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Numerical Analysis of The Thermo-Convective Behaviour of an Al_2O_3-H_2O Nanofluid Flow Inside a Channel with Trapezoidal Corrugations

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ABSTRACT

In this present article, a study of the dynamic and thermal behavior of the Al_2O_3-water nanofluid flow through a channel provided with trapezoidal undulations, under the action of a constant heat flux. To do this, the effect of various volume fractions (0-4%) and that of the nanoparticle diameter (30, 40, 60 nm) on the heat transfer and pressure drop within the channel was analyzed, for a range of Reynolds numbers between 100 to 1000. The equations governing the fluid flow, namely the equations of continuity, momentum and energy were integrated and discretized based on the finite volume method (FVM). The obtained results indicated that using nanofluids with a high-volume fraction and a small nanoparticle diameter makes it possible to improve the performance of the system in terms of heat transfer, pressure drop and friction factor.

1. Introduction

Since Maxwell [1], it is known that adding particles into a fluid in-creases the thermal conductivity of the mixture. With the development of nanotechnologies, side effects of the usage of millimetric and micrometric particles like erosion, sedimentation and an increase in pressure drop have attenuated. In 1995, Choi and Eastman [2] innovated a novel heat transfer fluid called nanofluid. It is a suspension consisting of nanoscale solid particles and conventional base fluid. These tiny particles are composed of high thermal conductivity and their large surface-to-volume ratio can even enhance the heat exchange interaction between solid and fluid particles. After that, many researchers conducted investigations by adding metallic, non-metallic and even the combinations of two or more different nanoparticles as hybrid in conventional base fluids, e.g., Cu nanoparticles in water [3], Al_2O_3 nanoparticles in water [4], Fe_3O_4 nanoparticle in water [5], TiO_2 nanoparticles in water [6], ZnO nanoparticles in water [7], Carbon nanotube in therminol [8] etc. to measure the potential in various heat transfer applications such as in nuclear systems [9,10], solar energy systems [11, 12], domestic refrigerators [13], air conditioning systems [14], heat exchangers [15, 16], heat pipes [17, 18]and

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thermo siphons [19] etc. Although many publications exclusively deal with the thermophysical properties of nanofluids [20–28], the results are heterogeneous, especially for the thermal conductivity and the viscosity making the development of a single correlation difficult. Turgut *et al.,* [23], Barb’es *et al.,* [24] and Yang *et al.,* [29] measured thermal conductivities of various nanofluids in good agree-ment with the model of Hamilton-Crosser (HC) [30]. On the other hand, Murshed *et al.,* [21] reported increases in thermal conductivity of 18% and 45% for a particle volume concentration of 5% of Al and TiO_2 in ethylene glycol which is much higher than the predicted values of HC model. They proposed a model to determine the relative thermal conductivity taking into account the particle size and the thickness.

Due to their enhanced thermal conductivity, nanofluids have become good candidates for heat transfer fluids. Kim *et al.,* [31] studied the flow of an Al_2O_3-water nanofluid in a pipe and reported an enhancement of 15% and 20% in the convective heat transfer coefficient in laminar and turbulent regimes respectively. At 0.3% of Al_2O_3 in water, Hwang *et al.,* [32] observed an increase of 8% in the convective heat transfer coefficient in laminar flow that is higher than the enhancement of the thermal conductivity (+1.44%). The friction factor is unchanged with the increasing volume concentration up to 0.3% while the viscosity is 3% higher than pure water at the maximum volume concentration. Xuan and Li [33] experimentally studied the heat transfer and flow of copper–water nanofluid in a tube. They have observed that the enhancement in heat transfer increased as the concentration of solid particles increased. Kolade *et al.,* [34] measured the effective thermal conductivity of nanofluids flowing through a circular pipe in the laminar flow regime. The effect of nanoparticle's diameter on laminar mixed convection flow in a circular curved tube has been numerically investigated by Akbarinia and Laur [35]. The numerical results show that as the diameter of the nanoparticle increases, Nusselt number as well as the secondary flow decrease. While the axial velocity augments when the diameter of nanoparticles increases. Ahmad *et al.,* [36] proposed a numerical study of the effect of the characteristics of nanofluids in laminar flow on the heat transfer and friction factor, inside a rectangular channel. The efficiency of metallic oxide nanoparticles (Al_2O_3), metallic nanoparticles (Cu) and semiconductor nanoparticles (SiO_2) in improving the heat transfer rate was also examined by varying the volume fractions from 0.5% to 2.5%, while keeping a constant nanoparticle diameter (25 nm). The numerical results showed that the convective heat transfer coefficient, thermal conductivity, pressure drop and average velocity of all nanofluids increased as the Reynolds number and volume concentration augmented, while the friction factor went down. Das *et al.,* [37] conducted an experimental study on the stability and properties of the nanofluid Al_2O_3-water and studied the effects of temperature (20 - 60 °C) and volume fraction (0.1% - 2%) of nanofluids on the heat transfer. The results obtained show that the thermal conductivity increased as the volume fraction and temperature went up. Ahmed *et al.,* [38], they carried out an experimental study on the preparation of the nanofluid Al_2O_3-water. Nanoparticles Al_2O_3 were added to water in the cooling tank, with different volume fraction. The results obtained indicated a decline in energy consumption and an increase in the cooling capacity, and consequently a 5% coefficient of performance (COP) increase. Wang *et al.,* [39] measured thermal conductivity of Al_2O_3 and CuO nanofluids using water, oil and ethylene glycol as base fluids and re-ported that the enhancement of thermal conductivity and the thermal conductivity ratio of nanofluids both were higher comparing to the base fluids. Hamid *et al.,* [40] experimentally investigated the viscosity of Al_2O_3 nanofluids prepared with water-EG mixture in 40:60, 50:50 and 60:40 by volume as base fluids and the nanoparticles dispersed up to 2 % concentration under 30℃– 70℃. They reported that viscosity increased with the concentration increase and decreased with the temperature increase. A similar result was found by Cie ́slı̆nski *et al.,* [41] using Al_2O_3 / thermal oil and TiO_2 / thermal oil nanofluids. Fedele *et al.,* [42] experimented with water based nanofluids containing TiO_2 in different concentrations $20℃–70℃$ and found all the nanofluids behaved like Newtonian fluids and the viscosity enhancement, related to pure water was independent from temperature for all concentrations. Halelfadl *et al.,* [43] studied the effect of temperature and concentration on viscosity of CNT/water nanofluids and reported that viscosity of nanofluids increased with increase in concentration of nanofluid and decreased with temperature rise.

A numerical study on the forced convection of Al_2O_3-water nanofluid in ribbed channel has been conducted by Manca *et al.,* [44]. It was found that the heat transfer rate enhanced with the concentration of nanoparticles as well as Reynolds number. But this enhancement in heat transfer was accompanied by increasing the pressure drop penalty. Ahmed *et al.,* [45] investigated numerically the laminar forced convection flow in a triangular corrugated channel using copper–water nanofluid. Results indicated that the enhancement in heat transfer increased with the nanoparticle volume fraction and with Reynolds number. Recently, Ahmed *et al.,* [46] numerically studied on the heat transfer enhancement of copper–water nanofluid in a sinusoidal wavy channel. The numerical results showed that the heat transfer enhancement mainly depends on the amplitude of the wavy wall, Reynolds number and nanoparticle volume fraction rather than the wave length of the wavy wall. Chavan *et al.,* [47] studied the effects of the volume fraction of nanoparticles and temperature on the effective viscosity and density of nanofluids. It should be noted that some stable nanofluids including different base fluids and different nanoparticles with various volume fraction were prepared. The experimental results clearly showed that the viscosity of nanofluids increased with the increase in the volume fraction of nanoparticles but decreased when the nanofluid temperature augmented.

Based on the above review, it is noted that all of the previous studies on corrugated channel in literature used conventional fluid as working fluid and the influence of different volume fractions and diameters of nanoparticles are very important for improving the heat transfer. In this study, we conducted a numerical investigation of the convective heat transfer coefficient h and the pressure drop ΔP of a nanofluid Al_2O_3-water flow through a channel provided with trapezoidal undulations, for several mass concentrations and diameter of nanoparticle, for a range of Reynolds numbers from 100 up to 1000. The objectives of this work are to study the flow and heat transfer of this nanofluid use the model of Vajjha and Das [48] which measured the thermal conductivity and an empirical correlation [49] which measured the dynamic viscosity to see the effect of various volume fractions and that of the nanoparticle diameter on the heat transfer and pressure drop. The results were computed using ANSYS Fluent and validated with the existing works carried out by Ahmed *et al.,* [50].

2. Mathematical Formulation of The Problem

2.1 Description of The Physical Model

The geometric parameters of this problem are taken from the reference [51]. The system under study is illustrated in Figure 1. This is a two-dimensional laminar flow, between two parallel plates, composed with trapezoidal undulations, and is subjected to a constant heat flow. The height (H), the length (Lch) and the width (wch) of channel is 0.2 mm, 10 mm and 0.1 mm respectively. In addition, the mixture of water and nanoparticles of aluminum oxide is assumed to be homogeneous and incompressible. The nanofluid enters the channel with uniform and constant velocity and temperature profiles.

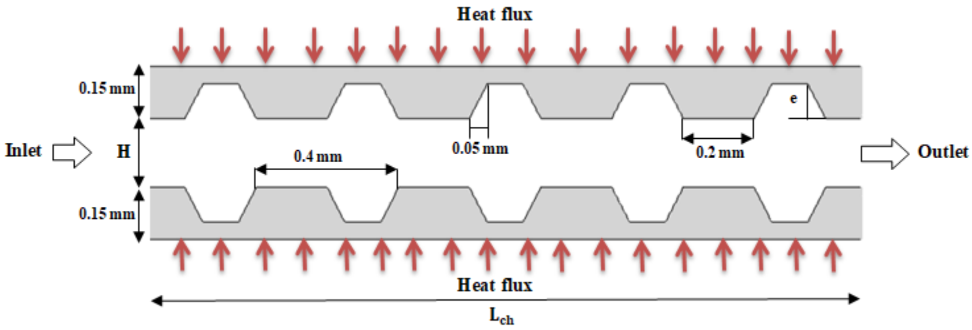

Fig. 1. Simplified diagram of the trapezoidal corrugated channel [51]

2.2 Governing Equations

The flow and Heat transfer are governed by the equations of continuity, momentum and energy (Izadi and al) [52]:

Continuity equation:

$$\rho \nabla U = 0 \tag{1}$$

Momentum:

$$\rho(U.\nabla U) = -\nabla p + \nabla(\mu \ .\nabla U) \tag{2}$$

Energy:

$$\rho C_p (U.\nabla T) = \lambda \nabla^2 T \tag{3}$$

2.3 Determination of Thermophysical Properties

The density and heat capacity of the nanofluid at the reference temperature T_0 [53] are determined from the following equations:

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_p \tag{4}$$

With ρ_f and ρ_p the densities of base fluid and nanoparticles.

$$(\rho C_p)_{nf} = (1-\varphi)(\rho C_p)_f + \varphi(\rho C_p)_p \tag{5}$$

With $(\rho C_p)_f$ and $(\rho C_p)_p$ the thermal capacities of the base fluid and of the solid nanoparticles.

2.3.1 Thermal conductivity

Thermal conductivity is an important parameter for the enhancement of the heat transfer performance of nanofluids. A wide range of experimental and theoretical studies were conducted in the literature to model the thermal conductivity of nanofluids. The classical models, originated from continuum formulation which typically involves the particle size/shape and volume fraction and assumes diffusive heat transfer in both fluid and solid phases, have been used to predict the thermal conductivity of nanofluids. Since the model reported by Maxwell [1], other classical models have been suggested by Bruggeman [54], Hamilton and Crosser [55], Jeffery [56], Wasp [57], Davis [58], and Lu and Lin [59].

According to these models, we use the model of Vajjha and Das [48] which measured the thermal conductivity of Al_2O_3 nanofluids of several volumetric concentrations in the base fluid with a Hilton [60] thermal conductivity apparatus suitable for liquids and gases. They developed a thermal conductivity model, which is a two-term function. The first term is called the static part and the second term is due to the Brownian motion. The second term takes into account the effect of particle size, particle volumetric concentration, temperature and properties of base fluid, as well as nanoparticles subjected to Brownian motion.

The effective thermal conductivity of a nanofluid is given by Eq. (6). The term $f(T,\varphi)$ in Eq. (6.2) is a function of temperature and particle volume concentration given by Eq. (6.3) [48] and the correlations for β (fraction of the liquid volume which travels with a particle) is given in Table 1.

$$\lambda_{eff} = \lambda_{static} + \lambda_{Brownien} \tag{6}$$

$$\lambda_{static} = \lambda_f \left[\frac{\left(\lambda_p + 2\lambda_f\right) - 2\varphi\left(\lambda_f - \lambda_p\right)}{\left(\lambda_p + 2\lambda_f\right) + \varphi\left(\lambda_f - \lambda_p\right)} \right]. \tag{6.1}$$

$$\lambda_{Brownian} = 5\times10^4 \beta\varphi\rho_f C_{p,f} \sqrt{\frac{\kappa T}{2\rho_P d_p}}\, f(T,\varphi) \tag{6.2}$$

Where *k* is the Boltzmann constant $\kappa = 1.3807 \times 10^{-23}\ J/k$

$$f(T,\varphi) = \left(2.8217\times10^{-2}\varphi - 3.917\times10^{-3}\right)\frac{T}{T_0} + \left(-3.0669\times10^{-2}\varphi - 3.91123\times10^{-3}\right) \tag{6.3}$$

Table 1
Curve-fit relations proposed by Vajjha and Das [48] and Sahoo [61]

Type of particles	β	Concentration	Temperature
Al_2O_3	$\beta = 8.4407(100\phi)^{-1.07304}$	$1\% \le \varphi \le 10\%$	$298K \le T \le 363K$

2.3.2 Dynamic viscosity

The dynamic viscosity is one of the key properties of nanofluids. It is believed that the viscosity is as critical as the thermal conductivity in engineering system because it is expected that nanofluids increase the thermal conductivity of base fluids without increasing the pressure drop that may affect the process of the convective heat transfer.

Although the Brinkman equation [62], and other traditional theories, notoriously under predict the effective dynamic viscosity of nanofluids, only few models have recently been proposed for describing the rheological behaviour of nanofluids, such as those developed by Koo [63], and Masoumi *et al.,* [64]. However, as these models contain empirical correction factors based on an extremely small number of experimental data, their region of validity is some way limited. Therefore, an empirical correlation [49] based on a large number of experimental data selected from literature has been developed for μ_{eff}/μ_f , where μ_{eff} is the effective dynamic viscosity of the nanofluid, and μ_f the dynamic viscosity of the base fluid. For oxide and metal nanoparticles suspended in water or ethylene glycol-based nanoparticles. The diameter of the nanoparticles and the volume fraction as well as the temperature were respectively: 10-150 nm, 0.2% to 9% and 294 k to 324 k.

$$\mu_{eff} = \mu_f \frac{1}{\left(1 - 34.87\left(d_p/d_f\right)^{-0.3} \times \varphi^{1.03}\right)} \tag{7}$$

$$d_f = \left[\frac{6M}{N\pi\rho_f}\right]^{1/3} \tag{7.1}$$

Where M is the molecular weight of base fluid
N is the Avogadro number $N = 6.022 * 10^{23} mol^{-1}$

The thermophysical properties of the base fluid (water) and solid nanoparticles (Al_2O_3) used in the present study are specified in Table 2.

Table 2
Thermophysical properties of water and nanoparticles at 20°C [65]

Thermophysical properties	$\rho(kg/m^3)$	$Cp(J/kgK)$	$k(W/mK)$	$\mu(kg/ms)$
Water	998.2	4182	0.6103	0.001003
Al_2O_3	3600	765	36	-

The above-mentioned formulas were incorporated into the User-Defined Function (UDF) subroutines.

2.4 Boundary Conditions

- channel inlet:

The input velocity was calculated from the Reynolds number by the relation:

$$U_{in} = \frac{\mathrm{Re}\,\mu_{nf}}{\rho_{nf} D_h} \tag{8}$$

$T_{in} = 293k$

- Channel wall: (heat flux) $q_w = 10^6\ W/m^2$
- Channel Outlet: $P = Patm$

Due to the rectangular cross section of channel, the hydraulic diameter is written as,

$$D_h = \frac{2W_{ch}H_{ch}}{W_{ch} + H_{ch}} \tag{9}$$

The average heat transfer coefficient is calculated as follows:

$$h = \frac{Q}{A_{ch}\Delta T} \tag{10}$$

$$A_{ch} = (W_{ch} + 2H_{ch})L_{ch} \tag{10.1}$$

$$\Delta T = T_b - \frac{1}{2}(T_{in} + T_{out}) \tag{10.2}$$

Where, Q is the heat flux, A_{ch} is contact area of channel between fluid and solid and ΔT is the temperature difference between the bottom and fluid.

The Nusselt number is then deduced from the convective heat transfer coefficient *h* using the expression,

$$Nu = \frac{hD_h}{\lambda_{nf}} \tag{11}$$

The friction coefficient is calculated by the expression:

$$f = \frac{2\Delta p D_h}{L_{ch}\rho_{nf}U_{in}^2} \tag{12}$$

Where Δp is the pressure drop along the channel; (Pa).

The comprehensive performance index is defined as follows [66]:

$$\eta = \frac{Nu/Nu_0}{(f/f_0)^{1/3}} \tag{13}$$

The index 0 designates the values relating to a smooth channel with a pure water flow.

3. Numerical Method

To study the dynamic and thermal behavior of the system, a numerical simulation of a nanofluid flow through a corrugated trapezoidal channel was proposed. The Ansys-Fluent code (under Workbench environment version 14.0) was used to solve the governing equations of continuity, momentum and energy. Using the finite volume method (FVM), it was decided to keep the default discretization schemes for the pressure, speed and relaxation factors with the SIMPLE algorithm for the velocity-pressure coupling. A specific User-Defined Function (UDF) module was developed and integrated into the Ansys-Fluent software in order to integrate the thermophysical properties of nanofluids. In order to analyze the independence of the mesh with respect to geometry, several grids were studied and analyzed in order to obtain a numerical grid-independent solution. For this, four grids were selected, namely 24360, 64430, 88088, and 110120. The results presented in Figure 2, show the influence of the mesh on the axial velocity, indicated that the grid composed of 88088 cells provides a satisfactory solution.

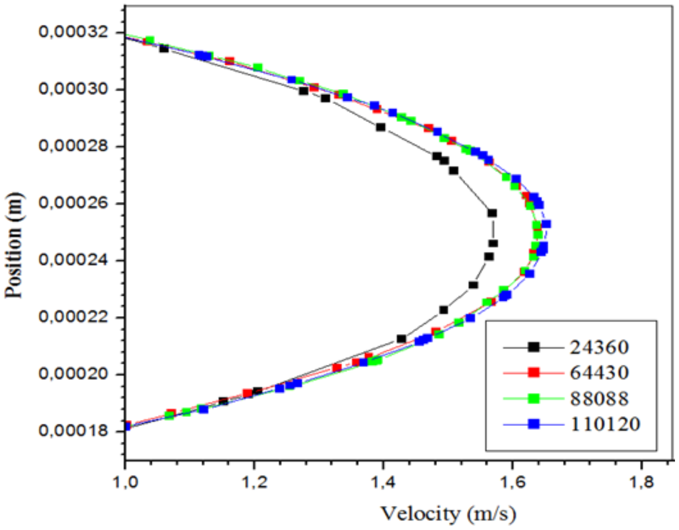

Fig. 2. Influence of the mesh on axial velocity

4. Validation of Results

In order to validate the numerical results, the average Nusselt numbers for the base fluid (pure water) and the nanofluid Al_2O_3-water through a corrugated trapezoidal channel, were compared with those obtained by Ahmed *et al.,* [50], for different Reynolds numbers (Figure 3). A good agreement was found between them.

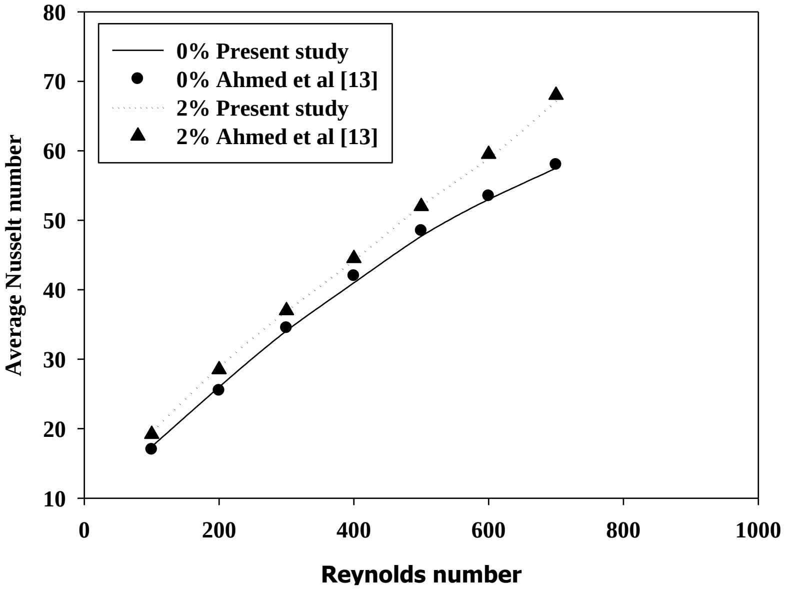

Fig. 3. Comparison of the obtained Average Nusselt numbers with those of Ahmed *et al.,* [50], for different values of the Reynolds number and different volume fraction

5. Results and discussions

5.1 Effect of The Volume Fraction of The Nanoparticles

Figure 5(a) shows the variation of the average Nusselt number as a function of the Reynolds number, for different volume fractions of the nanoparticles 0%, 2%, 3%, 4%. Therefore, the use of nanoparticles with a larger volume fraction and a higher Reynolds number can improve the heat transfer and Nusselt number. From Figure 5(b), one may clearly see that the larger the volume fraction of nanoparticles and the Reynolds number, the higher the pressure drop. This pressure drop is due to the increase in viscosity and density of the nanofluid Al_2O_3-water [65]. The performance index [66], expressed in equation (13), is used to analyze the thermo-hydrodynamic performance of the methods used for improving the heat transfer. This parameter is the comparison between the Nusselt number and friction factor in the indented channel for the volume fractions 0%, 2%, 3% et 4%. Figure 5(c) shows the thermo-hydraulic performance, for different volume fractions, as a function of the Reynolds number. It is noted that the increase in the volume fraction of nanoparticles makes it possible to improve the thermohydraulic heat transfer performance rate.

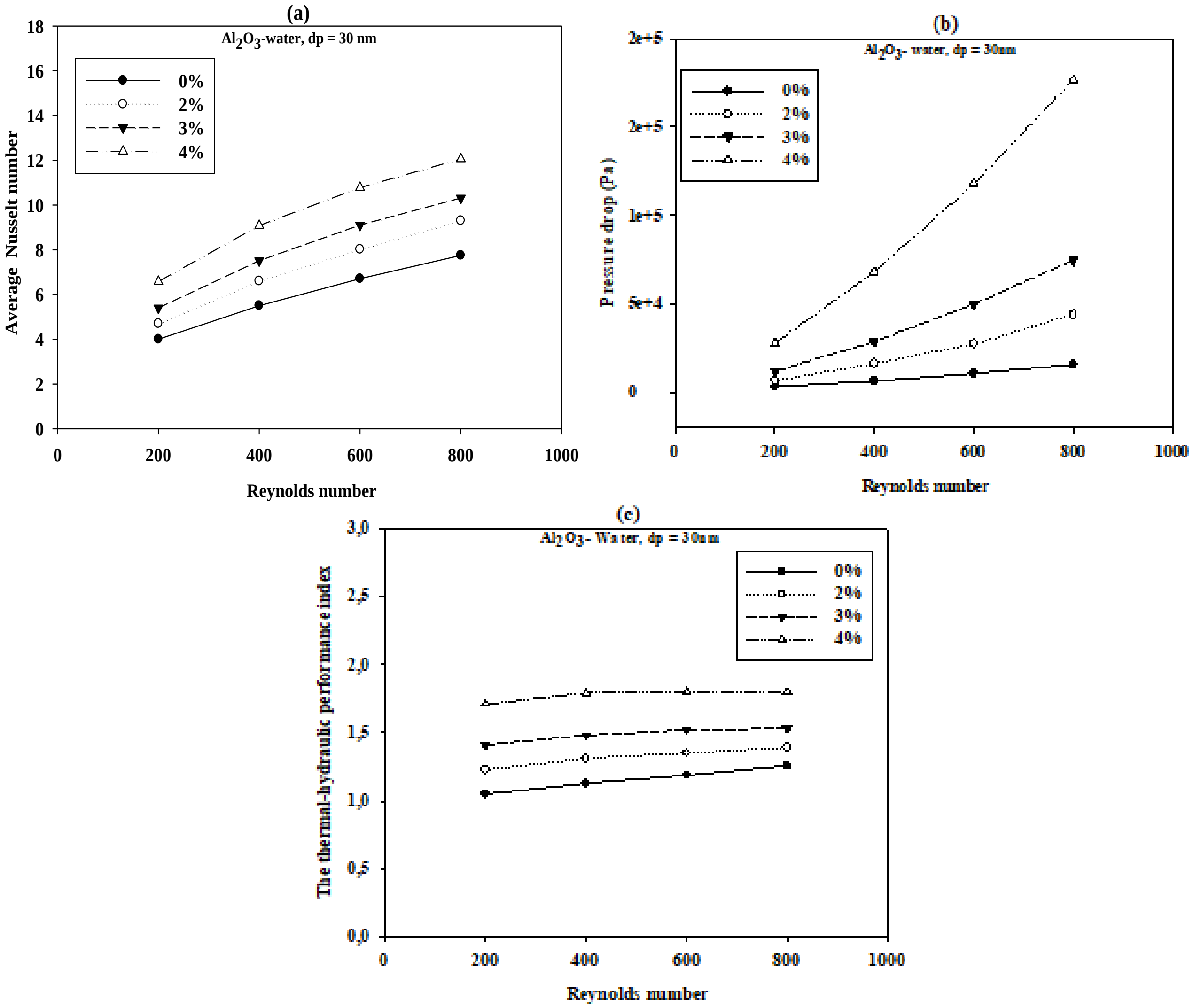

Fig. 5. Effect volume fraction of nanoparticle as a function of Reynolds number (a) Average Nusselt number at dp = 30 nm (b) Pressure drop (c) Thermo-hydraulic performance index of heat transfer for nanofluid Al_2O_3-water

5.2 Effect of The Diameter of Nanoparticles

Figure 6(a) shows the variation of the average Nusselt number as a function of the Reynolds number, for different diameters of the nanoparticles 30, 40, 60nm with a volume fraction of 4%. The use of nanofluids with a smaller nanoparticle diameter and larger Reynolds number makes it possible to increase the Brownian motion of the nanoparticles and consequently to enhance the thermal conductivity, which results in better heat transfer [67]. Figure 6(b), suggests that the pressure drop for the Al_2O_3-water nanofluid increases as the Reynolds number goes up and the diameter of the nanoparticles goes down. The relation (13) is used to analyze the thermohydraulic performance index [66] of heat transfer, for different diameters of nanoparticles and different Reynolds numbers Figure 6(c). The results obtained show that the heat transfer improves when the diameter of the nanoparticles decreases.

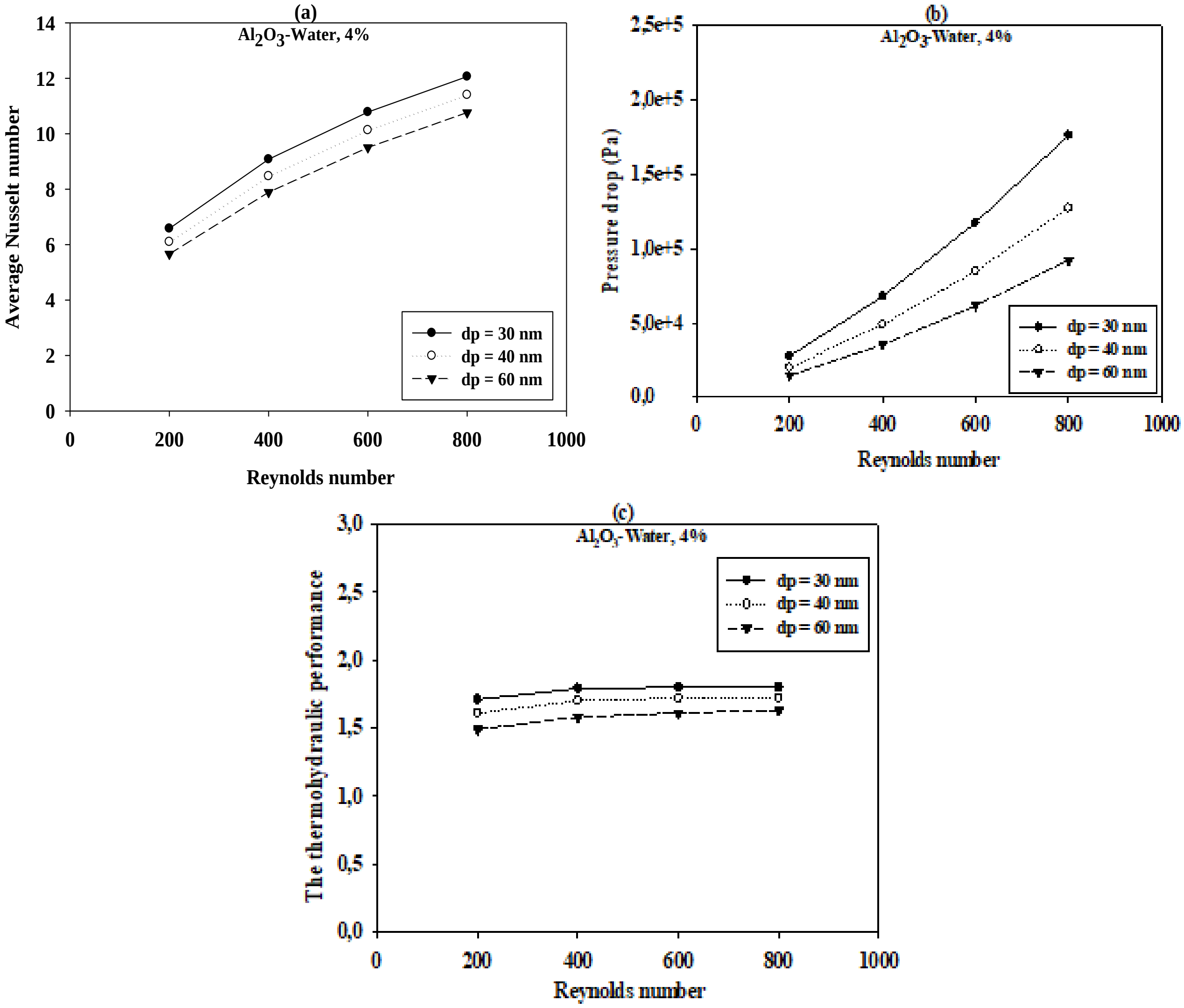

Fig. 6. Effect of nanoparticle diameter as a function of Reynolds number (a) Average Nusselt number (b) Pressure drop (c) Thermo-hydraulic performance index of heat transfer for nanofluid Al_2O_3-water at 4%

6. Conclusion

A numerical study was carried out to analyze the two-dimensional laminar flow of nanofluids as well as the heat transfer in a channel provided with trapezoidal undulations, under the action of a partially constant heat flux density. The effects of Reynolds number, volume fraction, and diameter of nanoparticles on the thermal and dynamic behaviour of a corrugated microchannel have been investigated. The main results observed are:

i. The more the volume fraction of the nanoparticles and Reynolds number increase and the diameter of the nanoparticles decrease, the more the Nusselt number increases and the more the pressure drop decreases.
ii. The thermohydraulic performance factor increases with the increase in the volume fraction of nanoparticles, and with the decrease in the diameter of nanoparticles.
iii. This study allows us to conclude that the use the two-dimensional laminar flow of Al_2O_3-water nanofluid as well as the heat transfer in a channel provided with trapezoidal undulations with 30 nm diameter nanoparticles, and a volume fraction of 4%, gives the best thermohydraulic performance over the entire range of Reynolds numbers.

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