fractions of nanoparticles flowing through a two-dimensional duct under constant heat flux condition was simulated by Rostamani *et al.,* [11]. The nanofluids considered are mixtures of copper oxide (CuO), alumina (Al_2O_3) and oxide titanium (TiO_2) nanoparticles and water as the base fluid. All the thermophysical properties of nanofluids are temperature-dependent. The results show that by increasing the volume concentration, the wall shear stress and heat transfer rates increase. Heidary and Kermani [12] studied numerically the effects of nanofluids on the heat transfer and flow field in a wavy channel. Copper–water nano-fluid is considered for simulation. Results show that the addition of nano-particles to the pure fluid and construction of wavy walls can significantly enhance the heat exchange between the wall and the flow. Ahmed *et al.,* [13, 14] studied numerically forced convection of flow and heat transfer enhancement in a corrugated channel using CuO nanofluid. The results show that the heat transfer increases as the volume fraction of nanoparticle increases. Khoshvaght-Aliabadi [15] experimentally studied on the copper–water nanofluid flow and heat transfer characteristics in the plate-fin channels with the different shapes. It was observed that heat transfer coefficient and the pressure drop increase with increasing in volumetric flow rate and the volume fraction of nanoparticles. Recently, Ajeel *et al.,* [16] numerically investigated on the heat transfer and friction factor in a turbulent flow regime in semi-circle corrugated channels with Al_2O_3-water nanofluid. Results show that maximum Nusselt number enhancement ratio 2.07 at Reynolds number 30,000 and volume fraction 6%.

Based on the above literature, it can be seen that the effect of corrugation profile on the thermal performance using nanofluid has not been investigated in the past and this has motivated the present study. Additionally, most of the previous studies examined a 2D turbulent convective heat transfer. Thus, the objective of this study is to investigate numerically the effect of various shapes of trapezoidal corrugated channel on the thermal performance using nanofluid in three-dimensional over Reynolds number ranges of 10000–30000. This study can be considered as reference for experimental work in the future.

2. Methodology

Figure 1 illustrated the 2-dimensional geometry of the trapezoidal corrugated channel and four models. (A) Geometrical model. (B) Diffuser groove -trapezoidal channel. (C) Nozzle groove - trapezoidal channel. (D) Diffuser rib-trapezoidal channel. (E) Nozzle rib - trapezoidal channel.

Generally, the total length of the channel is L_{total}=700mm. The length of the test section is L_2=200mm, with an upstream rectangular section of L_1=400mm upstream to ensure a fully developed flow at the leading edge. The downstream section has a length of L_3=100mm which is used to prevent the occurrence of adverse pressure effects caused by reversed flow which might at the trailing section. The channel height (H) is 10mm while the channel width (W) is 50mm. The trapezoidal corrugated height h= 2.5mm with fixed pitch (p= 1.5H). The geometry configuration was achieved by using SolidWorks. Regarding Fig.1(A), the corrugated walls for test section under constant heat flux q=10 kw/m2 while left side and right side represent velocity inlet and pressure outlet, respectively.

This simulation utilizes FLUENT (V16.1) as the solver to the governing equations and mesh generation for turbulent three-dimensional incompressible steady–state. The inlet temperature of the working fluid is T_{in}=300k while the water and nanofluid velocity can be set for different value according to the required Reynolds number. Flow was simulated at five Reynolds number values which are 10000, 15000, 20000, 250000, and 30000.

The modeling of turbulent flow forced convection in the corrugated trapezoidal channel with a single -phase and three-dimensional (3D) model is executed. The governing equations to solve for this case are given by,

Continuity equation

$$\nabla.(\rho_f V) = 0 \tag{1}$$

Momentum equation

$$\nabla.(\rho_f\, VV) = -\nabla p + \nabla.\tau \tag{2}$$

Energy equation

$$\nabla.\left(\rho_f V C_{p,f} T\right) = \nabla.(k_f \nabla T - C_{p,f}\rho_f\ \overline{\mathrm{vt}}) \tag{3}$$

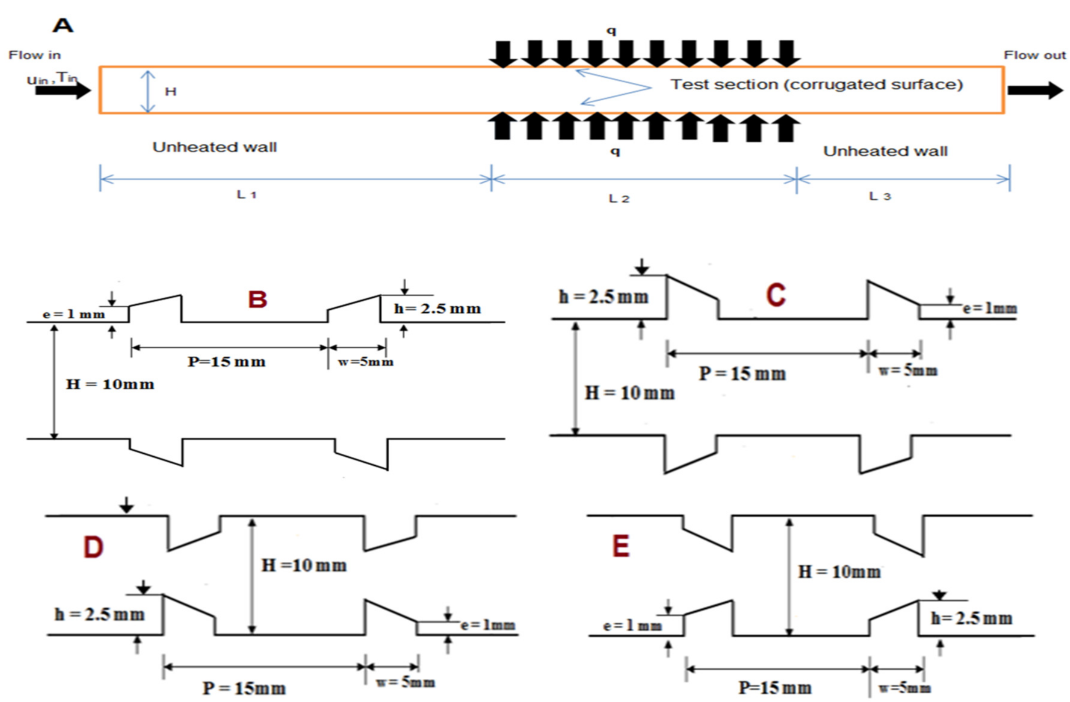

Fig. 1. Configurations of trapezoidal corrugated channel utilized in current study.

The Nusselt number, the Reynolds number are dimensionless parameters which are calculated, respectively, as follows

$$\overline{\mathrm{Nu}} = \frac{\bar{h} D_h}{k_f} \tag{4}$$

where k and h are the thermal conductivity and average heat transfer coefficient of nanofluid, respectively. The Reynolds number is defined as

$$\mathrm{Re} = \frac{\rho u_m D_h}{\mu} \tag{5}$$

where ρ , u_m, and μ are density, mean fluid velocity over the cross section and dynamic-viscosity of nanofluid, respectively. The hydraulic diameter (D_h) is defined as

$$D_h = \frac{4A_{\mathrm{cross}}}{P} \tag{6}$$

where A is the cross area and P is the wetted perimeter of the cross section. The pressure drop can also be obtained as

$$\Delta p = f \frac{\rho L_{corr} u_{in}^2}{2D_h} \tag{7}$$

The performance evaluation criteria index or thermal performance (PEC) is used to compare the thermal and fluid-dynamic performances of channels with differently shaped and to evaluate heat transfer enhancement. It is calculated using the predicted Nusselt numbers and friction factor as follows

$$PEC = \frac{\left(\overline{Nu}/\overline{Nu_0}\right)}{\left(f/f_0\right)^{1/3}} \tag{8}$$

The effective thermophysical properties of nanofluids to execute the simulations of the nanofluids as a working fluid should be obtained. Table 1 illustrates the thermo-physical properties of water –based nanofluids with dp = 20 nm and $\phi = 0.08$ at T=300K.

Table 1
The thermo-physical properties of water –based nanofluids

Thermo-physical properties	Al_2O_3	SiO_2	CuO	ZnO
Density ρ (kg/m^3)	1206.34	1094.344	1438.344	1366.344
Dynamic viscosity, μ(kg/m.s)	0.004795	0.004795	0.004795	0.004795
Thermal conductivity k(W/m.K)	0.796146	0.643072	0.796668	0.773534
Specific heat, c_p (J/kg.K)	3366.233	3622.483	2863.728	2973.164

3. Results

3.1 Validation of Straight Channel Simulation Results

For validation, the results obtained by simulation for straight channel which includes Nusselt number (Nu) and friction factor (*f*) are compared with empirical correlations of Dittus–Boelter and Petukov, respectively [17].

$$Nu = 0.023Re^{0.8}pr^{0.4} \quad (9)$$

$$f = (0.79\ \ln(Re) - 1.64)^{-2} \quad (10)$$

Comparisons of Nusselt number and friction factor which shows a very good agreement demonstrated in Figure 2.

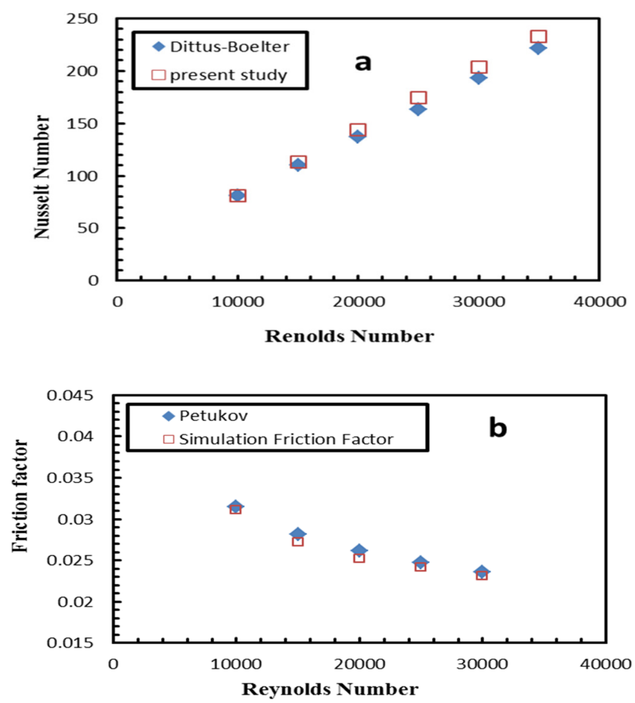

Fig. 2. Average Nusselt number (a) and friction factor (b) vs. Reynolds number

3.2 The Effect of Different Configurations of Corrugated Trapezoidal Channel

The variation of average Nusselt number with Reynolds number for different trapezoidal channel shapes is presented in Fig.3A. It can be seen that the Nusselt number increases with the increase of Reynolds number. This can be explained by the strong turbulence intensity of the presence of the corrugation leading to rapid mixing between the core and the wall of the channel. It is observed that the nozzle rib corrugated channel provided the highest heat transfer enhancement among the aforementioned shapes. This is because of a strong mixing of the fluid induced form turbulent flow and the appearance of reverse flow between the adjacent corrugations walls, leading to higher temperature gradients.

Figure 3B shows the variation of the ΔP along the trapezoidal corrugated channel in the investigated Reynolds number. The value of ΔP for the nozzle rib form of trapezoidal channel is the highest compared to the other configurations, while lowest value is related to the straight channel. It is obvious that the ΔP increases gradually for all of the rib configurations to the highest point at Re = 30000.

The ratio of the average Nusselt number for the different types of corrugated channels to that of the base fluid in straight channel is presented in Figure 3C. It is found the enhancement ratio for all types of the channels is decreased with Reynolds number, which means there is an optimum Reynolds number corresponding to the maximum enhancement ratio for each type of geometry. The optimum Reynolds number is related to Re = 10000 for all geometries. Moreover, it can be observed that the nozzle rib configuration of trapezoidal channel recorded the most significant ratio compared with other shapes.

Figure 3D depicts the PEC calculated using the computed Nusselt numbers and friction factors for all configurations of channels. It is clearly seen that the PEC decreases when Reynolds number increases for all types of corrugated channel. The PEC of the nozzle rib form is found to be the best among all shapes and is about 2.18 at the lowest value of Reynolds number.

The streamwise velocity and isotherms contours for different form of corrugated channels are shown in Figure 4. The reverse flow occurs in the furrow near the upper and lower walls of the corrugated channel. It can be clearly seen from velocity contour that the recirculation regions grow in wall trough of the corrugated channel, as expected. Therefore, the random movements will increase and consequently increase the size of recirculation regions. Subsequently, the recirculation flow becomes more disturbed. From the temperature contours, mixing the cold fluid in the core with the hot fluid near the walls of the corrugated channel increases with increasing Reynolds number. The temperature gradients increase with increasing Reynolds number because of the generated recirculation flow in the trough of the corrugated wall. This is identical to the numerical study of Naphon [9].

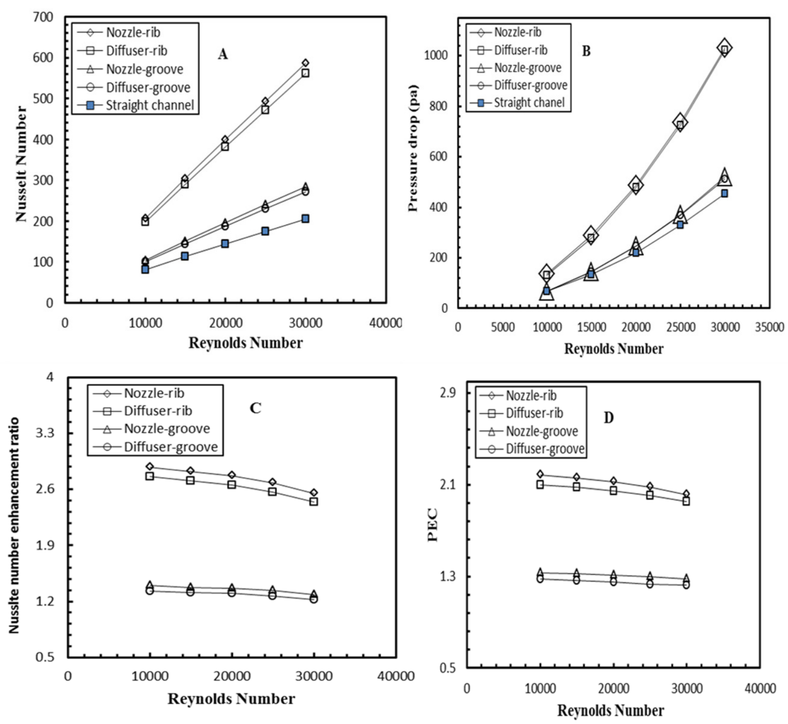

Fig.3. The effect of different forms of corrugated trapezoidal channel on (A) Nu, (B) ΔP, (C) Nu_{er}, and (D) PEC

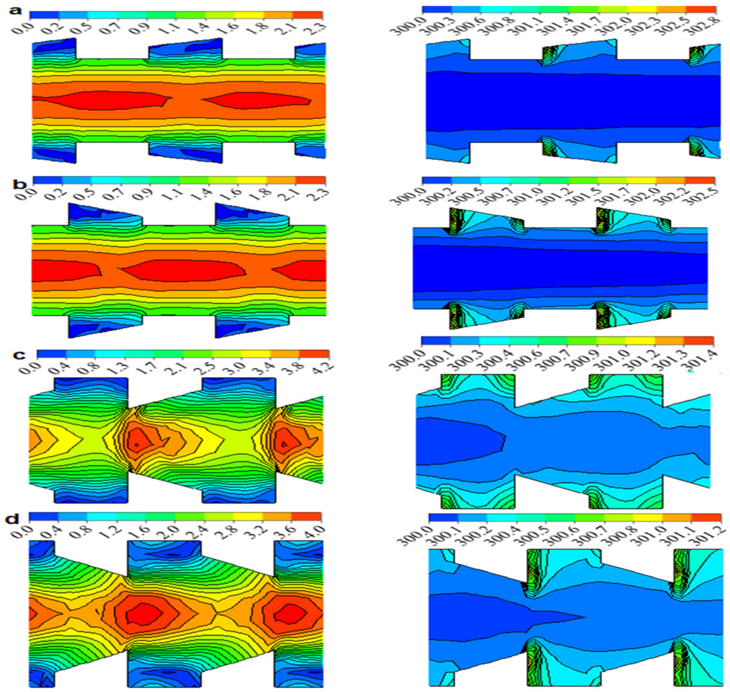

Fig. 4. Streamlines (left) and isotherm (right) contours for different configurations of trapezoidal channel at Re = 30000 (a) diffuser groove, (b) nozzle groove, (c) diffuser rib-shape, and (d) nozzle rib-shape

3.3 The Effect of Different Types of Nanoparticles

To study the effect of nanofluid types, four different types of nanofluids which are SiO_2, Al_2O_3, ZnO and CuO–water with φ = 8% and dp=20 nm have been presented. As expected, it can be seen from the velocity contours that the recirculation regions are generated in the walls troughs of the corrugated channel once the working fluid enters these channels, Figure 5. Furthermore, the velocity contours indicate that the stronger recirculation regions in the case of SiO_2–water nanofluid and followed by Al_2O_3, ZnO, CuO–water nanofluid and then the pure water. This because SiO_2–water nanofluid has the lowest density among other nanofluids and since the fluid velocity is inversely proportional with density of the fluid. The isotherms contours show that the thermal boundary layer thickness in the case of SiO_2–water nanofluid is less than that for the other nanofluids due to the highest Prandtl number of the SiO_2–water nanofluid. In addition, the stronger recirculation regions that developed with the use SiO_2–water nanofluid lead to the better improvement in the fluid mixing. Therefore, it is expected that the heat transfer augmentation for the SiO_2–water nanofluid will be the highest compared with the other types of nanofluids.

The variation of the average number with Reynolds number for different types of nanofluid is illustrated in Figure 6(A). It is found that the average Nusselt number for all types of nanofluid are considerably increased with increasing Reynolds number. It is also can be observed that the SiO_2–water nanofluid provides the highest Nusselt number among other types of nanofluids followed by Al_2O_3, ZnO, CuO–water nanofluids and pure water. This may be because the disturbance that is introduced due to the intensity effect of re-circulation regions is the higher for SiO_2– water nanofluid due to the highest velocity of the fluid, as pointed out before.

The pressure drop versus Reynolds number with different types of nanofluids is presented in Figure 6(B). It may be noted that the pressure drop for any type of nanofluid is higher than the pure water due to the high viscosity and density of nanofluid in comparison to the pure water. In addition, the SiO_2–water nanofluid gives the highest pressure drop among the different types of nanofluids due to the highest fluid velocity, at the given Reynolds number.

The ratio of the average Nusselt number for the different types of nanofluids in corrugated channels to that of the base fluid in straight channel is presented in Figure 6(C). It is found the enhancement ratio for all types of the fluids is sharply increased with Reynolds number. At a given Reynolds number, the heat transfer enhancement for any types of nanofluid is higher than that for the pure water. Also, the SiO_2–water nanofluid displays the highest enhancement ratio among other types of nanofluids followed by Al_2O_3, ZnO and CuO–water nanofluids due to the same reason mentioned earlier.

Figure 6(D) depicts the effect of different types of nanofluids on thermal performance factor. It can observe that the pure water displays the lowest performance factor compared with nanofluids. Furthermore, although SiO_2–water nanofluid produces the highest value of the pressure drop, but the enhancement in heat transfer is the higher. Therefore, SiO_2–water nanofluid has the highest thermal performance among the other types of nanofluids. It is found that the maximum value of thermal performance factor occurred at Re= 10000.

4. Conclusions

In this paper, the flow and thermal characteristics of turbulent forced convection flow in trapezoidal corrugated channel using nanofluids have been numerically investigated over Reynolds number rage of 10000–30000. Four different types of nanofluids which are Al_2O_3, CuO, SiO_2 and ZnO–water have been presented.

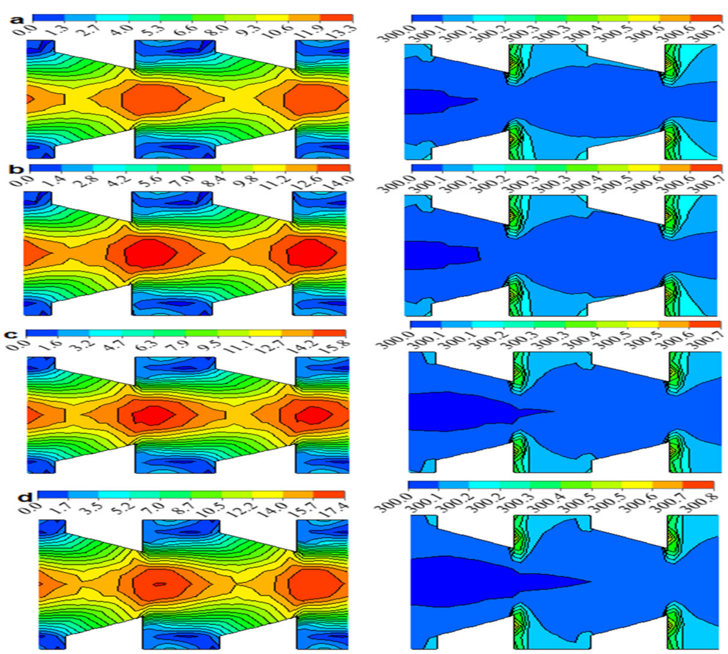

Fig. 5. Streamlines (right) and isotherm (left) contours for different types of nonofluids at Re=30000 : (a) CuO-water, (b) ZnO-water , (c) Al_2O_3-water, and (d) SiO_2-water.

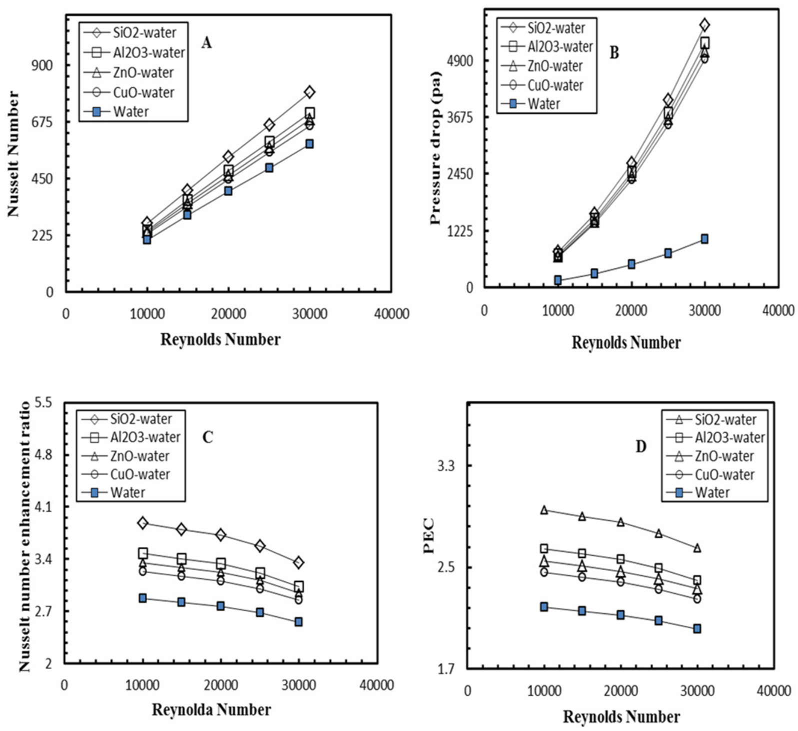

Fig. 6. The effect of various types of nanofluids of nozzle rib-shape corrugated channel on (A) Nu, (B) Δp, (C) Nu_{er}, and (D) PEC

The governing equations were solved using finite volume method with SIMPLE technique. Results show that the corrugation profile has a significant impact on the thermal performance compare with straight profile. Furthermore, the SiO_2–water nanofluid provides the highest thermal performance among other types of nanofluids followed by Al_2O_3, ZnO and CuO–water nanofluids. In addition, the pure water has the lowest heat transfer enhancement as well as thermal performance. Moreover, the adopted geometry of trapezoidal corrugated channel can improve heat transfer enhancement more than two times that of straight channel.

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