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Study of heat transfer due to turbulent flow of nanofluids through rib-groove channel

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Abstract. Nanofluids for improve characteristics flow in a rib-groove channel are investigate. The continuity, momentum and energy equations were solved by FLUENT program. The bottom wall of channel is heated while the upper wall is symmetry, the left side velocity inlet, and the right side is outlet (pressure out). Four different rib-groove shapes are used. Four different types of nanoparticles, Al_2O_3, CuO, SiO_2, and ZnO with different volumes fractions in the range of 1 % to 4 % and different nanoparticle diameter in the range of 25 nm to 70 nm, are dispersed in the base fluid water are used. In this paper, several parameters such as different Reynolds numbers in the range of 10000 < Re < 40000 are investigated. The numerical results indicate that the trapezoidal with increasing height in the flow direction rib- trapezoidal groove has the best heat transfer and high Nusselt number; the nanofluids with SiO_2 have the best behavior. The Nusselt number increases as the volume fraction increases and it decreases as the nanoparticle diameter increases.

1. Introduction

They are many researchers studied the forced convection heat transfer in a rib-groove channel. Recently, researchers have shown an increased in forced convection heat transfer. Attempts to enhance heat transfer in the heat exchangers by using roughen surfaces such as rib, groove and helical rib in disturbing the flow and in providing transverse/longitudinal vortices or three dimensional mixing. There many geometric shapes of the rib-groove channel had been studied in the past. The common geometric shape include rectangular, triangular, square, and circle. All these types of rib-groove channel were used in many engineering application such as cross-flow heat exchanger, gas turbine airfoil cooling design, solar air heater blade cooling system, and gas cooled nuclear reactor. One of the ways to enhance heat transfer in the separated regions is to employ nanofluids. Nanofluids are fluids that contain suspended nanoparticles such as metals and oxides. These nano-scale particles keep suspended in the base fluid. Thus, it does not cause an increase in pressure drop in the flow field. Past studies showed that nanofluids exhibit enhanced thermal properties, such as higher thermal conductivity and convective heat transfer coefficients compared to the base fluid.

Kamali and Binesh [1] studied turbulent heat transfer and friction characteristics in a square duct with various-shaped ribs mounted on one wall. The simulations were performed for four rib shapes, i.e., square, triangular, trapezoidal with decreasing height in the flow direction, and trapezoidal with increasing height in the flow direction. Bilen et al. [2] presented an experimental study of surface heat transfer and friction characteristics of a fully developed turbulent air flow in different grooved tubes. Tests were performed for Reynolds number range 10,000 – 38,000 and for different geometric groove shapes (circular, trapezoidal and rectangular). Eiamsa-ard and Promvonge [3] performed the combined effects of rib-grooved turbulators on the turbulent forced convection heat transfer and friction characteristics in a rectangular duct under a uniform heat flux boundary condition (UHF). Promvonge and Thianpong assessed turbulent forced convection heat transfer and friction loss

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behaviors for air flow through a constant heat flux channel (CHF) fitted with different shaped ribs. The rib cross-sections used were triangular (isosceles), wedge (right-triangular) and rectangular shapes. Jaurker et al [4] presented the heat transfer and friction characteristics of rib-grooved artificial roughness on one broad heated wall of a large aspect ratio duct shows that Nusselt number can be further enhanced beyond that of ribbed duct while keeping the friction factor enhancement low. . Manca et al. [5] presented a numerical investigation on air forced convection in a rectangular channel with constant heat flux applied on the bottom and upper external walls.

Several investigations have been reported in the literature on the convective heat transfer in nanofluids; see, for example, Mohammed et al. [6] investigated nine different rib–groove shapes which were three different rib shapes with three different groove shapes including rectangular, triangular and trapezoidal and they were interchanged with each other. Four different types of nanoparticles Al_2O_3, CuO, SiO_2, and ZnO with different volume fractions in the range of 1% to 4% and different nanoparticle diameters in the range of 25 nm to 80 nm were used. They found that the rectangular rib–triangular groove has the highest Nusselt number among other rib–groove shapes. The SiO_2 nanofluid has the highest Nusselt number compared with other nanofluid types. Nguyen et al. [7] investigated experimentally the behavior and heat transfer enhancement of Al_2O_3/water nanofluid flowing inside a closed system that is used for cooling of micro-electronic components. For a 6.8 vol.% concentration, the heat transfer coefficient was found to increase as much as 40 % compared to that of the base fluid. Liu et al. [8] investigated the thermal conductivity of copper–water nanofluids produced by chemical reduction method. Results showed 23.8% improvement at 0.1% volume fraction of copper particles. Higher thermal conductivity and larger surface area of copper nanoparticles were attributed to this improvement. It was noted that thermal conductivity increases with particles volume fraction but it decreases with the elapsed time.

The forced convection heat transfer in rib-groove channel occurred in many industrial devices with the base heat transfer fluids such as air, water, or ethylene glycol. However, the low thermal conductivity has always been the primary limitation in the development of energy-efficient heat transfer fluids, performance and compactness of many engineering equipment such as electronic devices and heat exchanger. To overcome this limitation, there is a strong motivation to improve advanced heat transfer fluids with substantially higher thermal conductivity. Hence, in recent years, nanofluids have attracted more attention for cooling in various industrial applications. This new generation of heat transfer fluids consists of suspended nanoparticles, which have a better suspension stability compared to millimeter or micrometer size ones.

2. Numerical Model

2.1. Physical Model

Schematic diagrams of rib-groove channel for geometrical model and four cases (five rib-five groove) are shown in **Fig.1** (a) Geometrical model, (b) Trapezoidal with increasing height in the flow direction Rib-Isosceles Trapezoidal Groove. (c) Isosceles Trapezoidal Rib- Trapezoidal with increasing height in the flow direction Groove. (d) Trapezoidal with increasing height in the flow direction Rib-Groove. (e) Trapezoidal with decreasing height in the flow direction Rib- Isosceles Trapezoidal Groove. The general case is Isosceles Trapezoidal Rib-Groove, Trapezoidal with increasing height in the flow direction Rib-Groove and Trapezoidal with decreasing height in the flow direction Rib-Groove. Both the height and length of the rib-groove channel are fixed and the shapes of rib and groove were changed. The channel height is set to H=60 mm while the channel rib width w=20 mm, rib height e=10 mm, and groove width w=20 mm, and the groove height e=10 mm. To ensure a fully developed flow, the entrance section smooth channel L1= 200 mm, and the exit L3= 90 mm. As shown in **Fig.1** the left side is velocity inlet and the right side is pressure outlet, the down wall is uniform heat flux q=10000 w/m^2, and the up wall is symmetry.

2.2. Boundary Conditions

The boundary conditions for this study are specified for the computational domain as shown in **Figs 1 b-e.** These figures show the general rib-groove channel model selected from this study, whose top wall Symmetry and bottom wall is subject to heat flux while the left side is velocity inlet and the right side is pressure outlet. The turbulence model is very important to accommodate the flow behavior of each application. To attain accurate prediction in the rib-groove channel, the standard k-ε turbulence model, the Renormalized Group (RNG) k-ε turbulence model were selected. To evaluate the pressure field, the pressure-velocity coupling algorithm SIMPLE was selected. At the inlet, uniform velocity profile has been imposed. The turbulence intensity was kept at 1% at the inlet. The solutions are considered to be converged when the normalized residual values reach 10^{-5} for all variables.

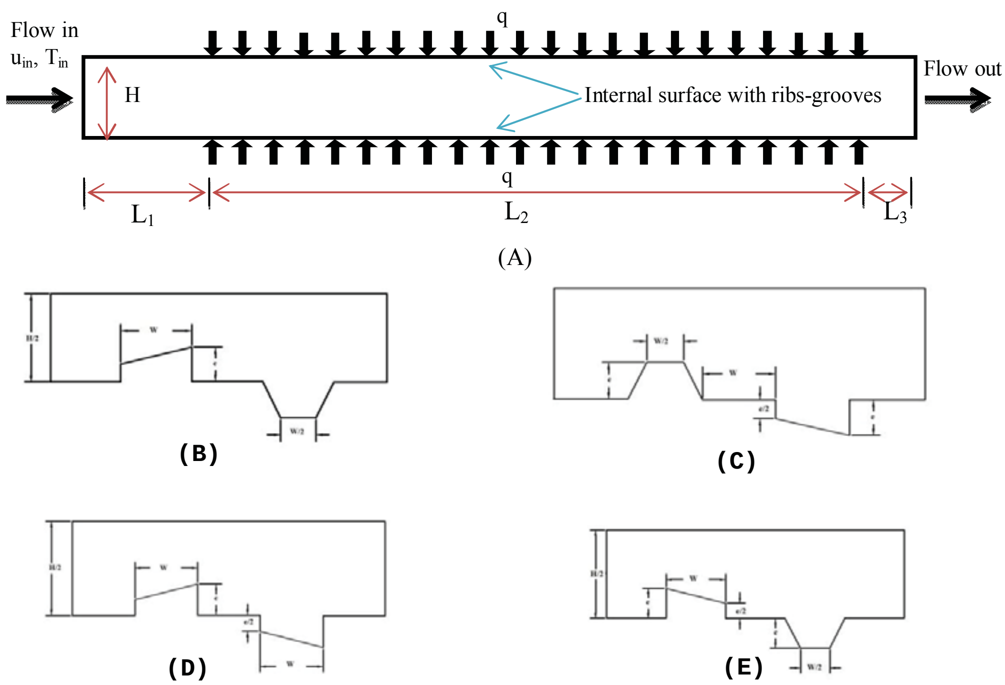


Figure 1. Schematic diagram of Rib-Groove Channel.

2.3. *Thermophysical Properties of Nanofluids*

In order to carry out simulations for nanofluids, the thermal properties of nanofluids must be calculated first. The nanoparticles being used are Al_2O_3, CuO, SiO_2, and ZnO. The effective properties of mass density, specific heat, thermal conductivity, and viscosity are actually calculated according to the mixing theory.

The density of nanofluid, ρ_{nf} can be obtained from the following equation [9]:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_{np} \tag{8}$$

The effective heat capacity at constant pressure of nanofluid, $(\rho\, C_p)_{nf}$ can be calculated from the following equation [9]:

$$(\rho\, C_p)_{nf} = (1-\phi)(\rho\, C_p)_f + \phi\,(\rho\, C_p)_{np} \tag{9}$$

By using Brownian motion of nanoparticles in rib-groove channel, the effective thermal conductivity can be obtained by using the following mean empirical correlation [10]:

$$k_{eff} = k_{static} + k_{Brwnian} \tag{10}$$

$$k_{static} = k_f \left[\frac{(k_{np}+2k_f) - 2\phi(k_f - k_{np})}{(k_{np}+2k_f) + \phi(k_f + k_{np})}\right] \tag{10.1}$$

$$k_{brwnian} = 5 * 10^4\, \beta\, \phi\, \rho_f\, C_{p,f} \sqrt{\frac{KT}{2\,\rho_{np}\, R_{np}}}\, f(T,\phi) \tag{10.2}$$

Where: Boltzmann constant: $k = 1.3807 * 10^{-23}\, J/K$

Modeling, $f(T,\phi)$

$f(T,\phi) = (2.8217 * 10^{-2}\phi + 3.917 * 10^{-3})\left(\frac{T}{T_0}\right) + (-3.0669 * 10^{-2}\,\phi - 3.3.91123 * 10^{-3})$ For 1% $\leq \phi \leq$ 4% and 300K<T>325K.

The effective viscosity can be obtained by using the following mean empirical correlation [10]:

$$\mu_{eff} = \mu_f * \frac{1}{(1 - 34.87\,(d_p/d_f)^{-0.3} * \phi^{1.03})} \tag{11}$$

$$d_f = \left[\frac{6M}{N\pi\rho_{fo}}\right] \tag{11.1}$$

Where: M is the molecular weight of base fluid, N is the Avogadro number = $6.022*10^{23}$ mol^{-1}, ρ_{f0} is the mass density of the based fluid calculated at temperature T_0=293K.

3. Results and Discussion

3.1. The Effect of Different Rib-Groove Shapes

In this study, four different Rib-Groove shapes which (Trapezoidal with increasing height in the flow direction Rib-Isosceles Trapezoidal Groove, Isosceles Trapezoidal Rib-Trapezoidal with increasing height in the flow direction Groove, Trapezoidal with increasing height in the flow direction Rib-Groove, and Trapezoidal with decreasing height in the flow direction Rib- Isosceles Trapezoidal Groove) on thermal and fluid fields. The variation of heat transfer Nusselt number with Reynolds number is presented in **Fig.2**. As shown in **Fig.2** the heat transfer rate increase with the increase of Reynolds number. The Trapezoidal with increasing height in the flow direction Rib-Isosceles Trapezoidal Groove (Trap+R-TrapG) channel provided the mean heat transfer enhancement over the smooth channel. This is because of a strong mixing of the fluid induced form turbulent flow, leading to higher temperature gradients.

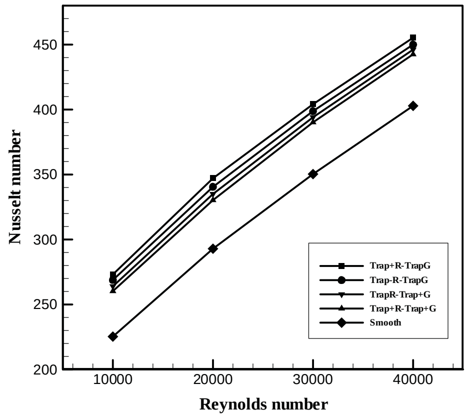
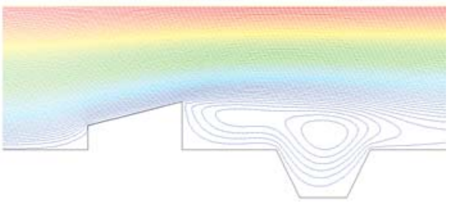
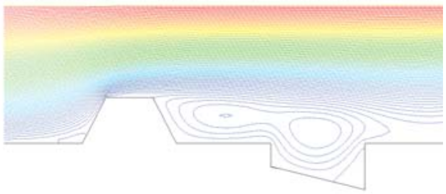


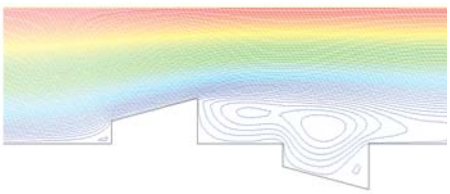
Figure 2. Normalized Nusselt number for channel with different Rib-Groove shapes at different Reynolds number.



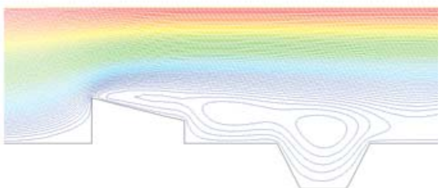
(A) Trap.+ Rib-Trap. Groove



(B) Trap. Rib-Trap.+ Groove



(C) Trap.+ Rib-Trap.+ Groove



(D) Trap.- Rib-Trap. Groove

Figure 3. Velocity streamlines contours at Reynolds number = 40000

As shown in **Fig.3** the velocity streamline for four different rib-groove channel, at Re=40000. It is clear to show the recirculation zones (vortex) behind ribs and grooves.

3.2. The Effect of Different Types of Nanoparticles

Four different types of nanoparticles Al_2O_3, CuO, SiO_2, and ZnO and pure water as a base fluid are used. The Nusselt number for different nanofluids and different values of Reynolds number are shown in **Fig.4**. This figure show for the different range of Reynolds number, it is clear that nanofluid with SiO_2 has the best heat transfer rate, followed by Al_2O_3, ZnO, CuO and pure water respectively. This phenomenon can be attributed to the fact of the high thermal properties of SiO_2-water compared with the lower thermal properties of other nanofluids types or with pure water.

3.3. The Effect of Different Volume Fractions, φ of Nanoparticles

The volume fraction of nanoparticles is actually referred to the volume of nanoparticles constituent divided by the volume of the all constituents of the mixture prior to mixing. In fact, pure water has zero volume fractions of nanoparticles. The volume fraction range of 1-4% with different values of Reynolds number is investigated. It is clear shown in **Fig.5**, increasing nanoparticles volume fraction enhances the Nusselt number. By increasing the volume fraction of nanofluid the thermal conductivity of the fluid increases which enhanced the heat transfer. It is clear that the volume friction, φ=0.01, has the best heat transfer rate followed by 0.03, 0.02, 0.01, 0.00 respectively.

3.4. The Effect of Different Nanoparticles Diameters, d_p

In this study used SiO_2-water as a working fluid with fixed other parameters such as volume fraction 4% except Reynolds number was in the range of 1000 – 40000. The range of nanoparticles diameter is 25-70 nm. As shown in **Fig.6**, the results of Nusselt number increase with decreasing the nanoparticles diameter. This can be attributed to in increment of the thermal conductivity due to nanoparticles diameter decreases. It is concluded that by using smaller diameter of nanoparticles will lead to get better heat transfer enhancement. In all cases, it can be observed that Nusselt number increase with increasing Reynolds number for all nanoparticles diameter, d_p leading to better heat transfer.

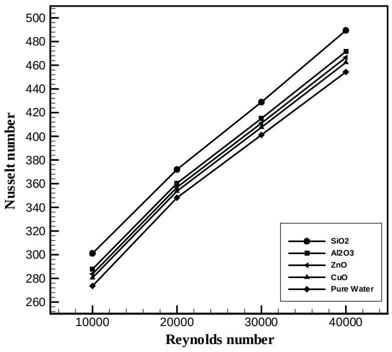


Figure 4. Normalized Nusselt number for channel with different nanofluids types at different Reynolds number.

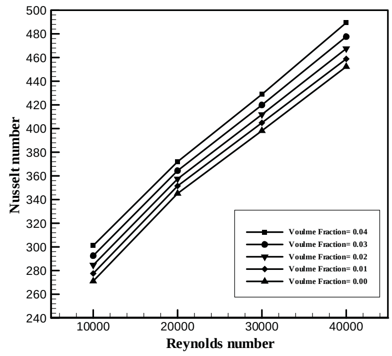
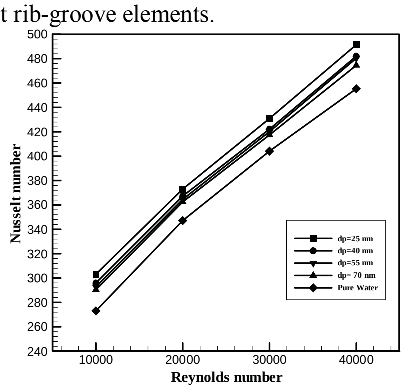


Figure 5. Normalized Nusselt number for channel with different volume fraction, φ of nanoparticles at different Re.

3.5. The Effect of Different Reynolds number

This study was done at Reynolds number in the range of 10000 – 40000. From **Fig.7**, it can observe that as the Re increases the average Nusselt number also increases. As shown in **Fig.7** the Reynolds number increases the convective current becomes more and more strong and the maximum value of isotherms reduces. The variation of heat transfer Nusselt number with x-position at different Reynolds number is presented in **Fig.7**. The Reynolds number Re=40000 provided the mean heat transfer enhancement over other Reynolds number. This is because of a strong mixing of the fluid induced form turbulent flow and appearance of reverse flow between the adjacent rib-groove elements.



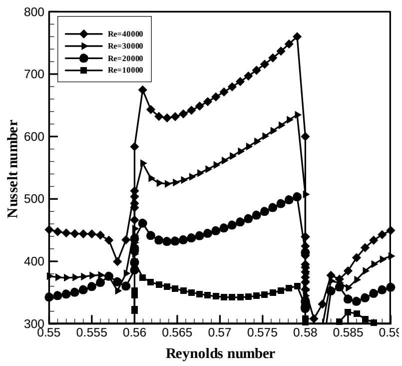


Figure 6. Normalized Nusselt number for channel with different nanoparticles diameters, d_p at different Re.

Figure 7. Normalized Nusselt number with x-position for different Reynolds number.

4. Conclusion

Numerical simulation of turbulent forced convection heat transfer in a rib-groove channel was carried out. The heat transfer enhancement resulting from various parameters, which include the different shapes of rib-groove channel, the type of nanofluids (Al_2O_3, CuO, SiO_2, and ZnO with water), volume fraction of nanoparticles in the range of $1 \leq \varphi \leq 4$, nanoparticles diameter in the range of $25 \leq dp \leq 70$, and the Reynolds number in the range of $10000 \leq Re \leq 40000$. The governing equations were solved utilizing finite volume method with certain assumptions and appropriate boundary conditions to provide a clear understanding of the modelling aims and conditions for the present study. CFD software (GAMBIT and FLUENT) are employed in this study to simulate the current study.

A number of conclusions can be drawn from the current work as follows:

1- By changing the rib-groove shapes on thermal and fluid fields, the results show that Trapezoidal with increasing height in the flow direction Rib-Isosceles Trapezoidal Groove (Trap+R-TrapG) gives the highest Nusselt number and the best heat transfer from thermal enhancement factor test.
2- By changing the types of nanoparticles, (Al_2O_3, CuO, SiO_2, and ZnO), the results show that SiO_2 gives the highest Nusselt number followed by Al_2O_3, ZnO, and CuO respectively while pure water gives the lowest Nusselt number.
3- The Nusselt number increased with increasing the volume fraction of nanoparticles.
4- The Nusselt number increase gradually when decreasing the nanoparticles diameter.
5- The Nusselt number increased gradually by increasing the Reynolds number, Re in the range of 10000 – 40000.

5. References

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