A numerical study of laminar forced convection flow of Al₂O₃-water nanofluid in triangular-corrugated channel

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Abstract. In this paper, laminar forced convection flow of Al₂O₃-water nanofluid in triangular-corrugated channel is numerically studied. The governing mass, momentum and energy equations in body-fitted coordinates are solved using finite volume method. Reynolds number and nanoparticle volume fractions are in the ranges of 100- 800 and 0- 5%, respectively. The effect of Reynolds number, nanoparticles volume fraction and nanoparticles diameter on the flow and thermal characteristics are examined. The results indicate that the Nusselt number increased as Reynolds number and nanoparticles volume fraction increased but the pressure drop increased as well. Also, Nusselt number increased as the nanoparticle diameter decreased, while there is no effect of nanoparticle diameter on the pressure drop.

1. Introduction

Heat transfer enhancement in many thermal devices such as heat exchangers is required to reduce size, weight and cost of these devices. For this purpose, the corrugated surfaces which are one of the passive methods have been used to improve the thermal performance of heat exchangers in several applications. For further enhancement in heat transfer, the addition of nanoparticles to the working fluids can improve thermal conductivity and consequently enhancement in heat transfer rate. Several numerical and experimental studies on the forced convection flow of conventional fluids or nanofluids in channels exist in the literature [1-8]. Laminar forced convection of copper-water nanofluid in straight channel was numerically studied by Santra et al. [4]. Manca et al. [5] and Mohammed et al. [6] numerically studied of the convective heat transfer of nanofluid in a ribbed channel. Heidary and Kermani [7] and Ahmed et al. [8] studied on the forced convection flow of copper-water nanofluid in a wavy channel. Results displayed that the heat transfer rate increased with Reynolds number, amplitude of wavy wall, and nanoparticle volume fraction.

In this article, forced convection of nanofluid in triangular-corrugated channel is numerically studied using finite volume method. The effects of Reynolds number, nanoparticles volume fraction(ϕ) and nanoparticle diameter(dp) on flow and thermal characteristics are presented and analyzed.

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2. Geometry and boundary conditions
The physical model of present study is shown in Figure 1. The model consists of upper and lower walls with average spacing between these walls of (H). The length of corrugated channel is six cycles (pitch) and the amplitude of corrugated wall is \((a=0.2H)\). The axial length of each pitch is \((\lambda=2H)\). The boundary conditions for the computational domain were specified. Dirichlet boundary conditions were assigned at the channel entrance (i.e. \(u= u^\text{in}, v= 0\) and \(\theta= 0\)) and Neumann conditions adopted in the channel outlet. Along the walls of channel, a no-slip boundary condition were prescribed with a constant wall temperature condition (i.e. \(u= 0, v= 0\) and \(\theta= 1\)).

Figure 1. Physical model of the present study.

3. Governing equations and Thermophysical properties of nanofluid
Governing equation in non-dimensional form and in term of body-fitted coordinates for steady, laminar, incompressible and two-dimensional flow are:

\[
\frac{\partial}{\partial \zeta}((\rho\phi U^') + \frac{\partial}{\partial \eta}((\rho\phi V^')) = \Gamma \left[ \frac{\partial}{\partial \zeta}((\beta_1 \frac{\partial \phi}{\partial \zeta}) + \frac{\partial}{\partial \eta}((\beta_2 \frac{\partial \phi}{\partial \eta})) + \frac{\partial}{\partial \zeta}((\beta_1 \frac{\partial \phi}{\partial \zeta}) + \frac{\partial}{\partial \eta}((\beta_3 \frac{\partial \phi}{\partial \eta})) \right] + S_\phi 
\]

(1)

The thermophysical properties of the nanofluid used in present study are the ones used by Mohammed et al.[6].

4. Numerical method
The non-dimensional governing equations are discretized using finite volume method and solved iteratively using SIMPLE algorithm [9]. The convection term is discretized using power-law scheme and the collocated grid arrangement is used in this study. The under-relaxation of velocities and pressure is applied to achieve the convergence of numerical simulation and the convergence criterion is set to \(10^{-5}\).

Figure 2. Average Nusselt number vs. Reynolds number.

5. Code validation and grid independence test
In order to validate the CFD code which is developed in this study, \(\text{Nu}\) for copper-water nanofluid flow in a straight channel is obtained and compared with previous numerical results of Santra et al.
and decrease in dp. From Figure 4(a), it is observed that Nu increases due to increase the density and viscosity of nanofluid. From Figure 6(b), it is found that Nu increases due to improve thermal conductivity of nanofluid. Moreover, the nanoparticles diameters have no effects on the pressure drop, see Figure 4(b).

Looking at isotherms contours, the temperature gradient near the walls of channel is increased with Re increased and consequently the flow becomes more disturbed. Moreover, the nanoparticles diameters have no effects on the pressure drop, see Figure 4(b).

Figure 3 shows that the streamlines and isotherms contours. It is found that from the streamlines contours the secondary flow regions appear in cavities near the upper and lower walls of channel. The size of these regions increase as Re increased and consequently the flow becomes more disturbed.

Figure 6(a) display that the effect of nanoparticles volume fractions on Nu at dp= 5% and dp=30nm.  

6. Results and discussion

Figure 3 shows that the streamlines and isotherms contours. It is found that from the streamlines contours the secondary flow regions appear in cavities near the upper and lower walls of channel. The size of these regions increase as Re increased and consequently the flow becomes more disturbed. Looking at isotherms contours, the temperature gradient near the walls of channel is increased with Re due to improve the mixing of the cold fluid in core with hot fluid near the walls. Figure 4 display that the non-dimensional pressure drop for different values of φ and dp. From Figure 4(a), it is observed that the pressure drop increase as φ increases due to increase the density and viscosity of nanofluid. Moreover, the nanoparticles diameters have no effects on the pressure drop, see Figure 4(b).

The effect of nanoparticles volume fractions on Nu at dp= 30 nm is displayed in Figure 6(a). As expected, Nu increases with φ due to improve thermal conductivity of nanofluid. From Figure 6(b), it is found that Nu increases with a decreases in dp. Because of as dp decreases, the surface area of nanoparticle per unit volume and the Brownian motion of nanoparticles are increased.
7. Conclusion
The results of numerical solution showed that Nu increases with increasing the Re, and nanoparticles volume fraction but the pressure drop penalty also increased. Further, as the nanoparticle size decreases Nu increased, while the nanoparticle size has no effect on the pressure drop. Based on the above results, the use of nanofluid in triangular-corrugated channel is a suitable method to achieve a good enhancement in the performance of many thermal devices.

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References

[1] Rush T A, Newell T A and Jacobi A M 1999 An experimental study of flow and heat transfer in sinusoidal wavy passages *Int. J. Heat and Mass Transfer* 42 1541-1553.
[2] Wang C C and Chen C K 2002 Forced convection in a wavy-wall channel, *Int. J. Heat and Mass Transfer* 45 2587–2595.
[3] Zhang L and Che D 2011 Influence of corrugation profile on the thermalhydraulic performance of cross-corrugated plates *Numerical Heat Transfer, Part A*, 59 267-296.
[4] Santra A K, Sen S and Charaborty N 2009 Study of heat transfer due to laminar flow of copper-water nanofluid through two isothermally heated parallel plates *Int J.Thermal Science* 48 391–400.
[5] Manca O, Nardini S and Ricci D 2012 A numerical study of nanofluid forced convection in ribbed channels *Applied Thermal Engineering* 37 280-292.
[6] Mohammed H A, Al-Shamani A N and Sheriff J M 2012 Thermal and hydraulic characteristics of turbulent nanofluids flow in a rib-groove channel *Int Comm. Heat and Mass Transfer* 39 1584-1594.
[7] Heidary H and Kermani M J 2010 Effect of nano-particles on forced convection in sinusoidal-wall channel, *Int Comm. Heat Mass Transfer* 37 1520-1527.
[8] Ahmed M A, Shuaib N H and Yusoff M Z 2012 Numerical investigations on the heat transfer enhancement in a wavy channel using nanofluid *Int. J. Heat and Mass Transfer* 55 5891-5898.
[9] Versteeg H K and Malalasekera W 2007 An introduction to computational fluid dynamics the finite volume method 2nd edition. Longman Scientific and Technical, England.