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Numerical Study of Heat Transfer Enhancement in Contour Corrugated Channel Using nanofluid and Engine Oil

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ABSTRACT: improving the design of geometrical parameters of heat exchanger leads to enhance heat transfer and makes it further compacted which in turn increases the efficiency of the thermal process, leading to save operating costs. In the present investigation, thermal and hydraulic performance of laminar flow of the trapezoidal counter heat exchanger with nanofluid and engine oil was carried out numerically over Reynolds number ranges of 1100-2300 for nanofluid and 250 for engine oil. A numerical simulation of laminar flow of nanofluids with volume fractions of 0–4% was carried out. Thermal and flow characteristics are explored with the help of the isotherms contours and streamwise velocity for trapezoidal-corrugated channels. The results showed that the average Nusselt number value increased when adding nanomaterials to water as a result of increasing thermal conductivity on the other side the pressure drop increased by adding nanomaterials to water due to increase the viscosity of the fluid. The results also indicated that the increase in the concentration of suspended nanoparticles in the water led to an increase in the value of the Nusselt numbers, accompanied by an increase in pressure drop. It should be noted that the SiO_2/ water nanofluid has yielded significant heat transfer improvement for all Reynolds numbers followed by MgO and pure water respectively. Consequently, the use of corrugated surfaces in reverse heat exchangers with nanofluid can improve heat transfer in many applications

INTRODUCTION

In recent years, the advance in heat exchanger performance was to cover the industry needs and demands for premium heat transfer quality. However, the usages of corrugated surfaces in heat exchangers have reached the optimum limit of heat transfer augmentation. Research for further enhancement methods in heat transfer has become essential. On the coolant side, the traditional heat transfer fluids (such as water, oil, and ethylene glycol) with low thermal conductivities considered a fundamental obstacle to improving heat exchangers' performance. To overcome this limitation and improve conductivities of traditional heat transfer of thermal liquids a nanoparticle was suspended with average sizes less than [100] nm, to these fluids. It is known that the convective heat transfer coefficient is directly dependent on the thermal conductivity of the fluid. Several studies found an increase in the enhancement of heat transfer with particle volume fractions. Khoshvaght-Aliabadi 2014[1] examined channel have a sinusoidal-corrugated with nanofluid [Al2O3-water] using a 2-D numerical simulation heat transfer and flow characteristics. They found the most effective factors on values of Nusselt number and friction factor were the channel height and wave amplitude, respectively. Compared to traditional base fluid, the result showed the sinusoidal-corrugated channels with nanofluid flow inside efficiently increase the Nusselt number, however, the friction factor keeps the same. Akdag, Akcay, and Demiral, 2014 [2] investigated numerically the characteristics of [Al2O3–water] in terms of heat transfer based nanofluids in a wavy mini-channel under pulsating inlet flow conditions. Navaei et al., 2015[3] investigated to check the geometrical parameter effects and various nanofluids on the thermal performance of rib–grooved channels under uniform heat flux. The results showed that the nanofluid containing [SiO2] has the highest Nusselt number compared with other types. Al-Shamani *et al.*, 2015 [4] numerically studied the effects of turbulent flow of nanofluids on heat transfer through the rib–groove channel. The results show the efficacy of the trapezoidal with increasing height in the flow direction rib–groove (rectangular, semi-circular, and trapezoidal) in increasing heat transfer rate and Nusselt number. In comparison to another nanofluid, the [SiO_2] nanofluid has the highest value of the Nusselt number. S. Harikrishnan *et. al*., 2018[5] conducted a numerical study to verify the influence of Ahmed on Muhammad. The study was conducted using the ANSYS Fluent software for various values of skewness angle, corrugated amplitude, Reynolds number (Re), the width of the channel, and wavelength. The study showed that the Nusselt numbers have increased significantly with the increase of each of Reynolds Number, skewness angle, and corrugated amplitude, while a decrease in the Nusselt number with the increase in wavelength was observed. (Selimefendigil and Hakan, 2017) [6] examined numerically the pulsating of nanofluid flow in terms of laminar forced convection over a backward-facing step with a corrugated bottom wall. The results showed that the increase in the average heat transfer rate was due to the inclusion of the nanoparticles, however, these enhancements rely on the solid volume fraction of nanoparticle interval. Yang, Wang, and Tseng, 2014[7] studied forced laminar flow in a corrugated channel using different types of nanofluids to improve heat transfer experimentally and numerically. Cu/water, and Al2O3/water, with different concentrations, were investigated in this study. The results showed that the thermal improvement was achieved by 15% and 24% in the wavy channel flow for the numerical study compared to the base fluid with □=3% and □=5% of Cu/water nanofluid. Sadeq *et al.*, 2019[8] presented a numerical study to verify the effect of amplitude height inside the corrugated channel on heat transfer rates and flow behavior under the conditions of turbulent flow. The study showed that the Nusselt number has clearly increased with increasing amplitude height, and they explained the reason for this phenomenon by generating eddies at the corrugate walls. Whereas, with the increase in the height of these corrugates, it leads to an increase in eddies, which helps to increase the heat transfer due to the increase in temperature gradients. While the study showed that friction factor has also increased with amplitude height increasing, they have set a standard performance evaluation criteria (PEC) to indicate the validity of the heat exchanger. As this criterion whenever its value is higher than one means that the rate of improvement in the heat transfer is higher than the value of the loss due to friction**.** Akbarzadeh et al., 2016[9] studied the effect of the change in the concentration of nanomaterials on the rate of heat transfer and indicate the effect of these changes on pressure drop. In this study, the values of Re were between 300 to 600, and the different concentrations were between 0.01 and 0.05**.** The numerical and experimental studies have shown that the average Neselt number increased with increasing Reynolds and with increasing concentration of nanomaterials in the base fluid. Rashidi et al., 2016 [10] investigated the effect of incorporating surface improvement technique under the influence of the magnetization field and the technique of adding nanoparticles on the heat transfer rate with considerations of pressure drop. This study was performed for $500 \leq R \leq 1000$ and the flow is assumed laminar, two dimensional, and incompressible steady. The results obtained from the numerical study showed that the Nusselt number has increased with the increase of the Grashof number for nano-fluid as well with the increase in the concentration of nanomaterials in the base fluid. The main goal of this study is to improve the effectiveness of heat transfer of counter corrugated channel with a moderate increase in the pressure drop penalty by passive methods; corrugated walls (surface extensions) and nanofluid. The geometrical parameters change such as amplitude or height of corrugated channel utilized to raise the rate of heat transfer was accompanied by further pressure drop. The present study has numerically investigated the heat transfer enhancement and pressure drop by using nanofluid flow in a model of corrugated channel. A numerical simulations study was done by Ansys software that used the finite difference approach and solving the governing equations in a stream function–vortices formulation. In this study, the range [1100 to 2300] for Re and [0 to 0.4%] for nanoparticle volume fraction were used. The change of heat transfer and pressure drop have been investigated to measure the effects of nanofluid inside the channel.

MATHEMATICAL MODEL

Problem Description

The basic geometry of the corrugated contour channel is shown in Figure 1. It consists of one corrugated aluminum wall with an amplitude of wavelength of Lw. The flat surface of the channel has been modified in wavy shape with ten corrugations and neglected the thickness of the well. The basic geometry of the corrugated contour channel is shown in Figure 1. It consists of one corrugated aluminum wall with an amplitude of wavelength of Lw. The flat surface of the channel has been modified in wavy shape with ten corrugations and neglected the thickness of the well. The upstream inlet of the corrugated section has an axial length of Ld= 200 mm and the downstream exit has an axial length of Le=60mm mm for both the channels. The average height (H_{av}) of all these sections was 10mm [11]. The test section Lc=200mm However, the following geometric parameters are considered in the current study; the amplitude of corrugated channel (a) is 5 mm and the wavelength of the corrugated wall (Lw) is 20mm. In the current study and to get the numerical solution and final form of governing equations, several expectations have been taken into account. The flow is assumed steady, two-dimensional, and incompressible. the SiO_2 and MgO/water nanofluid and oil in thermal equilibrium and run through the channel at the same velocity.

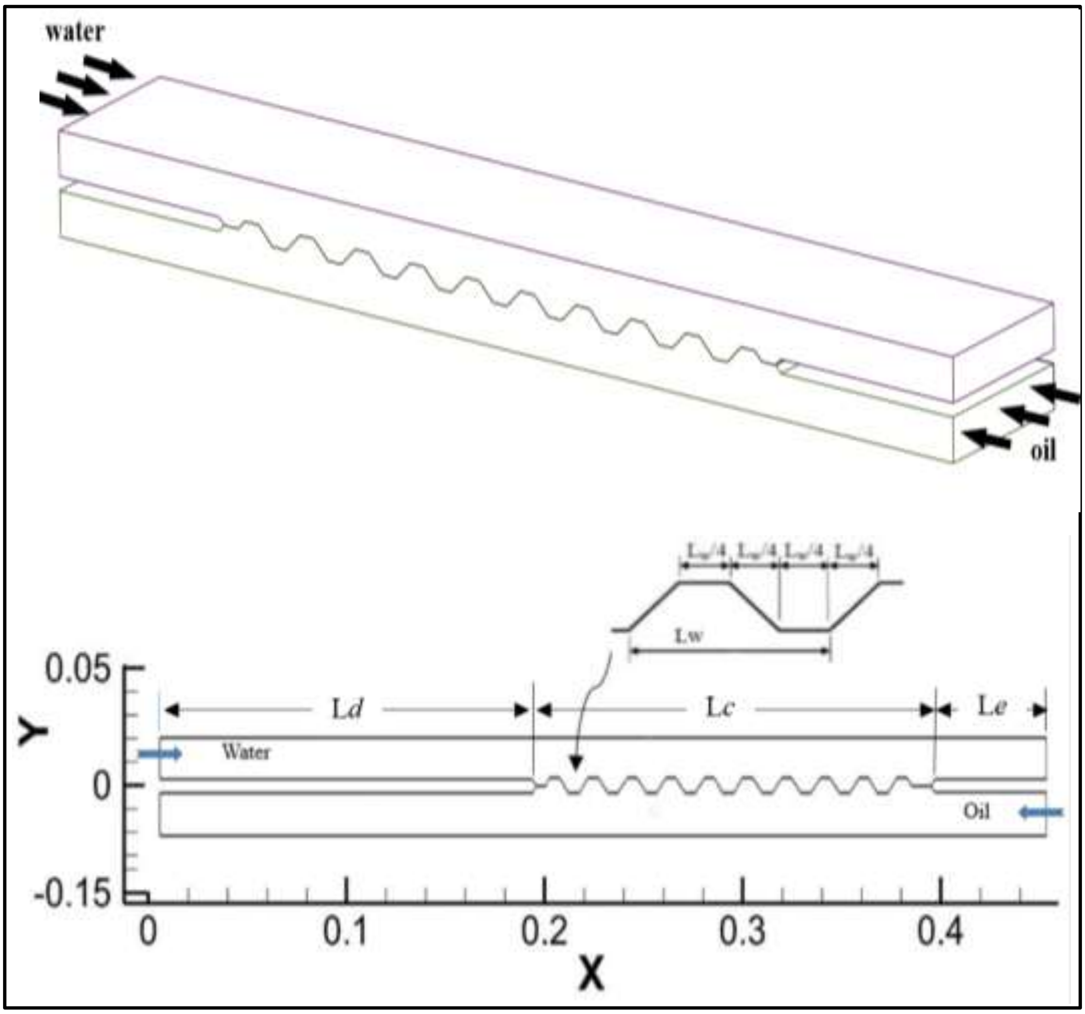


Figure 1: Physical domain of the present study

Inlet Boundary Conditions

A uniform velocity and temperature distributions are commonly assumed at the inlet of water and engine oil channel.

$u = u_{in}$, $v = 0$, $T_{in}= 298$ K for water

$u = u_{in}$, $v = 0$, $T_{in}= 350$ K for engine oil

Assumptions And Governing Equations

To complete the numerical results and find the last form of governing equations for this investigation, considering some assumptions. The flow is adopted to be steady-state conditions, fully developed, and two-dimensional. Sidewalls and all the upstream walls are considered to be adiabatic surfaces. The base fluid is assumed to have a thermal equilibrium and the no-slip condition occurs. The fluid flow is considered to be Newtonian and incompressible. the SiO_2 and MgO/water nanofluid and oil in thermal equilibrium and run through the channel at a similar velocity.

In this model, the governing equations were discretized using the finite volume approach. Continuity equation, Momentum equation, and Energy equation can be written as (Moraveji et al.) [12]:

Continuity equation:

$$\nabla.(\rho v) = 0 \quad (1)$$

Momentum equation

$$\nabla.(\rho v v) = -\nabla P + \nabla.(\mu \nabla v) \quad (2)$$

Energy equation:

$$\nabla.(\rho C v T) = \nabla.(k\ \nabla T) \quad (3)$$

THERMOPHYSICAL PROPERTIES OF NANOFLUID WATER-BASED SUSPENSION

Although some studies designed to investigate the thermophysical properties of the fluid, the traditional models are not considered nanofluids. Indeed, experimental outcomes allow us to choose a suitable model for a specified feature. The influencing features of nanofluid MgO/water and SiO_2/water are described as below:

$$\rho_{nf} = \phi_p \rho_p + (1 - \phi_p)\, \rho_{bf} \quad (4)$$

Equation (4) was originally presented in Ben-Mansour and Habib, 2013 [13] for determining the density

Equation (5) that is used for identifying heat capacity was first utilized in (Moraveji and Ardehali, 2013 [12]:

$$C_{nf} = \frac{\phi_p \rho_p C_p + (1 - \phi_p)\, \rho_{bf} C_{bf}}{\rho_{nf}} \quad (5)$$

Besides, for calculating the conductivity of nanofluids equation (6) was proposed by Hamilton and Crosser [14].

$$\frac{k_{nf}}{k_{bf}} = \frac{k_P + (n-1)\, k_{bf} - (n-1)\, \phi_p (k_{bf} - k_p)}{k_p + (n-1)\, k_{bf} + \phi_p (k_{bf} - k_p)} \quad (6)$$

In this equation, n represents the empirical shape factor to measure the particle shape effects and in a varied value (0.5 to 6.0). 3/ stated for (n) The shape factor, where ψ represents the sphericity of particle and defined as a sphere surface area to the particle surface area. So, n =3 for spherical nanoparticles. The Hamilton and Crosser model in this case of (n = 3) is similar to the Maxwell model as the following:

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p + 2k_{bf} - 2\phi_p\, (k_{bf} - k_p\,)}{k_p + 2k_{bf} + \phi_p (k_{bf} - k_p)} \quad (7)$$

the predicted values are subjected to comparison by Maxwell models, Corcione, 2011 [15] replicas, and experimental results by Suresh et al., 2011 [16]. Figure 2 shows that the Maxwell models unable to exactly calculate the thermal conductivity, particularly if volume concentrations were high. Indeed, it is found that the Corcione models appear to be satisfactory to ensure with results by Suresh et al., 2011 [16] the classical models, in general, not valuable and effective as experimental data. So, to achieve the most precise numerical data in the current study viscosity values and thermal conductivity for different concentrations of nanofluid have been reported by Corcione, 2011[15]. they produced empirical correlation with a standard deviation of error equal 1.86%.

thermal conductivity of nanofluid:

$$\frac{k_{nf}}{k_{bf}} = 1 + 4.4 Re^{0.4} Pr^{0.66} \left(\frac{T}{T_{fr}}\right)^{10} \left(\frac{k_p}{k_{bf}}\right)^{0.03} \phi^{0.66} \quad (8)$$

where

Re: nanoparticles Reynolds number.
Pr: base liquids Prandtl number.
T: nanofluids temperature.
T_{fr}: base liquid freezing point.
k_p: nanoparticle thermal conductivity.
ϕ: nanoparticles volume fraction.

The Reynolds number of nanoparticle defines as:

$$Re = \frac{\rho_{bf} u_B d_p}{\mu_{bf}} \quad (9)$$

Where
ρ_{bf}: mass density.

μ_{bf}: base fluid dynamic viscosity.
d_p: diameter of the nanoparticle.
u_B: Brownian velocity.

u_B equation is:

$$u_B = \frac{2k_{bf}T}{\pi\mu_{bf}d_p^2} \tag{10}$$

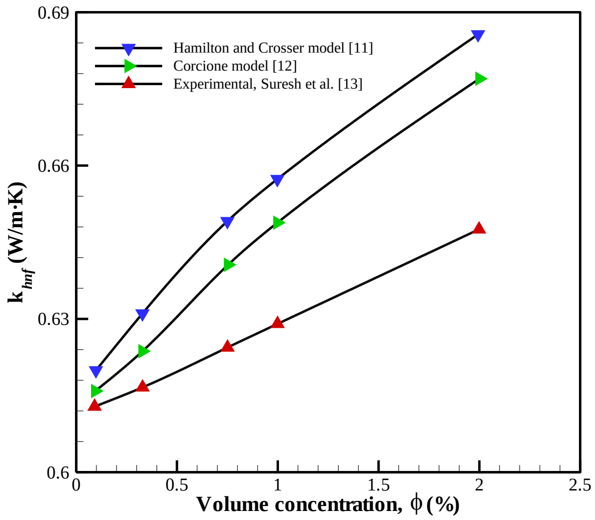


Figure 2: Al2O3-Cu/water nanofluid Thermal conductivity.

Three models frequently were employed theoretically to predict the nanofluid viscosity. These models are presented as follows Brinkman, 1952[17]

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\phi)^{2.5}} \tag{11}$$

[18] model:

$$\mu_{nf} = \mu_{bf}(1 + K_1\phi + K_2\phi^2) \tag{12}$$

where $K1$ is equal to 2.5 and $K2$ defines the deviation from the very dilute limit of suspension; by allowing a superimposed Brownian motion, the value of the coefficient $K2$ is calculated as 6 (Suresh et al., 2011[16]. Figure 3 shows the classical models underestimate significantly the viscosity of nanofluid, specifically in high volume concentration. Therefore, in the present study and for numerical results high accuracy, a viscosity of nanofluids depends on Corcione, 2011[15] equation.

$$\mu_{nf} = \left[\frac{1}{1-34.87(\frac{d_p}{d_{bf}})^{-0.3}\phi_p^{1.03}}\right]\mu_{bf} \tag{13}$$

where

$$d_{bf=0.1(\frac{6M}{N\pi\rho_{bf}})^{0.33}} \tag{14}$$

Where

M: Molecular weight of water, M (kg/mol) = 1.80E-02.

N: Avogadro number, N (mol^ (-1)) =6.02E+23.

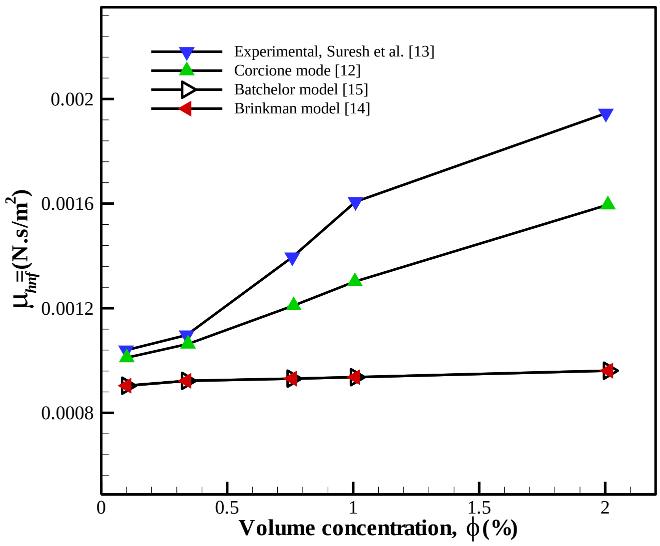


Figure 3: Al2O3-Cu/water hybrid nanofluid Dynamic viscosity.

CODE VALIDATION AND GRID TESTING

Grid Independence Test

Generally, grid resolution plays an essential role in the accuracy of the numerical results. To evaluate the required element size of the current study, elements size 0.4,0.3,0.2 and 0.15 were selected as in Table 1. These elements' size were studied at Re=1200 and over the distance X=0.25 to 0.3m. The parameters local Nusselt number and pressure drop distribution have been studied over this distance. (figure 4) shows that a uniform grid mesh of the 0.2 was found to be appropriate to ratify the numerical results.

Table 1: Different element's size with elements number

Grid size	Elements number
0.4	158690
0.3	264044
0.2	539280
0.15	920766

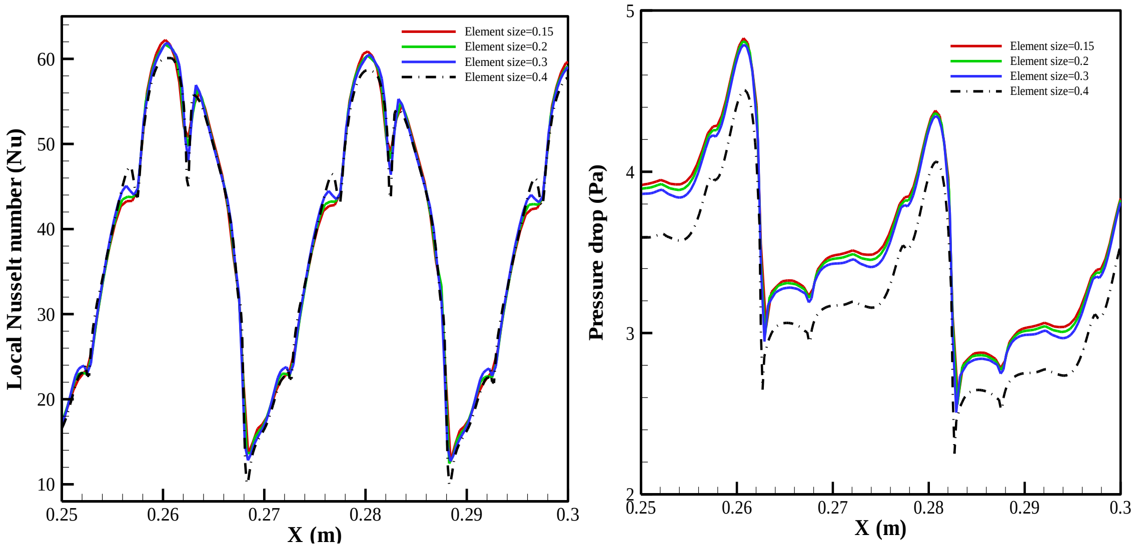


Figure 4: (a) local Nusselt number and (b) Pressure drop a long-distance X=0.25 to 0.3m for water at Re = 1200

Numerical Validation

To test the validity of the proposed numerical model, experimental and numerical investigation of the turbulent forced convection of SiO_2-water nanofluid flow in a corrugated channel has been studied by (Ahmed et al) [11]. A comparison was made between the results of the average Nusselt number and pressure drop that obtained from the current study, which took into consideration the condition in which (Ahmed *et al.*) [11] experimental and numerical study was conducted. It is observed from the figure (5) that the results of the current study of the average Nusselt number and pressure drop are almost identical to the results of (Ahmed *et al.*) [11]. The error deviation of the Nusselt number in figure 5a is 0.0102% and 0.0208% with numerical and experimental work and the error deviation of the pressure drop in figure 5b is 0.0512% and 0.0325% with numerical and experimental work respectively over Reynolds number=4000.

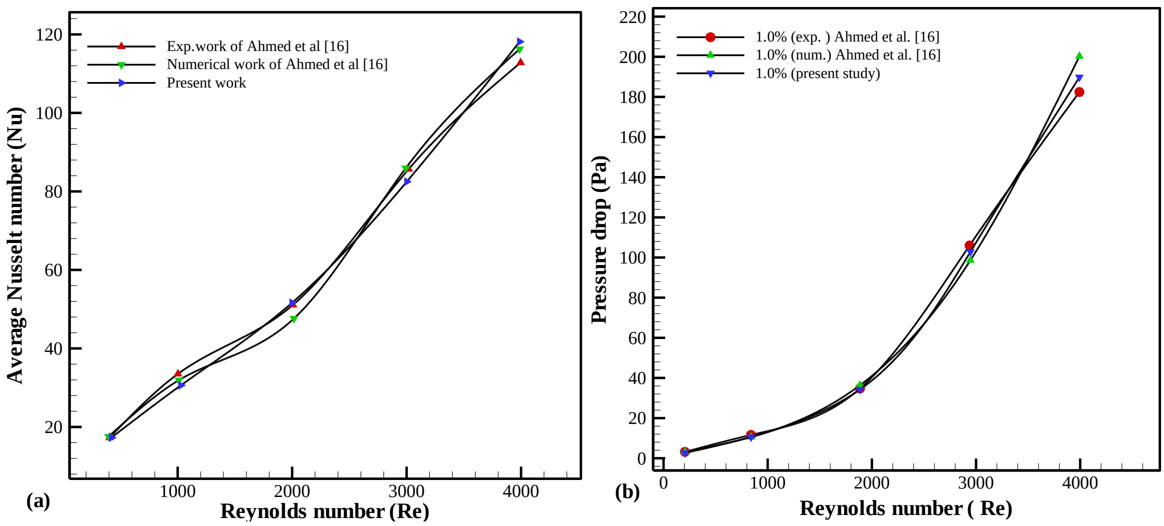


Figure 5: Comparison results of turbulent convection in a corrugated channel with Ahmed et al [11]. (a) average Nusselt number versus Reynolds number. (b) pressure drop versus Reynolds number.

RESULTS AND DISCUSSION

In this part of the study, it was investigated the effect of two types of nanomaterials suspended in water with different concentrations ranging from 0 to 4% over Reynolds number range of 1100 to 2300 and engine oil with constant Reynolds number of 250 in the Contour Corrugated Channel. The main purpose of this study is to increase the rate of heat transfer in the channel through two techniques, the first is to change the surface shape and the second is the addition of nanomaterials for the purpose of increasing the thermal conductivity of the flowing fluid.

Figure 6 shows the streamwise velocity contours and the isotherms contours for the trapezoidal-corrugated channel with an amplitude of 4mm and wavelength 20mm at Re=1100. Furthermore, the figure shows a comparison between two types of nanofluid, SiO_2/water nanofluid and MgO/water nanofluid. The change in the shape of the channel surface leads to an increase in turbulence and generates eddies near the lower wall resulting rise in temperature gradients and, consequently, an increase in the rate of heat transfer in this region. This is what is observed in this figure, where eddies are seen near the corrugated surface. The figure also shows that the temperature gradient increases near this surface. This can be attributed to the fact that the vortices expel the hot fluid next to the wall and replace it with cold water from the center of the channel. Also, the suspended nanomaterials in the fluid increase the thermal conductivity, which leads to an increase in the heat transfer rate. It is also seen that vortices were generated more in the SiO_2/water nanofluid, compared to MgO/water nanofluid, because the density of SiO_2/water nanofluid is lower than MgO/water nanofluid which is resulting in a higher velocity. Moreover, many studies and theories have shown that liquids molecules have a random and irregular movement called Brownian motion, and this movement increases with the increasing flow velocity. When adding nanoparticles with high thermal conductivity to water, as a result of this random motion, these molecules absorb heat while hitting the hot wall, then return to lose this heat in the liquid which augments energy exchange rates between the heated walls and the flowing fluid.

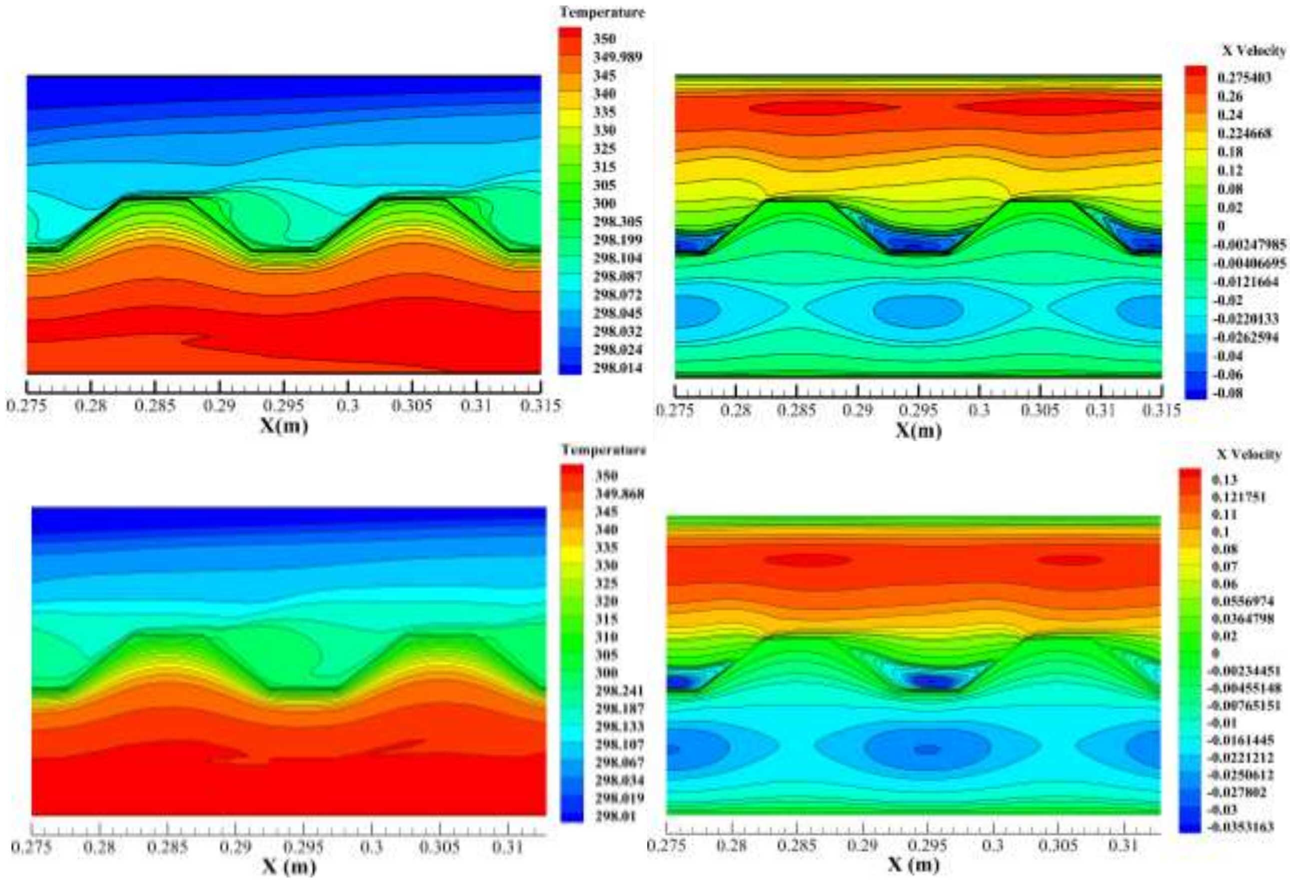


Figure 6: streamwise velocity contours and isotherms contours for the trapezoidal-corrugated channel with an amplitude of 4mm and wavelength 20mm at Re=1100.

Effect Of Nanofluid Types

To investigate the influence of nanofluid types, two several kinds of nanofluids (SiO2 and MgO-water) with a volume fraction of 4% and the particle diameter of 20 nm have been considered in the current study. Trapezoidal corrugated channels with wavelength (Lw) of 20 mm and amplitude (a) of 4.0 mm are presented over Reynolds number range of 1100-2300 for water and 250 for the engine oil. The variation of the average Nusselt number with Reynolds number for different types of nanofluid is illustrated in Figure7. It is found from this figure the average Nusselt number for all fluids is shown to rise as the value of Reynolds number rises. It is also can be observed that the highest Nusselt number was found by using the SiO2-water nanofluid than the use of MgO-water nanofluids and pure water. This may be because the disturbance that is introduced due to the intensity effect of re-circulation regions is higher for SiO2-water nanofluid due to the highest velocity of the fluid. Moreover, the channel walls temperature gradient rises, as a result, rising the heat transfer rate among the fluid and wall of the channel. Moreover, the distilled water (ϕ=0%) has the lowest average

Nusselt number due to the low conductivity of the distilled water compare to the SiO2-water Nanofluid.

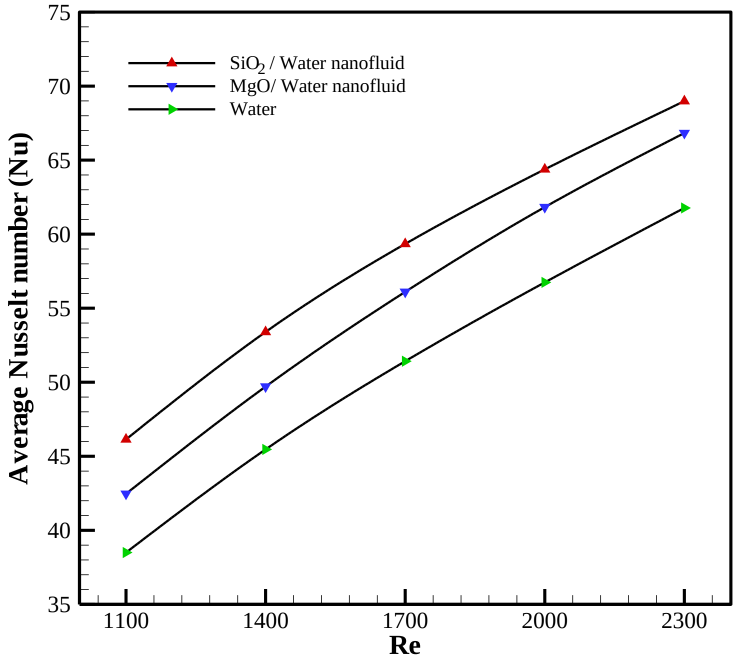


Figure 7: Average Nusselt number vs. Reynolds number for different nanoparticles types at a=4.0 mm, Lw=20 mm, dp=20 nm, and ϕ=4% in the trapezoidal channel.

The effects of two types of nanoparticles which are SiO2, MgO at the practical diameter of 20nm, the volume fraction of 4% with pure water as a base fluid in the trapezoidal channel at a=4 mm and Lw=20mm on pressure drops were investigated numerically in this section. It may be noted from Figure 8 that the pressure drop of nanofluid is higher than the pure water since the nanofluids have more density and viscosity in comparison with the pure water. Also, the MgO-water nanofluid gives the biggest values of the pressure drop among the different fluids due to the highest viscosity as shown in Figure 8, at the specific Reynolds number. Consequently, the channel walls velocity gradient rises, so the wall shear stress will rises and rising by that the values of the pressure drop.

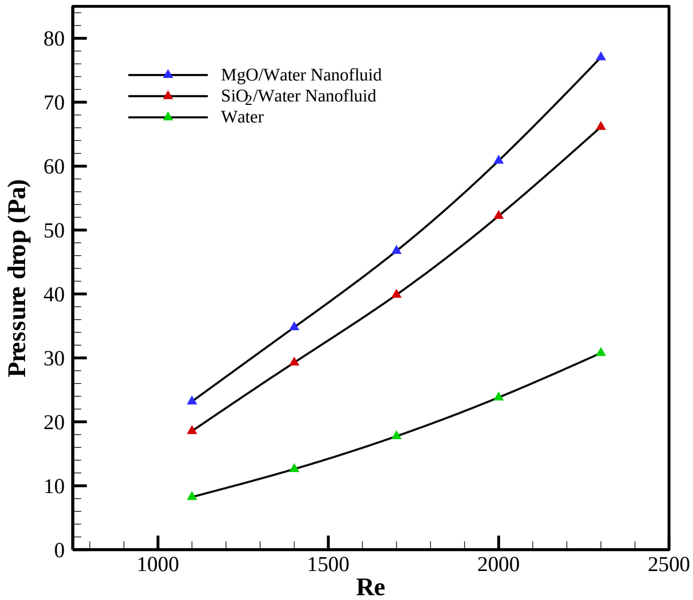
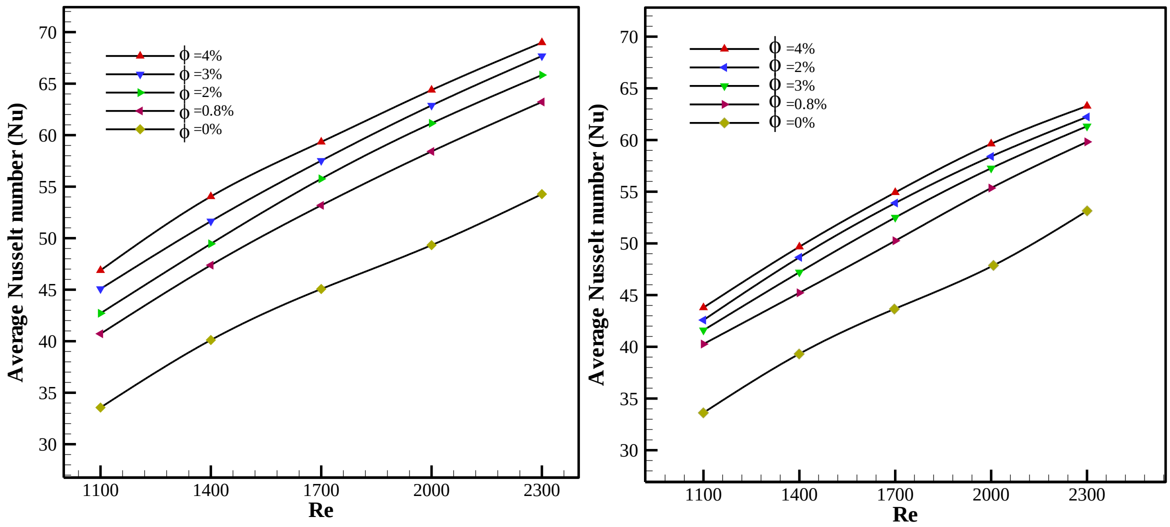


Figure 8: Pressure drop vs. Reynolds number for different types of fluids at a=4.0 mm, Lw=20 mm, dp=20 nm, and ϕ=4% in the trapezoidal channel.

Effect Of Nanoparticles Volume Fraction

The effect of SiO2-water nanofluid and MgO/water nanofluid with volume fractions of (0, 0.8%, 2%, 3%, and 4%) and dp=20 nm in the trapezoidal-corrugated channel at a=4.0 mm and Lw=20 mm on the average Nusselt number have been numerically investigated. Figure 9 depicts the average Nusselt number variation with respect to the Reynolds number using several volume fractions of SiO2-water nanofluid and MgO/water nanofluid in the trapezoidal-corrugated channel. As expected, the average Nusselt number of trapezoidal-corrugated channel, at a given volume fraction, increases as the Reynolds number increases. The rate of the heat transfer increase, The turbulent intensity leads to an increase in the channel wall temperature gradient and by that reduces the thermal boundary layer thickness due to the rises in the Reynolds number. Moreover, as the nanoparticles volume fraction rises, the value of the Nusselt number rises as well. Due to the nanoparticle's Brownian motion and the improvement in the base fluid thermal conductivity. Besides, the figure shows that the SiO2-water nanofluid has led to a higher Nusselt number than the MgO/water nanofluid. The reason for this is attributed to the fact that the density of SiO2-water nanofluid is less than MgO/water nanofluid. This means that the speed of SiO2-water nanofluid is higher than MgO/water nanofluid, and therefore the rate of heat transfer with SiO2-water nanofluid is higher than MgO/water nanofluid.



(a) (b)

Figure 9: Variation of average Nusselt number vs Reynolds number for different volume fractions, ϕ of (a) SiO_2, and (b) MgO/ water nanofluid at dp=20nm in the trapezoidal channel.

Figure 10 displays the difference of the pressure drop versus Reynolds number for SiO2-water nanofluid and MgO/water nanofluid at the different volume fractions of 0%, 0.8%,2%,3%, and 4%, with dp=20 nm in the trapezoidal-corrugated channel at a=4.0 mm and Lw=20 mm. According to this figure, at specific nanoparticles volume fraction, the pressure drops considerably rises with Reynolds number rising owing to the channel wall high-velocity gradient. The results showed that the pressure drop increases with nanoparticle volume fractions because of the increasing of the nanofluid viscosity. Besides, the intensity of re-circulation regions becomes stronger due to the increase of the nanoparticles volume fraction, as pointed out before, resulting in a further increase in the pressure drop.

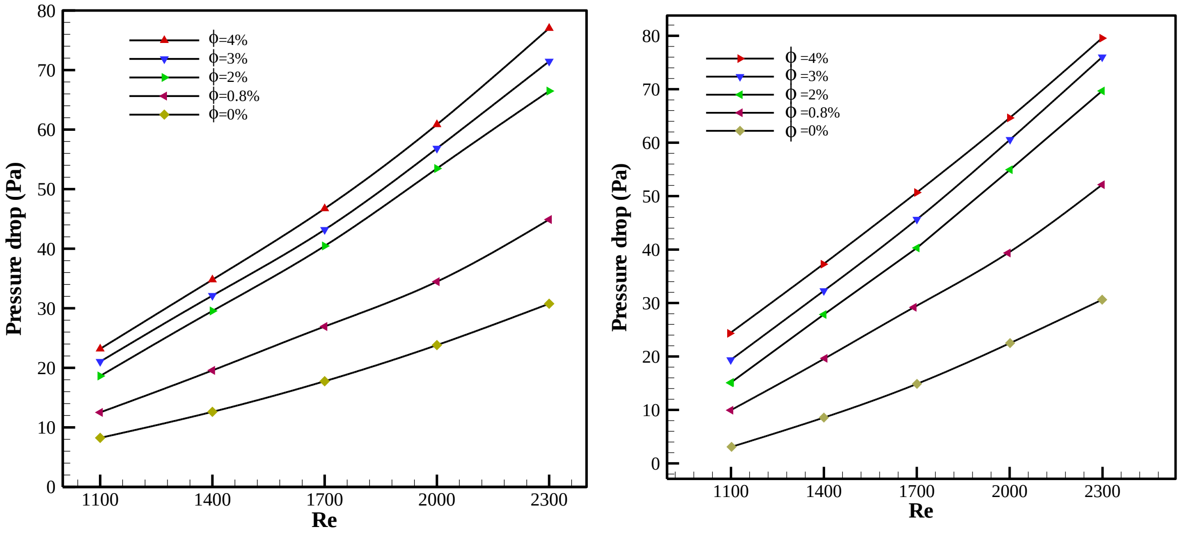


Figure 10: Pressure drops Variation vs Reynolds number for diverse volume fractions, ϕ of (a) SiO_2, and (b) MgO/water nanofluid at dp=20nm in the trapezoidal channel.

CONCLUSION

In the present investigation, heat transfer rate and hydraulic performance of the laminar flow of the trapezoidal counter heat exchanger with nanofluid and engine oil have been investigated numerically. Moreover, the study investigated the effect of the trapezoidal wall on thermal properties and hydraulic performance over Reynold number ranges of 1100-2300 for nanofluid and 250 for engine oil. Two types of nanoparticles, MgO and SiO2 with different volume fractions in the range of 0% to 4% with a diameter of 20 nm, are dispersed in the base fluids water. The study showed that the trapezoidal wall and nanofluid have a significant effect on Nusselt number values. The streamwise velocity and isotherms contours clearly helped to understand the reasons for improving the rate of heat transfer through the channels. The nanofluid containing SiO2 has the highest Nusselt number compared with MgO. Moreover, it can be perceived that the average Nusselt number rises with the nanoparticles volume fraction rising. In addition, the MgO-water nanofluid provides the biggest value of the pressure drop among the different fluids. Besides, the pressure drop increases with volume fractions of nanoparticles.

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