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Optimization of Forced Convection Heat Transfer Using ZnO-Water Nanofluid in a Square Cross-Section 3D Channel: A Numerical Investigation

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Abstract

The improvement of the performance of thermal systems is an important task in today's energy industry, for example, in solar collectors and solar heat exchangers. The enhancement of heat transfer and fluid dynamics inside different channel geometries is therefore of high technological and scientific interest. In this regard, exploitation of nanofluids has gained attention as an alternative strategy to improve thermal performance, as they possess better thermophysical properties. Current work is based on computational fluid dynamics (CFD) tools (Ansys Fluent) to enhance the heat transfer and the flow behavior of water by ZnO nanoparticles, also known as zinc oxide. Nanoparticles of zinc oxide (ZnO) are dispersed in the water at varying concentrations (0.4% and 1.3%) in a channel having a square cross section. The bottom face is maintained under a constant heat flux of 50kW/m² and the rest of the walls are thermally insulated. The flow is assumed to be turbulent, single-phase, steady, 3D, and occurring in the range of Reynolds number from 4000 to 12000. The results indicate that the incorporation of ZnO nanoparticles can effectively enhance heat transfer, and the heat transfer coefficients increase by 23.79% and 28.10% when the volume fractions are 0.4% and 1.3%, respectively. In addition, the friction factor is reduced with a higher Reynolds number and by adding nanoparticles. These results indicate that not only can ZnO nanofluids greatly enhance the system performance.

1. Introduction

In the field of general engineering, there are basic problems, including forced convection heat transfer for many industrial or domestic applications, including heat distributors or heating in foodstuffs, heat exchangers located in oil refineries, as well as a fuel heater for a diesel engine. There have been many concerns by researchers over the years about the process of increasing heat transfer, where there are various methods, for example, increasing the surface area, inserting fins, mixing nanomaterials with the base fluid, etc. Another option is to enhance convection for heat transfer performance by improving the thermophysical properties of energy transfer fluids [1-5]. Researchers are interested in nanotechnology. After all, it is considered one of the research fields because, in the near future, it will lead to an industrial revolution. Using nanofluids, which are small in size and particles, researchers have made a huge research effort to investigate the enhancement of heat transfer using the fact that ordinary working fluids have low thermal conductivity compared to nanomaterials, as it is considered a new generation that improves the thermophysical properties of most liquids. Many previous studies have been conducted in this field, including numerical and experimental studies to investigate the coefficient of heat transfer by forced convection and factors affecting the thermal conductivity of nanofluids, including nanoparticles, basic liquids, volume concentration in nanomaterials, volumetric fractions, etc. [6-9]. Mohammad Parsaiemehr *et al*. [10] presented a numerical analysis using nanomaterial (Al_2O_3) with volumetric fractions (0-4%) of the range of Reynolds number (15000-30000) in a channel with a rectangular cross-section. Several parameters whose influence on heat transfer has been numerically studied include the angle of attack of the oblique rib, the Reynolds number, and nanofluid volumetric fractions. The results indicated the generation of vortices when the flow pattern changes as a result of a change in the angle of attack of the channel rib, as well as causing the mixing of liquids, where the highest improvement in the heat transfer rate occurred at an angle of (60°). H. A. Mohammed *et al*. [11] studied numerical simulations to examine the thermohydraulic properties of turbulent nanofluid flow for the Reynolds number range (5000-20000) in a constant-temperature heated channel with the upper and lower walls. The finite volume method was used in the Ansys program to solve the governing equations of flow are continuity, momentum, and energy. Different types of nanomaterials were used for the heating process, including (Al_2O_3, ZnO, CuO, and SiO_2) with different volumetric concentrations (1-4%) included in different working fluids (water, engine oil, and glycerin). N. Shehzad *et al*. [12] numerically introduced into a liquid-filled corrugated channel nanoparticles using Buongiorno's model, the effect of heat transfer by forced convection. The temperature distribution and the velocity of the fluid are obtained analytically. Furthermore, demonstrating how to discuss skin fiction with various buoyancy disciplines is streamlined. The correctness of the obtained findings is further supported by calculations for the hybrid Genetic Algorithm and the Nelder-Mead method. Mohamed Rafik Sari *et al*. [13] reviewed a numerical analysis of the properties of nanofluid and heat transfer between the walls of the channel with a stable single-phase flow. The nonlinear partial differential equations were reduced to Ordinary Differential Equations by appropriate transformations of both velocity and temperature, after which the part of the values of the governing parameters was solved analytically and numerically, including the Reynolds number, the Prandtl number, and the angle of the half-channel. The results gave an improvement of the Nusselt number using the nanomaterial included with the basic working fluid. A group of researchers presented studies on the enhancement of heat transfer by forced convection using volumetric concentrations of the range (1-5%) for nanoparticles mixed with the working fluid, where the thermal conductivity factor is increased by about (20%) using nanofluids compared to empty channels [14-16]. H. Heidary *et al*. [17] presented a numerical analysis of the fluid flow in a straight channel subjected to magnetic overflow by inserting the nanofluid with the working fluid to improve its thermophysical properties, thereby increasing the rate of heat transfer by turbulent forced convection. The effect of the local Nusselt number and the volume fractions of nanomaterials on the Reynolds number was studied numerically. The results showed that the effect of the nanomaterial and the magnetic field improved the heat transfer rate in the channel by 75%. M. Hatami *et al*. [18] numerically introduced heat transfer between two parallel plates using three different types of nanomaterials (Ag, Cu, and Al_2O_3) using the First (Least Squares) and second (Galerkin) methods. One of the plates is heated externally, and the other expands or contracts over time as a result of the injection of coolant through it. Several parameters have been numerically investigated, including the size of nanoparticles, the Reynolds number, the expansion ratio, as well as the energy law on flow and heat transfer. Yuan Ma *et al*. [19] presented a numerical study of laminar flow forced convection heat transfer of the Reynolds number range (50-100) for a two-dimensional channel highlighted by a magnetic field filled with nanomaterial (Ag and MgO) inserted with basic water. The results showed that the rate of Nusselt number increases and improves by increasing the volume fractions of nanomaterials. A. I. Alsabery *et al*. [20], under the impact of heating from the upper wavy surface, computationally analyzed the forced convection of a nanomaterial suspension in a horizontal wavy channel. Newton's second law is being used in conjunction with the single-phase nanofluid method, which has experimentally derived correlations between viscosity and thermal conductivity, to investigate and characterize the motion of nanoparticles inside the channel. The finite element approach (Ansys Fluent) was used to formulate the boundary value problem. The Reynolds number, channel ripple number, dimensionless time on the nanofluid flow, energy transfer, flow of nanoparticles within the channel, and average parameters. Sarmad A. Ali [21, 22] performed a comprehensive review on the use of nanofluids to enhance the thermal conductivity in those industrial and engineering applications that have low thermal conductivity, thus typically requiring the use of higher heat transfer coefficient via the enhancement of the thermal conductivity of base fluid and the reduction of the thermal resistance, where these particles, mainly metals, oxides and carbides, play a significant role in increasing the efficiency of heat transfer based on increasing of the thermal conductivity and decreasing the thermal resistance according to a set of parameters such as size, shape and aspect ratio, collision, aggregation and others. Further proposed a study that includes numerical analysis of the heat transfer performance in tubes with cavities under the condition of turbulent flow by ANSYS_ Fluent program, and the simulation results show that the presence of cavities increases the value of nuslet and considerably enhances the thermal performance of the smooth pipes, and the improvement rate is up to 94.47% at a cavity radius of 4 mm, suggesting that it is feasible and effective for the engineering design of high-efficiency heat exchange.

The purpose of this work is to explore the possibility of enhancing the heat transfer efficiency in thermal systems through the performance investigation imposed by using a such nanofluid [The cooled nanofluid is used for both the prefixed Reynolds numbers range of laminar and turbulent flow through a channel with square cross section (this point was almost neglected)] filled with ZnO nanoparticles on heat transfer in turbulent channel, which have not been reported before in most of the literatures. In contrast to former studies, which were more dealing with conventional fluids or laminar flow patterns, this study, using a numerical technique (CFD) evidences a great effect of nanoparticles on the heat transfer improvement, the rise being of the order of 28.10%, as well as an improvement in the flow behaviour; thus, contributing in the increase of their efficiency at the level of the solar collectors and heat exchangers. Numerical investigation using the Ansys Fluent program to improve forced convection heat transfer and flow characteristics using a nanomaterial (ZnO) inside a channel with a square cross-section projected on the wall of the channel below a uniform constant heat flux of ($50kW/m^2$) while the other walls are thermally insulated. The steady-state three-dimensional single-phase flow is turbulent for the Reynolds number range (4000-12000).

2. Definition of Problem Statement

Figure (1) shows the forced convection heat transfer with a single-phase turbulent flow of a mathematical model assuming a channel with a square cross-section of equal width (W) and length (L) of (0.15 m), respectively. Channel length (1.2 m), the bottom wall is exposed to a constant uniform heat flow ($50kW/m^2$) along the flow of the fluid, as the other walls are thermally insulated. A commercial program (Ansys Fluent) was used for numerical simulation to solve all the governing equations of the flow. The temperature of the thermophysical properties of the nanomaterial and the basic fluid is set to a constant value (300K), which is one of the initial boundary conditions for the numerical simulation process. Realization of numerical parameters change based on Reynolds number ranges (4000-12000) of the flow. In this study, nanofluids (ZnO) included with the basic fluid (water) are assumed to be incompressible with steady-state turbulent flow and constant thermophysical properties. Table (1) briefly presents the engineering and physical parameters adopted in the simulation, including the channel dimensions, the value of the heat flux, the entry temperature, the Reynolds number range, and the proportions of the added nanomaterial (ZnO).

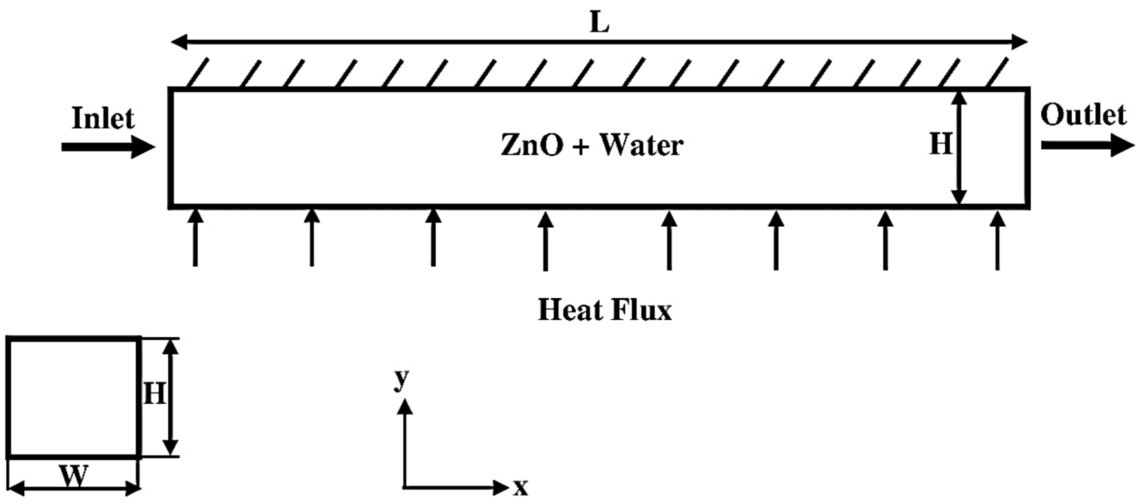

Figure (1): Schematic diagram of physical model.

Table (1): Engineering and physical parameters adopted in the study.

Parameter	Symbol	Value	Unit	Description
Channel width	W	0.15	m	Width of square cross-section
Channel height	H	0.15	m	Height of square cross-section
Channel length	L	1.2	m	Length of the channel
Heat flux	q″	50,000	W/m²	Applied to the bottom wall
Inlet fluid temperature	Tin	300	K	Initial temperature of the fluid
Reynolds number range	Re	4000–12000	–	Turbulent flow regime
Nanoparticle type	–	ZnO	–	Zinc Oxide nanoparticles
Volume fractions	ϕ	0.4%, 1.3%	–	Nanoparticle concentration in water

3. Governing Equations of Fluid Flow

The continuity and momentum equations represent the governing equations for the velocity distribution of the fluid within the channel, while the energy conservation equation represents the governing equation for the temperature distribution. As follows, all equations can be listed [23-26]:

3.1. Mathematical Equation of Continuity

The Continuity equation is considered the basis of the mathematical equation for the conservation of mass and can be expressed as follows:

$$\nabla.(\rho_{nf} V) = 0 \qquad \textbf{(1)}$$

3.2. Mathematical Equation of Momentum

Based on Newton's second law of motion, the mathematical equation of momentum can be derived as follows:

$$\nabla.(\rho_{nf} VV) = -\nabla p + \nabla.\tau \qquad \textbf{(2)}$$

3.3. Mathematical Equation of Heat Energy

The energy conservation equation has another name, the thermal energy equation, which can be formulated as follows:

$$\nabla.(\rho_{nf} V C_{p,nf}) = -\nabla.(k_{nf} \nabla T - C_{p.nf} \rho_{nf} \overline{V} t) \qquad \textbf{(3)}$$

4. Equations of Thermophysical Properties

The nanomaterial is added to the basic fluid (water) in volumetric fractions (0.4 and 1.3%). In the process of numerical simulation, the main assumption was taken into account the achievement of thermal equilibrium on behalf of the simulated liquid of the channel wall by the absence of any equilibrium state, in addition to constant thermophysical properties. Calculation of all thermal and physical properties of nanofluid mixed with water is carried out according to the following equations [27-31]:

4.1. Volume Fraction of Nanofluid

$$\phi = \frac{V_{np}}{V_{bf} + V_{np}} \qquad \textbf{(4)}$$

4.2. Density of Nanofluid

The density of the nanofluid can be expressed as follows:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_{np} \qquad \textbf{(6)}$$

4.3. Heat Capacity of Nanofluid

The heat capacity of a nanofluid can be formulated according to the following mathematical equation:

$$C_{p,nf} = \frac{(1-\phi)\rho_{bf} C_{p,bf} + \phi\rho_{np} C_{p,np}}{\rho_{nf}} \qquad \textbf{(7)}$$

4.4. Thermal Conductivity of Nanofluid

The coefficient of thermal conductivity of the nanofluid is calculated by the following equation:

$$\frac{\lambda_{nf}}{\lambda_{bf}} = \frac{(\lambda_{np} + 2\lambda_{bf}) - 2\phi(\lambda_{bf} - \lambda_{np})}{(\lambda_{np} + 2\lambda_{bf}) + \phi(\lambda_{bf} - \lambda_{np})} \qquad \textbf{(8)}$$

4.5. Dynamic Viscosity of Nanofluid

The viscosity of the nanofluid inserted with water can be expressed as follows:

$$\mu_{nf} = \mu_{bf} \frac{1}{(1-\phi)^{2.5}} \qquad \textbf{(9)}$$

4.6. Thermophysical Characteristics of ZnO

ZnO (zinc oxide) also has Thermal-physical properties that make it an excellent nanofluid in enhancing the heat transfer rate of nanofluids mixed with basic fluids such as water. The heat transfer is increased within the thermal channels due to ZnO has higher thermal conductivity than water. Their compact and small nano-scale size further aids in enhancing heat transmission and diminishing the thermal resistance in the fluid. In addition, it has good chemical stability and optical properties, so it is commonly used in low volume ratios in a heat exchanger and a solar collector to the extent that not deteriorate much in the fluid's viscosity and flow. The thermophysical properties of the nanomaterial and the basic fluid at a temperature of (300 K) are highlighted in Table (2), while the nanofluid with changing fractional volumes is reviewed in Table (3) as follows:

Table (2): Characteristics of thermophysical of nanoparticle and base fluid [32].

Working Fluid	ρ (kg/m^3)	Cp (J/kg. K)	λ (W/m. K)	μ (N.s/m^2)
Water	998.2	4182	0.6	0.0001
ZnO	5600	495.2	13	0

Table (3): Thermophysical properties of nanofluid (Water / ZnO) at different volume fractions.

Φ	ρ (kg/m^3)	C_p (J/kg. K)	λ (W/m. K)	μ (N.s/m^2)
0.4 %	1015.412	4098.713	0.613	0.000899
1.3%	1056.839	3926.173	0.627	0.00092

5. Turbulence of Computational Model

An achievable perturbation (k-ε) model was used for the nearby optimized wall function associated with it and using a driver for numerical simulations, it is activated. When it comes to the turbulent viscosity and dissipation rate ε transport equation, the Realizable k-ε turbulence model and the conventional k-ε model are different in two key ways. The Realizable k-ε turbulence model was responsible for introducing novel formulations for turbulent viscosity and dissipation rate ε. These were derived from an exact equation that governed the transport equation of the mean-square value of vorticity perturbations. For the physics of turbulent fluid flow, the model can be considered within a certain radiometric context of the Reynolds number and is also conformal [33].

5.1. Equations of Transport in Commercial Code

The following is the expression for the computational model equation of steady-state turbulent kinetic energy [34-36]:

$$\frac{\partial}{\partial x_j}(\rho k u_j)+\frac{\partial}{\partial t}(\rho k)=\frac{\partial k}{\partial x_j}(\mu+\frac{\mu_t}{\sigma_k})+G_k+S_k-\rho\varepsilon \qquad \textbf{(10)}$$

$$G_k=(-\rho\,\overline{u_i}\,\overline{u_j})\frac{\partial u_j}{\partial x_i} \qquad \textbf{(11)}$$

And according to Boussinesq's theory, G_k is described as:

$$G_k=\mu_t S^2 \qquad \textbf{(12)}$$

The definition of the turbulence kinetic energy dissipation rate is as follows:

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon v_j)=\frac{\partial\varepsilon}{\partial x_j}[\frac{\partial}{\partial x_j}(\mu+\frac{\mu_t}{\sigma_\varepsilon})]+\rho(c_1 s\varepsilon-c_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}})+s\varepsilon \qquad \textbf{(13)}$$

where;

$c_{1\varepsilon}=1.44, c_2=1.9, \sigma_\varepsilon=1.2$

$c_1=\max(0.43,\frac{\eta}{\eta+5})$

$$\eta = S\frac{k}{\varepsilon}$$

$$S = \sqrt{2(s_{ij})^2}$$

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

$$C_\mu = \frac{1}{A_o + A_s \frac{ku^*}{\varepsilon}}$$

A set of physical symbols is used in the analysis of forced convection heat transfer and the study of the behavior of flow inside channels; each of these symbols indicates specific physical properties or quantities. Cp is denoted by the specific heat capacity of the fluid at constant pressure (J. $kg^{-1}.K^{-1}$), it expresses the amount of heat necessary to raise the temperature per unit mass of the fluid by one Kelvin degree. G refers to the generation rate resulting from the turbulent kinetic energy velocity gradient. H is used to denote the height of the channel (m), L for the length of the channel (m), while W represents the width of the channel. The symbol k expresses the model of turbulent kinetic energy ($m^2.s^{-2}$), which is one of the components of numerical models used to simulate turbulent flow. Nu is the Nusselt number, which is a dimensionless number used to assess heat transfer by load, while Re is the Reynolds number, which expresses the ratio between inertial forces and viscous forces, and is used to determine the type of flow, whether it is laminar or turbulent. T represents the temperature of the fluid in Kelvin (K), and P the fluid pressure in units of Newtons per square meter ($N.m^{-2}$). As for the triple compounds of the fluid velocity, they are: u for the velocity towards the X-axis ($m.s^{-1}$), and V towards the Y-axis, and W towards the z-axis. Finally, V is used to express the total volume of the studied sphere (m^3). The symbol λ is also used to denote the thermal conductivity of the fluid (W. m^{-1}. K^{-1}), and ε for the perturbation energy dissipation rate ($m^2.s^{-3}$), while υ represents the kinetic viscosity (m^2. s^{-1}) and μ dynamic viscosity (N.s. m^{-2}). The symbol ρ is used to express the density of the fluid ($kg.m^{-3}$), while Φ symbolizes the volume ratio of nanoparticles added to the basic fluid.

6. Analysis of Grid Independence

In the current numerical work, the non-uniform mesh size was selected by constructing the mesh size near the channel wall more precisely to obtain accurate details of the boundary layer near the wall. To evaluate the effects of the selected mesh sizes on the Nusselt number with the extension of the fluid flow inside the channel, the independence of the mesh was chosen. Several sizes of the grid were created by minimizing the elements to ranges of (15876-736653). The Nusselt number was observed to have stabilized at a value of (574172) as shown in Figure (2). Using the Ansys Fluent program, the edges of the front and rear sides were determined, as well as the upper and lower sides. The size of the edges was also determined, so the grid was generated for the walls of the square channel by controlling the number of nodes and elements as shown in Figure (3). Mesh of the numerical elements used to analyze the flow of a fluid across a three-dimensional channel with a square cross section. The image was taken from the ANSYS program. The lower scale shows that 0.5 m is the length of the channel, and its highly dense mesh means only typical small-sized elements were used to provide high numerical accuracy in the flow representation within the channel. This kind of grid design with complete and homogeneous form is required for representing the velocity, pressure distribution, and flow features accurately, particularly in nanofluids that influence the flow characteristics exactly. Furthermore, this three-dimensional construction allows for representing the complex physical processes occurring within the channel as the boundary layer develops and shear effects dominate near the walls. A good model setup should reach the stability of the numerical solution with a minimum computational time, which is achieved by balancing the element size between numerical accuracy and computational efficiency.

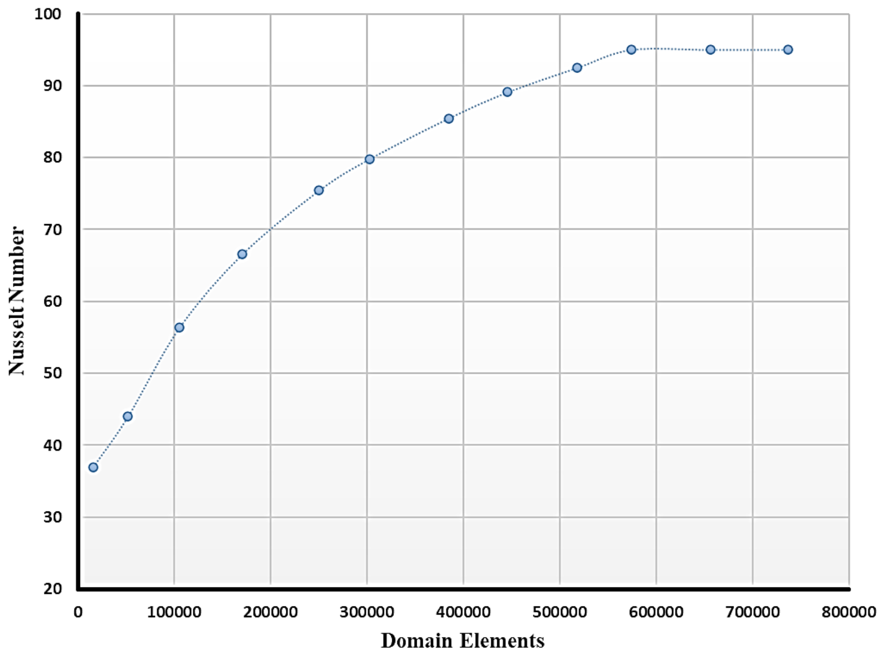

Figure (2): Fluctuation of Nusselt number against domain element in grid independence test.

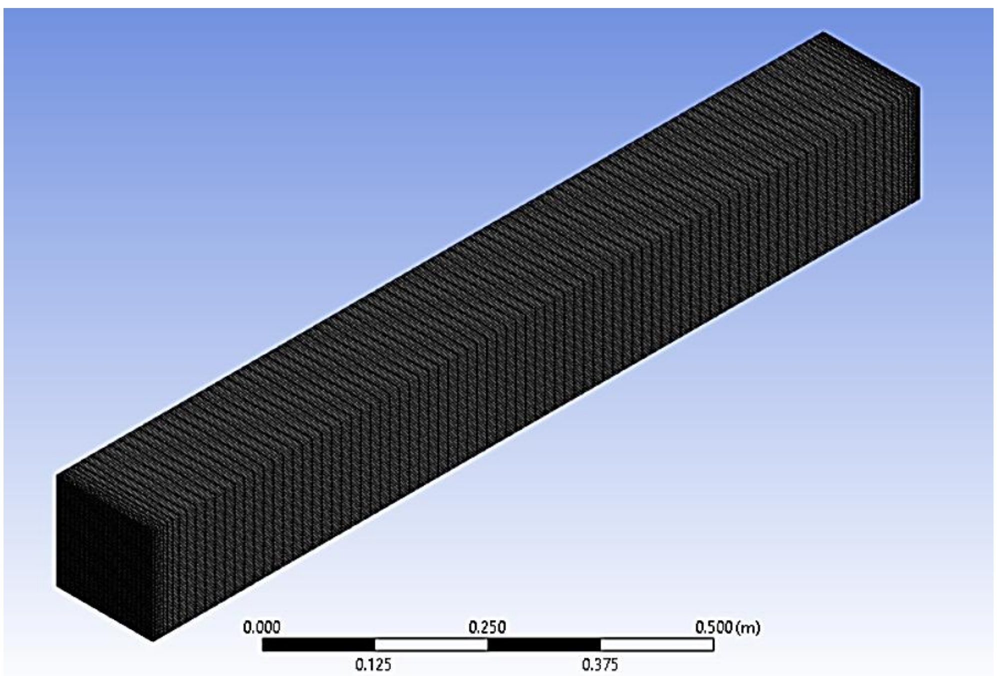

Figure (3): Grid generation for square channel walls.

7. Results and Discussions

7.1. Validation of Numerical Result

To validate the numerical data of the ground state (empty channel without the nanoparticles) the result was compared with the known experimental Dittus–Boelter relation, which is used to estimate the Nusselt number for turbulent flow inside a smooth pipe when water is used as the working fluid. The comparison result was good, because of a 5% error between the numerical solution and the relationship comparison, which verified the numerical model accuracy for forced convection heat transfer inside the empty channel, and the credibility of the results obtained was strengthened, as shown in Figure (4).

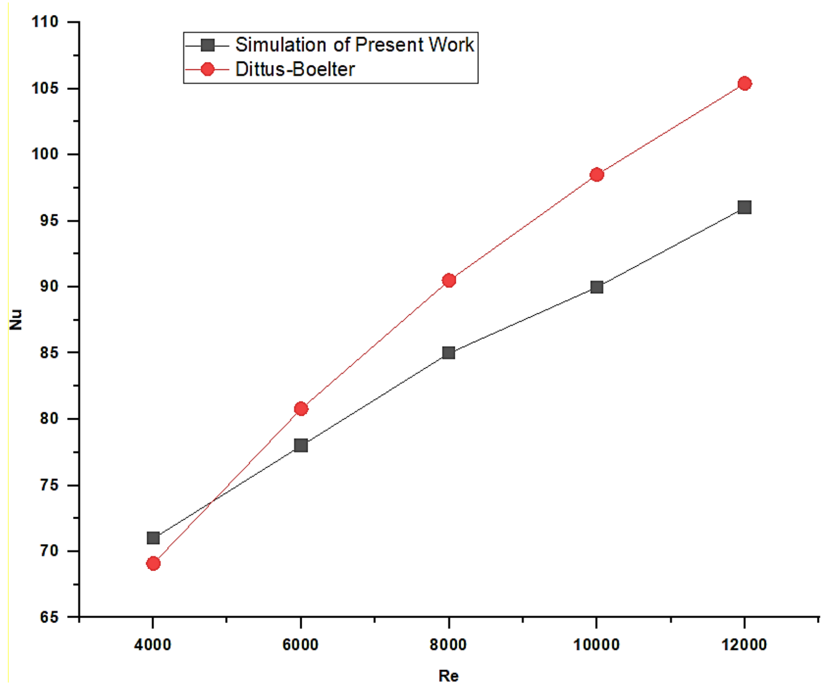

Figure (4): Numerical validation of heat transfer in a water-filled channel using the Dittus–Boelter equation.

7.2. Effect of Nusselt Number and Friction Factor

Based on the numerical results shown in Figure (5), which represents the change of the Nusselt number against the Reynolds number for the Channel free of nanomaterials and with the channel containing the nanofluid with different volume fractions. The increase in the Nusselt number can be observed gradually by increasing the Reynolds number, and the increase also occurred with the increase in volumetric fractions, where the highest value of the Nusselt number occurred when using the nanomaterial with volumetric fractions (1.3%). The inclusion of ZnO contributed to a significant increase in the heat transfer rate, where the percentage of increase at volumetric fractions (0.4 and 1.3 %) gave (23.79 and 28.104%), respectively. The variations of Nusselt number with Reynolds number are presented for empty channel and channels occupied by 0.4% and 1.3% suspensions as illustrated in Figure (5). The Nusselt number is the physical expression for the convective heat aspect, while the Reynolds number reflects how well-developed the flow is, and thus whether it's laminar or turbulent. It is observed from the figure that the Nusselt number increases with an increase in Reynolds' number for all the cases. This is to be expected, since the increase of the Reynolds number results in increased flow velocity, resulting in intensified forced convective heat transfer. Based on this, for Re ≈ 4000, the Nusselt number was ≈ 71 on the empty channel walls; however, it was found to be increased to ≈73 and 74 with 0.4 and 1.3% nanofluid, respectively. This represents, at its lowest velocity, an upgrade of about 2.8% and 4.2% respectively. Re ≈ 12000 As the Reynolds number further increases to Re = 12000, we observed that the Nusselt number is approaching Re ≈ 96 for a pure fluid, but it increases to ≈ 98 by adding 0.4% of nanofluid and ≈ 100 by adding 1.3% of nanofluid, thus the increment in Nusselt number becomes 2.1% and 4.1%, respectively. This indicates that the impact of the nanofluid is enhanced in high velocities; however, this enhancement is only moderate. This rise is because when nanoparticles (like ZnO or Al_2O_3) are added, the thermal properties of the fluid (i.e., thermal conductivity, viscosity, etc.) are enhanced, which eventually results in higher convection in the flow. Additionally, they produce little perturbations that can increase the permeability of the thermal boundary layer, resulting in an increased heat exchange between the wall and the flow. In general, the figure indicates that the application of nanofluids leads to a considerable increase in the thermal performance of the channel at the highest concentration, and consequently verifies the use of nanofluids as a reliable medium for enhancing heat transfer applications.

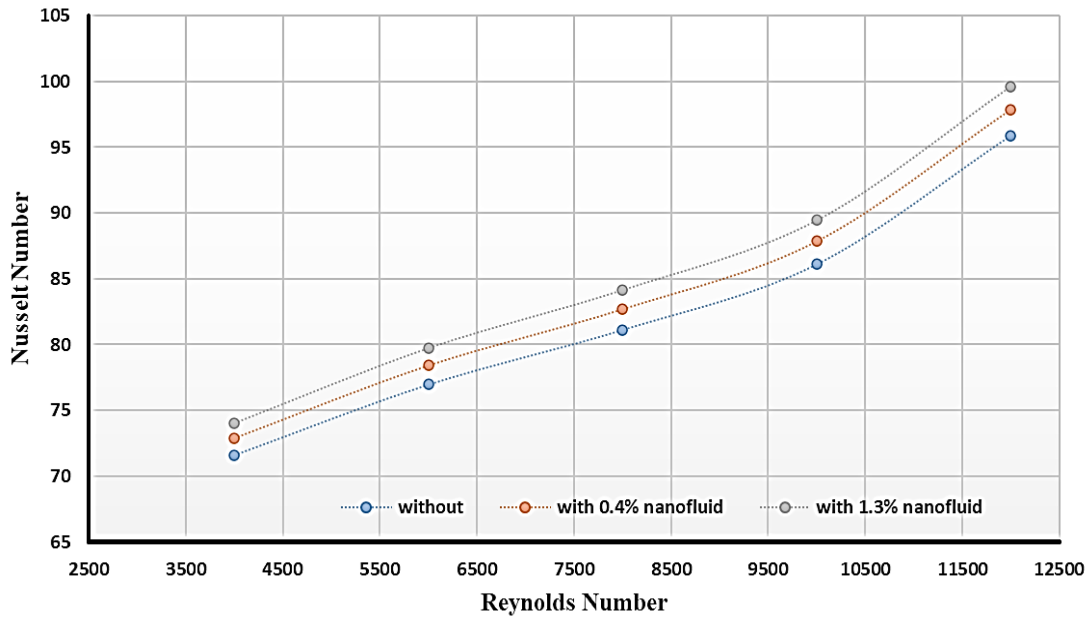

Figure (5): Fluctuation of Nusselt number with Reynolds number for smooth channel and different volume fractions.

As presented in Figure (6) for 3 scenarios of pure water (without nanofluid), 0.4% nanofluid, and 1.3% nanofluid, the correlation between the Reynolds number and friction coefficient in a channel is shown. A look at the results shows that in all cases, relatively internal flow in a pipe or channel yields the correct expected result, that is, the friction coefficient decreases with Reynolds number. Results also prove that the friction coefficient using a nanofluid is approximately lower than the results when using water, and the decrease in coefficient becomes greater with increasing concentration of nanoparticles. Using pure water gave a friction coefficient of around 0.075 at a Reynolds number (8000) while that was decreased to 0.072 at a 0.4 % nanofluid and failed to decrease below 0.068 (1.3% concentration). At Re≈12000, the friction coefficient decreased from about 0.057 (pure water) to 0.054 (low concentrations of nanofluids) and 0.051 (high concentrations of nanofluids). The results indicate that the flow characteristics of nanofluids can be worthily due to the reduction of frictional loss, implying a better hydrodynamic efficiency and therefore the possibility of a performance enhancement of heat transfer systems operating with nanofluids. The reduction of the friction factor with nanofluid is considered to be due to the synergy of physical and rheological factors affecting the flow aspects within the channel. First, the nanoparticles, which are obtained in the base liquid (water), enhance the thermal conductivity and temperature distribution of the fluid, lowering the thermal gradient inside the liquid and stabilizing the boundary layer. Second, nanoparticles produce a tiny reduction in liquid viscosity in some instances, or at least alter the flow properties in a way that makes the fluid become more slippery near the walls and reduces the friction between the fluid and channel wall. Additionally, the active Brownian motion of the nanoparticles due to self-diffusion generates micro perturbations in the flow, reinforcing the interfacial mixing of the layers as well as the hydrodynamic and thermal transport across the interface without increasing the total frictional loss. At last, due to the physical properties of nanoparticles (size, shape, distribution), the flow behavior is altered and leads to a reduction in the internal resistance that is directly reflected in the reduction of the friction factor. In these applications, it is vital to have both high thermal and hydrodynamic efficiency, and as a combination of these advantages, nanofluids have shown superior performance than conventional fluids.

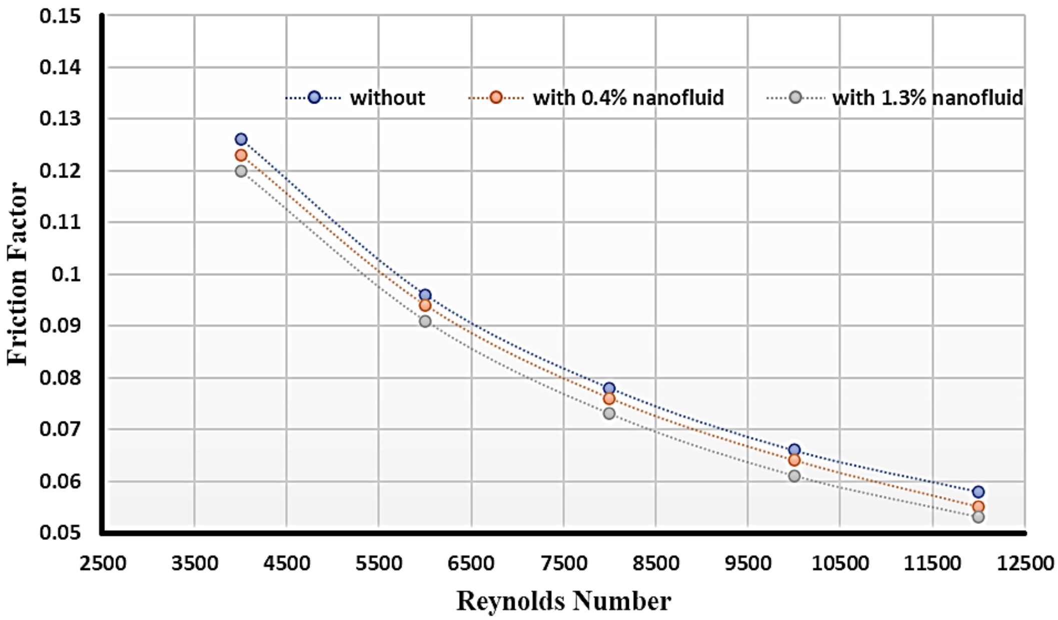

Figure (6): Fluctuation friction factor with Reynolds number for a smooth channel and different volume fractions.

8. Conclusions

Using a code for a commercial program (Ansys Fluent), the flow characteristics of the nanomaterial (ZnO), including pure water representing the working fluid in a horizontal channel with a square cross-section, were investigated to improve the forced convection heat transfer rate for the Reynolds number range (4000-12000). According to the results of the numerical study, the addition of nanoparticles improves heat transfer, but the pressure drops increase compared to the empty channel, so this is one of the disadvantages of using nanomaterials. Moreover, the Nusselt number increases gradually with increasing volume fractions of the nanomaterial and with increasing Reynolds number. The results also demonstrated that the application of nanofluids played an important role in heat transfer enhancement, as the Nusselt number was improved by as much as 4% in comparison with the base fluid case. Such enhancement is attributed to the higher thermal conductivity of the fluid containing nanoparticles and, accordingly, higher heat transfers due to the forced convection flow in the channel, along with the nanoparticle's incorporation. Adding two or more nanoparticles to the working fluid to create a hybrid nanofluid is the idea behind the present study's development. This will increase the system's efficiency and performance by improving its thermal conductivity factor. Prospectively, it is suggested, as a next stage, that two or more types of nanoparticles be mixed to produce a hybrid of nanofluids for an improved advantage in thermal conductivity and the overall system.

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Conflict of Interest: There are no conflicts of interest related to this study effort, according to the author. I don't have any personal or financial ties that may skew our work or affect how the outcomes are interpreted.

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