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Effect of Al_2O_3/H_2O Nanofluid on the Flow and Forced Convection Heat Transfer Enhancement in a Pipe Using Commercial CFD Code

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Abstract

The use of advanced nanofluids increases and improves the heat transfer process in different industrial and engineering applications compared to conventional fluids. In recent years, researchers have used in their research investigations the addition of nanofluids with the basic fluid to improve its thermophysical properties. This research deals with a numerical study (simulation using commercial CFD code) of forced convection heat transfer in a two-dimensional (2D) pipe by adding aluminum oxide (Al_2O_3) as a nanofluid with water (H_2O) and by partially constant heat flux along the length of the pipe and in the direction of the axis of fluid flow. Several operational parameters have been studied, including the heat transfer coefficient, the Nusselt number, the friction factor, and the pressure difference as a function of the Reynolds number, as well as studying the temperature distribution, velocity, and pressure of fluid flow inside the test section. Reynolds number range of fluid flow (3000 - 6000) with volumetric fractions of nanofluids at (0.6% and 1.5%). The results of the study showed the addition of nanofluid with water improves and increases the heat transfer coefficient and thus increases the Nusselt number, also the friction factor gradually decreases by increasing the velocity of the fluid passing into the pipe.

1. Introduction

Various techniques are used to improve the physical-thermal properties of the basic fluid (such as water - oil) in many engineering and industrial applications such as heat exchangers and fluid flow inside various sections of ducts and pipes, cooling systems in cars and solar collector systems in the field of renewable energies and thus increase the thermal performance and efficiency of these devices. One of these techniques is the addition of nanofluids of various types with the original fluid to increase the heat transfer rate and raise the value of the heat transfer coefficient and thus increase the Nusselt number [1-5]. In recent years, many researchers in their numerical and practical research and investigations have been studying the improvement of the properties of fluid flow inside pipes through the use of different types and diameters of nanofluids. The research involved conducting a numerical study using commercial code (Ansys fluent software) to explore the flow of nanofluids inside a circular and rectangular corrugated channel and compare it with the non-corrugated channel and the Reynolds number range (10000-30000). Elhadi Kh. Abugnah et al. [6] presented a numerical study to improve forced convection heat transfer by inserting the nanomaterial with the basic fluid into a corrugated and another non-corrugated tube of turbulent flow in the range of Reynolds number (10000-30000) single-phase. The results showed that the non-corrugated channel has a small difference between the two-dimensional and three-dimensional shapes for each Reynolds number range, while the corrugated channel has a large difference at a high Reynolds number. Murat Erdem and Yasin Varol [7] conducted a numerical study using a commercial code (Ansys fluent software) of heat transfer and fluid flow inside a three-dimensional tube heated by a magnetic flux along the flow axis. The range of magnetic flux strengths is (0-10) with volumetric fractions of nanoparticles (0-0.04), respectively. Both the velocity curves of the fluid and the local Nusselt number as well as the average Nusselt number descents were graphically displayed. The results showed that the velocity of the fluid gradually decreases due to the influence of nanoparticles and the magnetic flux strength at each Reynolds number, and also the local Nusselt number increases with increasing magnetic flux strength, as a result, the magnetic flux strength and the volume fractions of the nanofluid and the Reynolds number have effectiveness in the heat transfer process. Some researchers have studied the effect of adding nanomaterials with the basic fluid to improve its thermal properties inside a two- or three-dimensional tube with single-length turbulent flow and forced convection. Several coefficients have been studied, including the coefficient of forced thermal transfer, Nusselt number, friction factor against the Reynolds number, and in different ranges. Their results showed the addition of nanomaterial improves the process of heat transfer [8-13]. M. R. Sohel et al. [14] conducted an experimental investigation deals with the study of heat transfer and fluid flow inside a small channel with a height of 0.0008 meters and a width of 0.0005 meters by adding a nanofluid as a technique to improve the thermal properties of pure water used as a basic fluid in the small channel at a Reynolds number range (395-989) and with a flow range of (0.5 - 1.25 L/min). The findings indicate the heat transfer coefficient improved by 18 percent. A. S. Sallal et al. [15] presented an experimental and numerical study of heat transfer in a tube of a heat exchanger made of three types) circular, triangle, elliptical, and without a hole) in which the nanomaterial was used to find out its effect on improving the physical and thermal properties of the basic fluid, including heat transfer coefficient, Nusselt number, viscosity, specific heat, and thermal conductivity. The results showed the thermophysical properties increase by increasing the fractional sizes of the nanomaterial (Al_2O_3 and CuO) compared to after its existence. Also, the comparison between the experimental and numerical results showed a good convergence. Khalid Faisal Sultan et al. [16] investigated an experimental study to improve the heat transfer process using copper and aluminum as nanofluids with distilled water as a working fluid inside the cooling system of the car, represented by the radiator. The change of the heat transfer coefficient was studied with a set of coefficients including the Nusselt number, the Reynolds number, and the fractional volumes of the nanomaterial. The results of the study showed that the number of nanoparticles gradually increases with increasing the internal temperature of the nanofluid species and also with increasing the Reynolds number as well as the thermal conductivity factor of copper is higher than aluminum as a result of the size of nanoparticles and the conductivity factor of copper. As a result, the type and size of nanoparticles significantly affect the improvement of heat transfer.

The current study deals with improving the process of heat transfer by forced convection and thus increasing the Nusselt number of single-phase flow by adding nanofluids (Al_2O_3) with the main working fluid (water) in different percentages of fractional volumes (0.6% and 1.5%) in a horizontal 2D pipe with length (5m) and diameter of (0.6 m) thermally insulated at the beginning (2m) and exposed to heat flux of (8000W/m^2) at the end (3m) at a Reynolds number range (3000-6000). The literature of previous studies dealt with improving heat transfer in channels, while the current study focuses on the use of a two-dimensional tube to enhance heat transfer by adding nanomaterial.

2. Formulations of Mathematical

2.1. Configuring Geometry

Figure (1) displays a schematic representation of the physical issue and its boundary conditions. Entering a 0.3 m radius pipe, the nanofluid travels at a constant velocity range of (0.005 to 0.01 m/s). This original fluid (water) has the following properties: its specific heat is 4180 J/kg-K, its density is 998.2 kg/m^3, its viscosity is (0.001 Pa.s), and its thermal conductivity is (0.6 W/m-K). 300 K is the isothermal temperature for the first 2 m of the pipe. An 8000W/m^2 constant heat flux is provided at the wall to the last 3 m of the pipe.

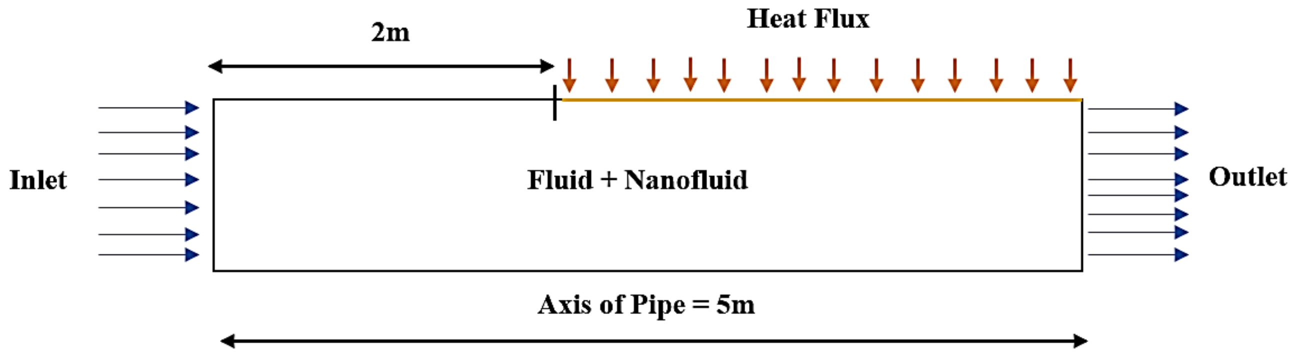

Figure (1): Description of the physical problem.

3. Method of Numerical

3.1. Grid Dependency and Generation of Mesh

The flow distribution was solved by applying the Navier-Stokes, energy, and continuity equations. To make sure that the temperature and velocity distribution were anticipated, the meshing was concentrated around the pipe wall. In this case, the test section's mesh creation is shown in Figure (2). The improvement of findings through the use of progressively smaller cell sizes for the calculations is referred to as "grid independence." Grid Independence is the word used to describe the situation where a computation should produce the proper answer, resulting in a smaller mesh. Typically, the CFD method begins with a coarse mesh and works its way up until the changes in the values are less than an acceptable error that has been predetermined. This is problematic in two ways. First of all, there might be some issues when using other CFD software to get even a single coarse mesh. Second, it may require extra time to refine a mesh by a factor of two or more. This is inappropriate behavior for software meant to be an engineering tool with limited production capabilities. Furthermore, the additional problems have contributed greatly to the reputation of CFD as a very complex, time-consuming, and expensive technology. To attain grid independence, the Nusselt number was ultimately calculated and organized in each case as shown in Figure (3).

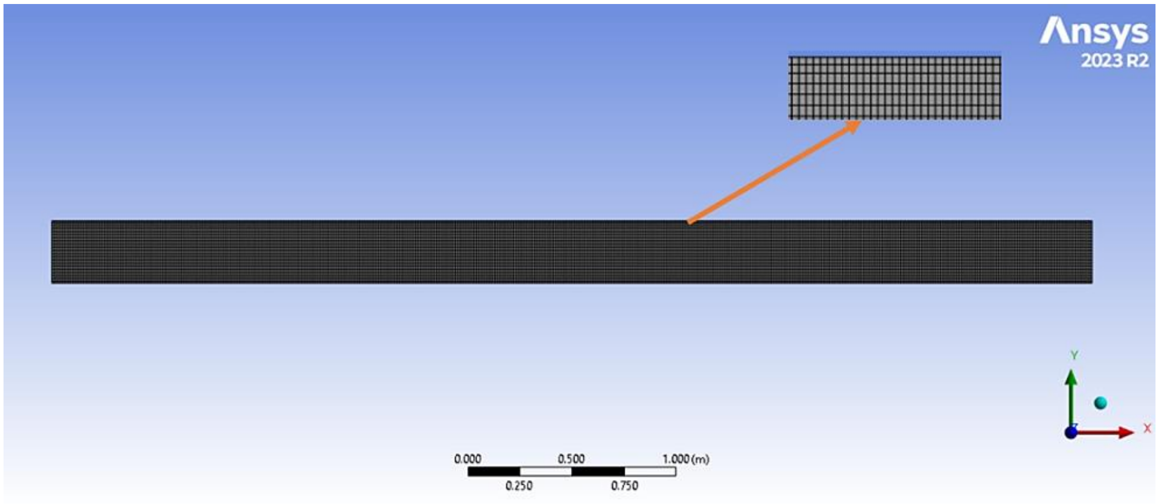

Figure (2): Mesh generation of 2D pipe and on the near wall castration region.

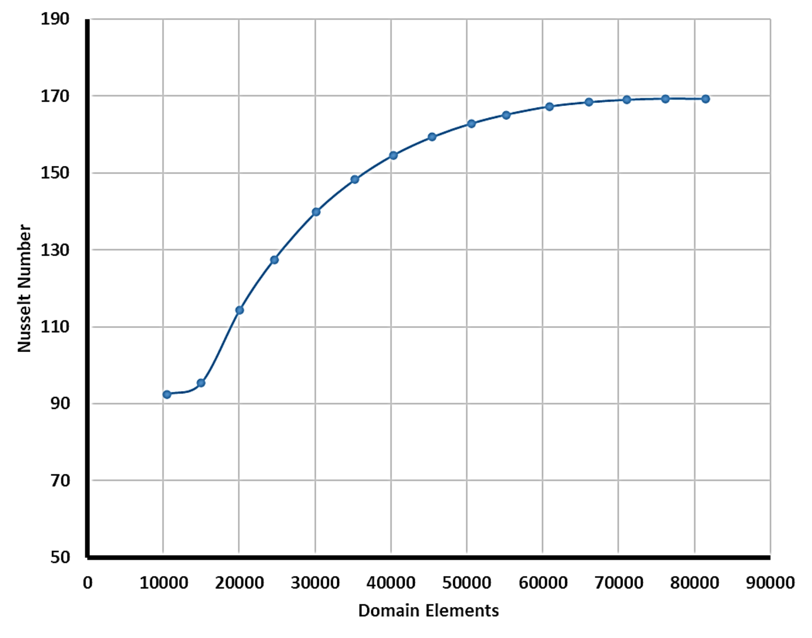

Figure (3): Grid independence test of a 2D pipe.

3.2. Boundary Conditions and Governing Equations on Turbulent Flow

Nanofluids are composed of very small particles and as a result, the basic fluids and nanofluids are considered to be in thermal equilibrium and flow at the same velocity inside the test section. The terms working pressure and viscosity dissipation are neglected in the energy equation. Based on these assumptions the equations of Navier – Stokes are as follows [17-21]:

Equation of Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

Equation of Momentum:

$$\rho_{nf}\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial P}{\partial x} + \mu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \qquad (2)$$

$$\rho_{nf}\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial P}{\partial y} + \mu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \qquad (3)$$

Equation of Energy:

$$\rho_{nf} C_{p,nf}\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k_{nf}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \qquad (4)$$

where u and v are the velocities (m/s) in the x and y component respectively, P is the pressure (Pa), T is the temperature (K), μ_{nf} is nanofluid viscosity (Pa.s), ρ_{nf} is nanofluid density (kg/m^3), Cp_{nf} is nanofluid heat capacity (J/kg.K), and k_{nf} is nanofluid thermal conductivity (W/m.K).

3.3. Thermal-Physical Characteristics of Nanofluids

Two components make up the nanofluid: nanosolid particles (Al_2O_3) and the base fluid (H_2O) are in thermal equilibrium and there is no slippage between them. The combination is incompressible and there is no chemical reaction or significant radiative heat transfer. Particle volume and temperature have a major role in determining the thermophysical characteristics of nanofluids as shown in Table (1) below [22 and 23].

Table (1): Thermophysical characteristics of the nanoparticle (aluminum oxide) and base fluid (water).

Property	Unit	Pure Water	Nanoparticle
Thermal Conductivity	W/m.K	0.6	40
Density	Kg/m^3	997	3970
Dynamic Viscosity	Pa.s	0.001	----------
Heat Capacity	J/kg.K	4180	765

Thermal conductivity, dynamic viscosity, density, and specific heat capacity of nanofluids are described as the following fractional functions since there is no experimental data [24-29]:

Nanofluid volume fraction:

$$\emptyset = \frac{V_{np}}{V_{bf}+V_{np}} \tag{5}$$

Nanofluid Density:

$$\rho_{nf} = (1-\emptyset)\rho_{bf} + \emptyset\rho_{np} \tag{6}$$

Nanofluid Capacity:

$$Cp_{nf} = \frac{(1-\emptyset)\rho_{bf}Cp_{bf}+\emptyset\rho_{np}Cp_{np}}{\rho_{nf}} \tag{7}$$

Nanofluid Thermal Conductivity:

$$\frac{k_{nf}}{k_{bf}} = \frac{(k_{np}+2k_{bf})-2\emptyset(k_{bf}-k_{np})}{(k_{np}+2k_{bf})+2(k_{bf}-k_{np})} \tag{8}$$

Nanofluid Dynamic Viscosity:

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\emptyset)^{2.5}} \tag{9}$$

Here in the above equations, $ø$ is the volume fraction of nanofluid, V_{nf} is the nanofluid volume (m^3), V_{bf} is the base fluid volume (m^3), ρ_{bf} is base fluid density (kg/m^3), Cp_{bf} is the base fluid heat capacity (J/kg.K), μ_{bf} is base fluid viscosity (Pa.s), and k_{bf} is base fluid thermal conductivity (W/m.K). Using the above equations (5-9), the thermophysical properties of the nanofluid with the basic fluid are calculated at different percentages of fractional volumes as shown in Table (2) below.

Table (2): Thermo-physical properties of nanofluids at different volume fractions.

Properties	Φ=0.6%	Φ=1.5%
Density (kg/m^3)	1016.03	1042.777
Heat capacity	4101.894	3986.864
Thermal conductivity (W/m.K)	0.6103	0.626
Dynamic Viscosity (Pa.s)	0.001015	0.001038

3.4. Criteria of Convergence in CFD Code

As seen in Figure (4), which displays the convergence history for continuity, momentum, energy, and turbulence equations, the CFD approach necessitates repeatedly solving the fluid flow equations until they converge. The iterations come to an end when the answer holds within the chosen convergence criteria's accuracy. The error residuals, or the difference in a variable's values between two successive iterations normalized by the highest absolute residual for the first five iterations, are the most commonly used techniques to verify the convergence of the solution. For any fluid flow equation shown above, the solution is considered to have converged when the residuals fall below a tolerance level of (10^{-7}).

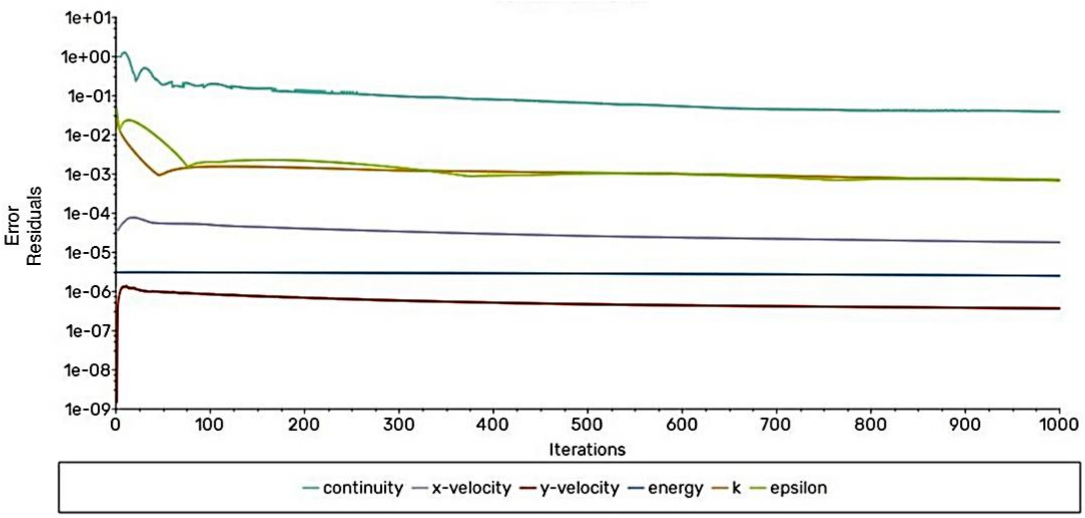

Figure (4): History iteration of numerical calculations.

4. Discussion and Result

4.1. Pipe Temperature Distribution

Figures (5-7) show the temperature distribution along the test section of the 2D pipe with a change in the values of the Reynolds number. The decrease in temperature distribution can be observed by increasing the velocity of the fluid passing inside the pipe and the reason is due to the inability of the fluid to gain the heat shed on the surface.

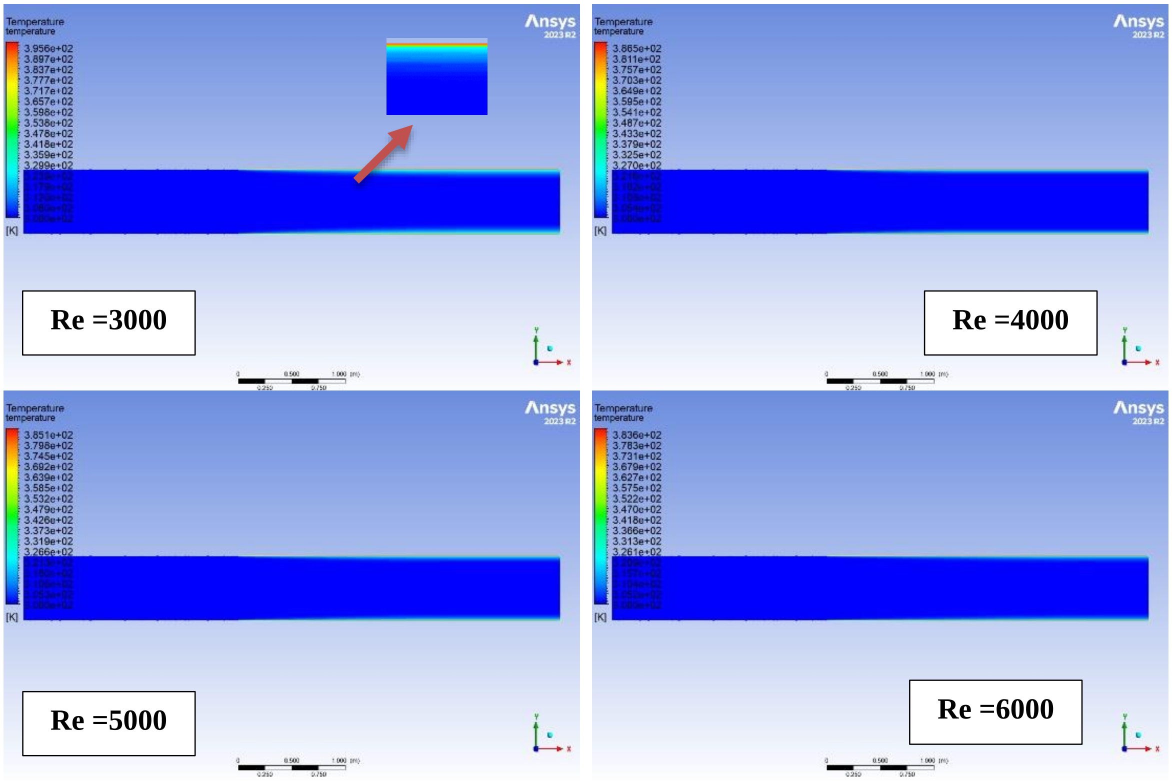

Figure (5): Temperature distribution along the axis of fluid flow of the pipe without nanofluid.

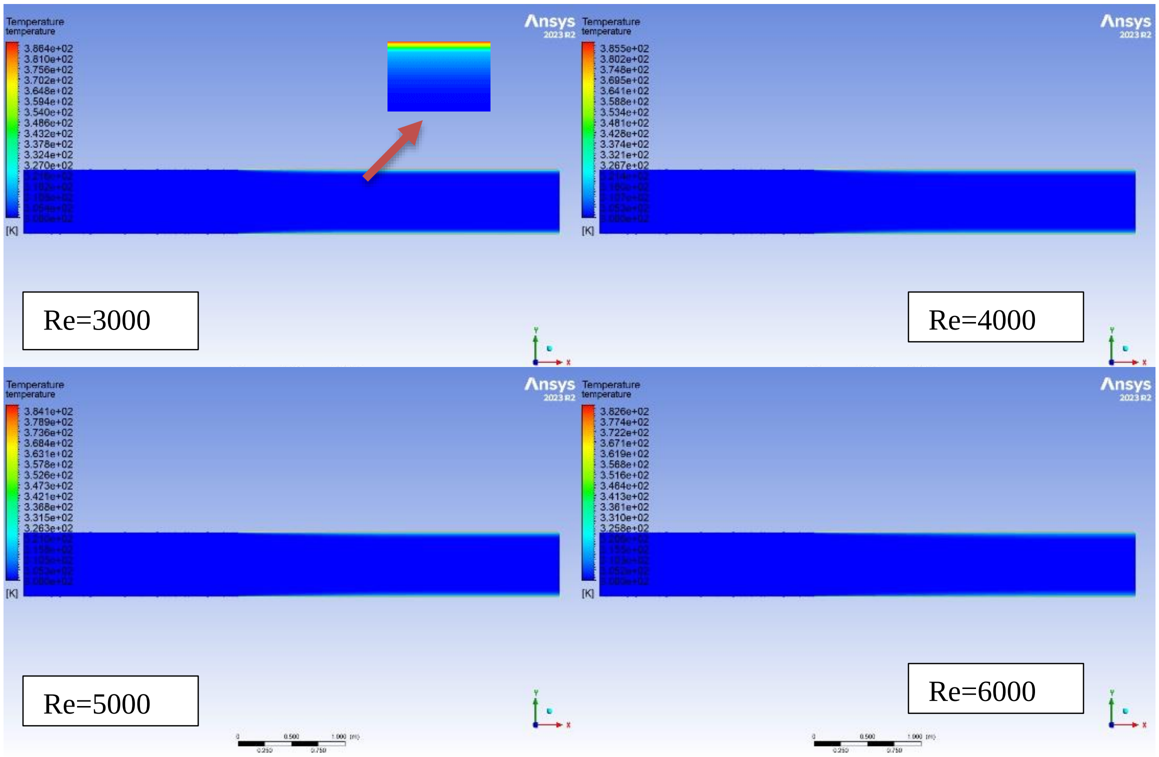

Figure (6): Temperature distribution along the axis of fluid flow of the pipe at Φ=0.1 percent.

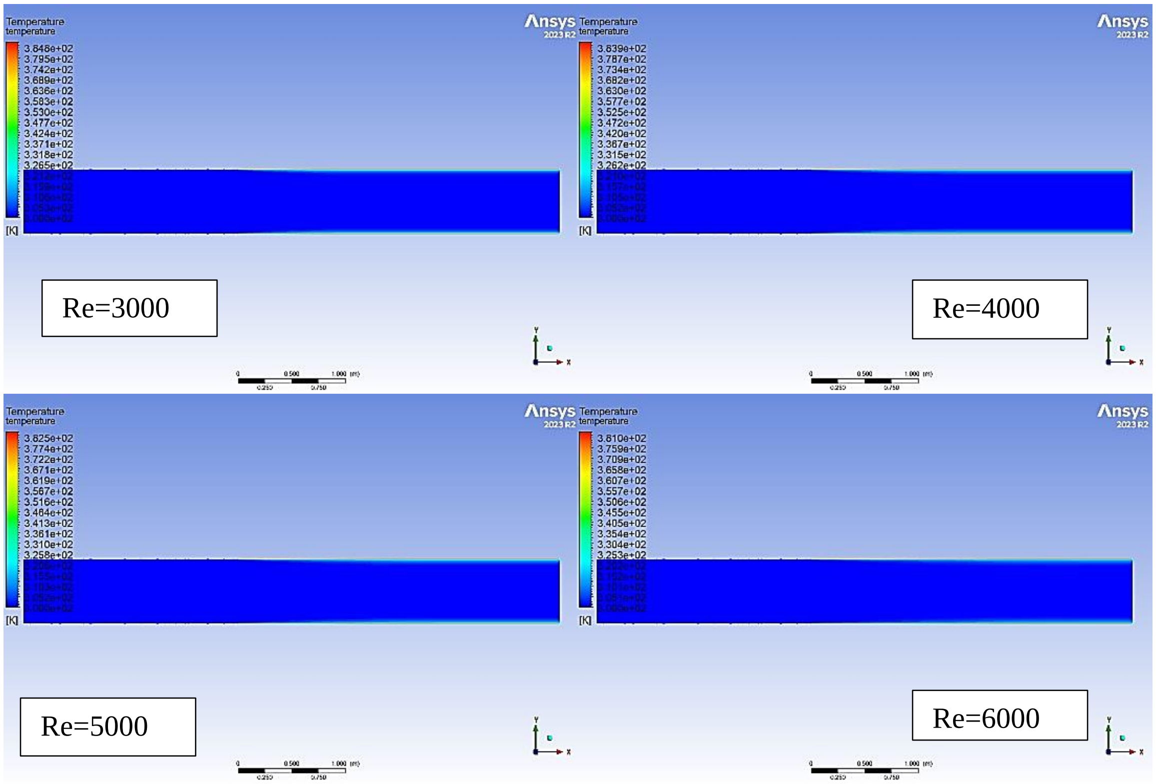

Figure (7): Temperature distribution along the axis of fluid flow of the pipe at Φ=1.5 percent.

4.2. Pipe Velocity Distribution

Figure (8) shows the distribution of the fluid velocity inside the tube at different values of the Reynolds number in the case without and with the nanofluid at different concentrations of fractional volumes. It can be observed that the velocity gradient is high in the middle and reaches zero at the surface.

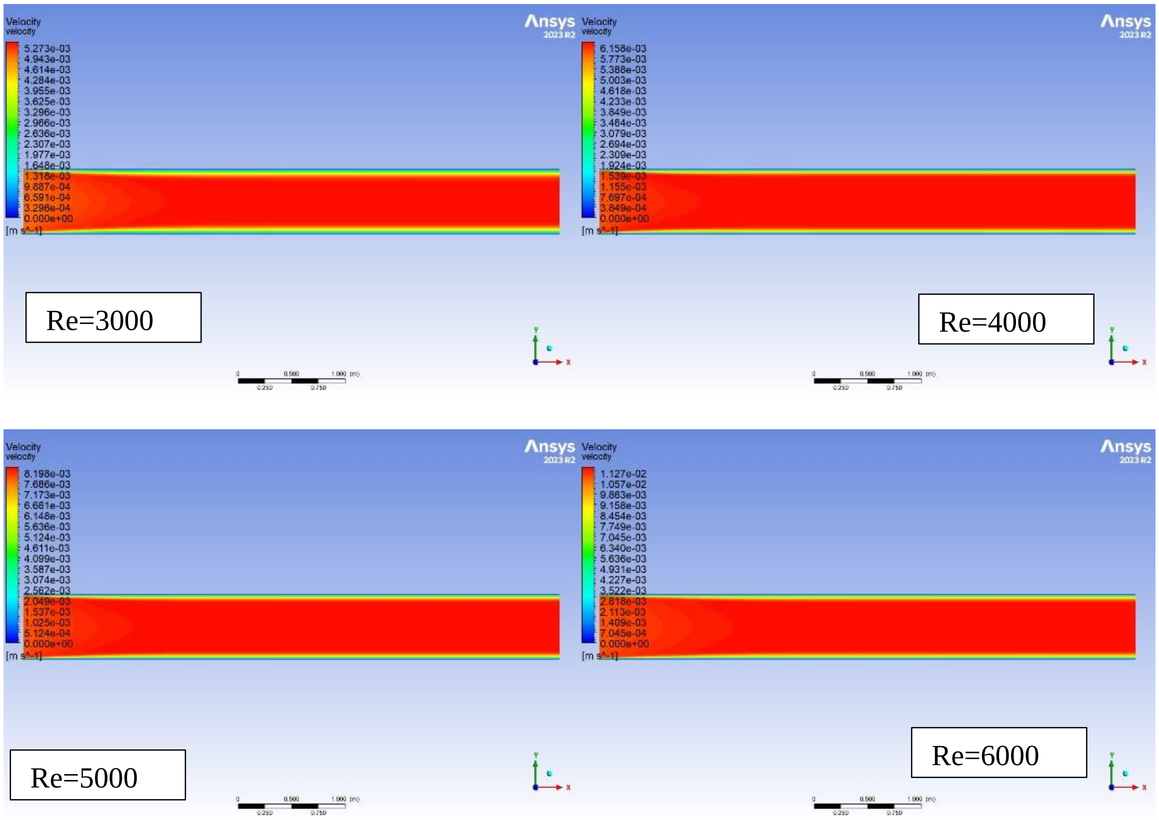

Figure (8): Velocity distribution along the axis of fluid flow of the pipe without nanofluid and volume fractions of (Φ=0.6 % and Φ=1.5%).

4.3. Pipe Pressure Distribution

Figures (9-11) show the distribution of pressure values for fluid flow inside the two-dimensional tube at different speeds, for two cases, the first with the presence of only the basic fluid, and the second when adding different concentrations of nanofluid. An increase in the distribution of pressure values can be observed by increasing the speed and adding the nanofluid, and the reason for this addition is that the physical-thermal properties of the working fluid improve and change.

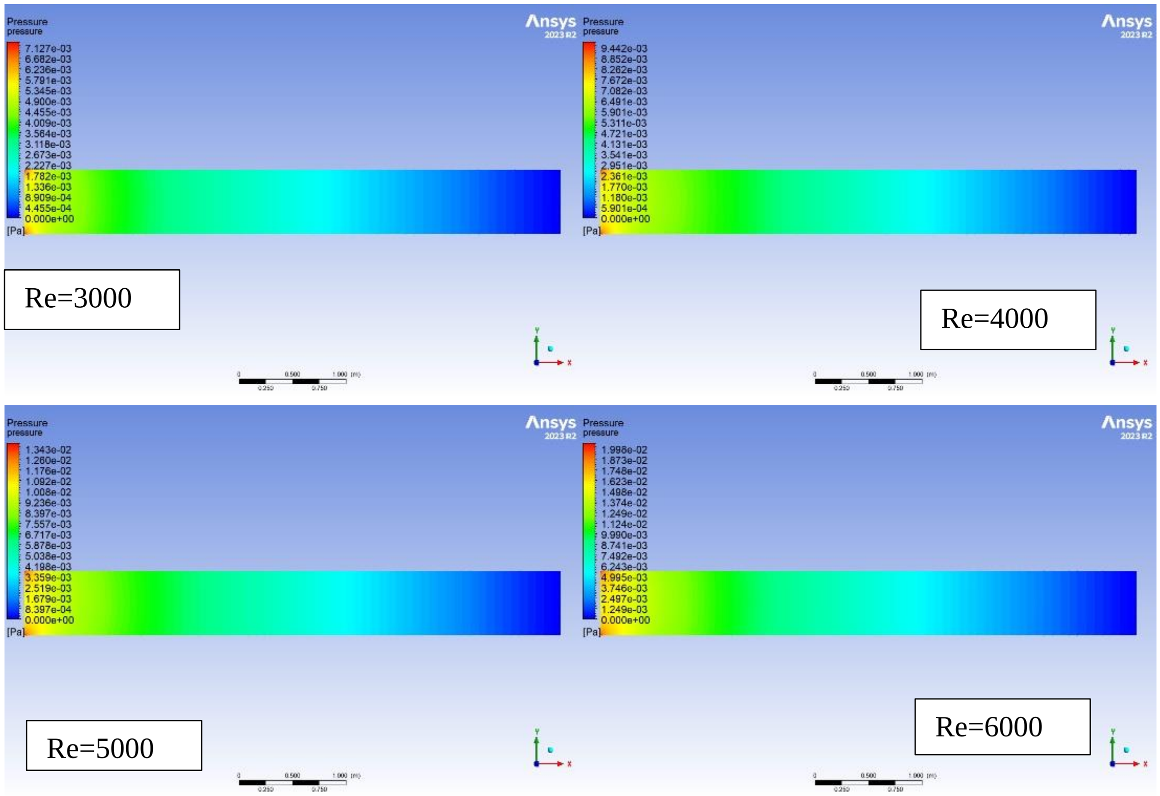

Figure (9): Pressure distribution along the axis of fluid flow of the pipe without nanofluid at different Reynolds numbers.

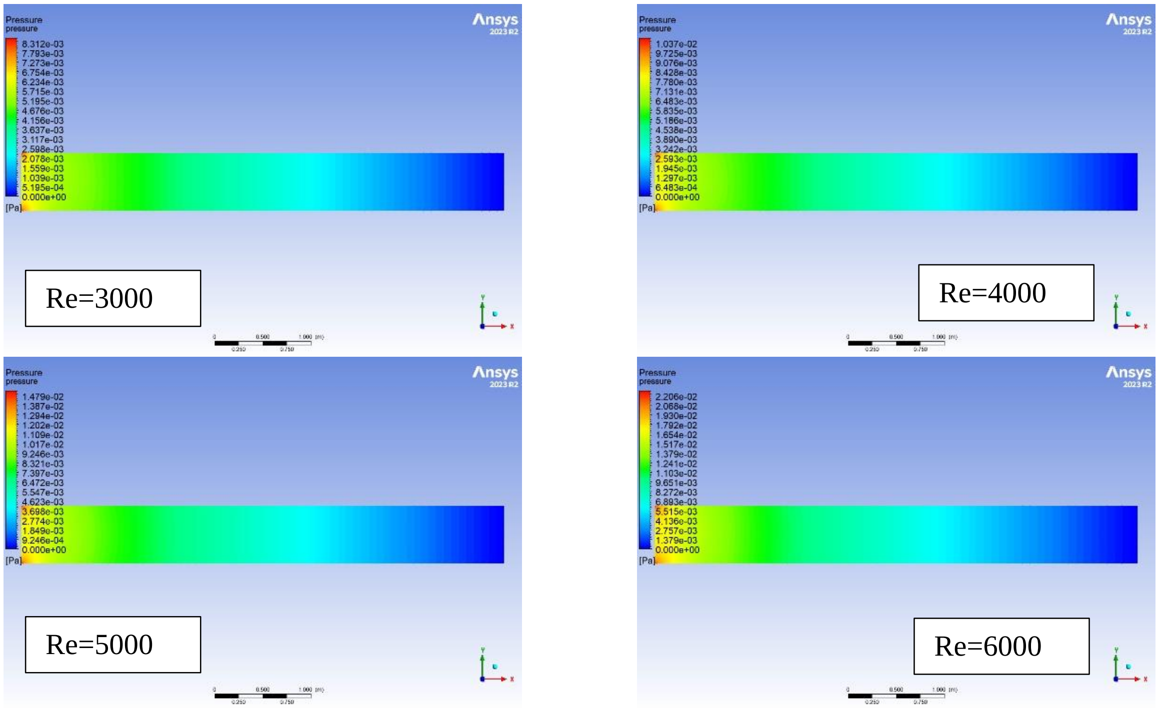

Figure (10): Pressure distribution along the axis of fluid flow of the pipe at Φ=0.1 percent at different Reynolds numbers.

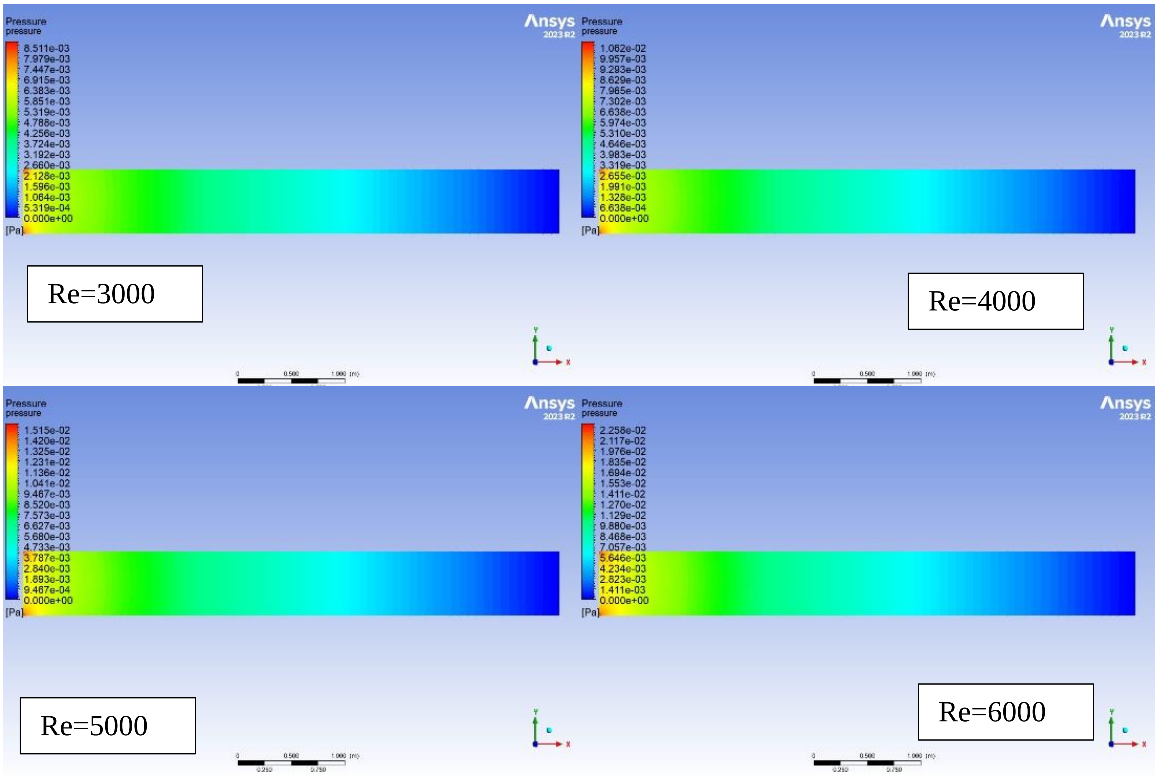

Figure (11): Pressure distribution along the axis of fluid flow of the pipe at Φ=1.5 percent at different Reynolds numbers.

4.4. Nusselt Number

Figure (12) shows the change of the Nusselt number against the Reynolds number in two different cases, the first with the presence of the nanofluid with the working fluid and the other without the nanofluid. It can be observed that the Nusselt number gradually increases with an increase in the Reynolds number and the addition of the nanofluid compared to its absence, and the reason is due to the increase in the velocity of the fluid, the Reynolds number increases and thus the coefficient of heat transfer increases by forced convection and leads to an increase in the Nusselt number for its centrifugal proportion.

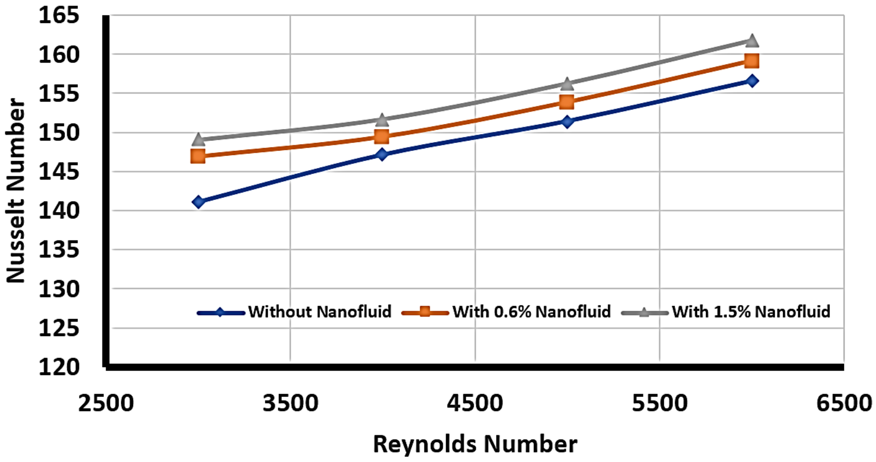

Figure (12): Variation of Nusselt number with Reynolds number of a pipe without nanofluid and volume fractions of (Φ=0.6 % and Φ=1.5%).

4.5. Friction Factor

The friction factor gradually decreases by increasing the Reynolds number in the two cases of adding the nanofluid and without it, and the reason for this is that the pressure difference increases with increasing the amount of fluid velocity and also the friction factor is inversely proportional to the pressure difference in the entry and exit area of the test section of the pipe as shown in Figure (13).

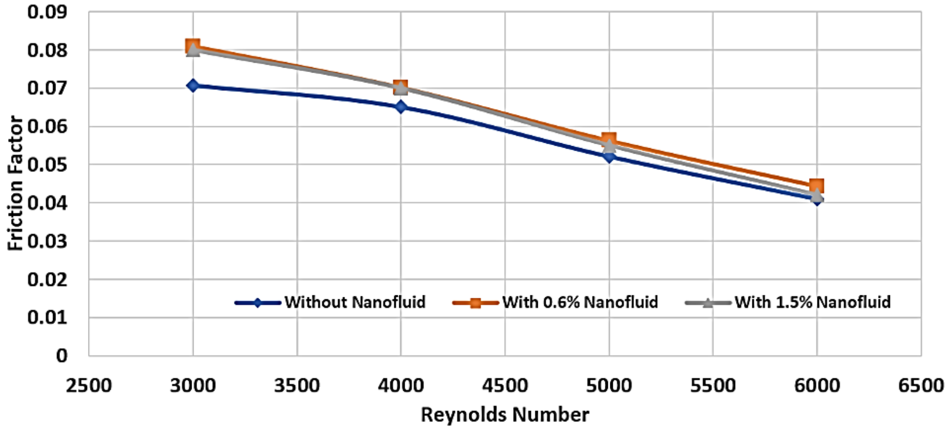

Figure (13): Variation of friction factor with Reynolds number of a pipe without nanofluid and volume fractions of (Φ=0.6 % and Φ=1.5%).

5. Conclusions

A numerical study of forced convection in a two-dimensional pipe subjected to partial heat flux to improve the heat transfer process using a nanofluid added with the basic working fluid (water). From the results obtained, some signs were recorded as follows:

1. The temperature distribution decreases by increasing the velocity of fluid flow inside the pipe.
2. The velocity distribution of the fluid gradually increases by increasing the Reynolds number for its homologous proportionality and also by increasing the volume fractions of the nanofluid.
3. The distribution of pressure values increases with increasing fluid velocity in the test section.
4. The coefficient of heat transfer by forced convection gradually increases with an increase in the Reynolds number, which contributes to an increase in the number of Nusselt.
5. The friction factor gradually decreases by increasing the velocity of the fluid passing into the pipe.
6. The addition of a hybrid nanofluid improves the heat transfer process compared to using the basic fluid alone.
7. The use of nanomaterial contributes to a decrease in the surface temperature of the pipe, which leads to an increase in the coefficient of heat transfer by forced convection, so the Nusselt number increases. This leads to improved performance and efficiency of the thermal system.

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Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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