

Heat transfer analysis of the cooling of TiO₂-water nanofluid in a pipe under magnetic field

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Adding nanoparticles to the basic fluid and applying an external magnetic field to a duct, which is one of the techniques to increase heat transfer in recent years, is one of the frequently studied topics in the literature. Nowadays, the rapidly depletion of fossil fuels due to the increasing human population is constantly prompting researchers to investigate new heat transfer enhancement techniques. For this purpose, in this study, heat transfer phenomena have been investigated by adding various amounts of TiO₂ nanoparticles to the base fluid and applying an external magnetic field to the duct (Both local and average Nu number). The numerical study was carried out with ANSY-Fluent commercial software programmer. The study has been analyzed for various Ha, nano fluid volumetric ratios and Re numbers. It has concluded that both nanoparticle and magnetic field strength are effective in changing the heat transfer, and the magnetic field can be used as a control parameter for the nanofluid.

Keywords: Nanofluid, Magneto-hydrodynamic, Forced convection, Heat transfer

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1. Introduction

In many technical applications such as solar collectors, heat exchanger, power plants, high-performance boilers, cooling systems, and chemical catalytic reactors, forced convection in any channel is one of the essential subjects [1 - 5]. One of the most important subjects of engineering science is heat transfer and the control of nanofluid motion by a magnetic field.

In relation to fluids with suspended nano-particles, Choi [6] is the first scholar to use the term nanofluids. Some studies [1,7,8,9] have shown that thermal conductivity can be increased by about 20 percent with low concentrations of nano-particles. Similarly, Hartmann [10] performed the first report on MHD. Hartmann studied the action of an incompressible viscous and electrically conductive fluid under a magnetic field between two parallel plates.

A lot of work has been done on this subject by researchers [11-15]. The works of some of them are listed as follows. In a microtube with continuous heat flux, Salman et al. [16] numerically studied convective heat transfer of nanofluids consisting of ethylene glycol-Al₂O₃, ZnO, CuO, SiO₂ at 1-

4 percent volume fraction. They found that with increasing volume fractions, heat transfer increases and decreases with increasing particle sizes (Ha=0). In a sudden expansion tube with constant wall temperature, Kimouche et al. [17] numerically examined convective heat transfer of nanofluids consisting of Ag-water, Cu-water, CuO-water, Al₂O₃-water at a volume fraction of 2- 20%. They found that with the growing volume fraction of nanoparticles and Reynolds number, heat transfer increases. Sheikholeslami et al. [18] numerically investigated natural convective heat transfer using the Lattice Boltzmann Method (LBM) in a semi-channel filled with a nanofluid composed of Al₂O₃-water under magnetic field intensity. Hatemi et al. [19] investigated the convective heat transfer phenomena of a nanofluid flow consisting of Al₂O₃-water on a flexible horizontal plate using the Homotopy Analysis Method (HAM) and numerical procedure to assess the characteristics of heat transfer as MHD functions and the volume fraction of nanoparticles.

In a pipe under magnetic field, Erdem and Varol [20], Erdem [21], Erdem et al. [22], and Erdem and Varol [23] examined in detail Cu-water, some different nanoparticles, lithium liquid and PbLi¹⁷ liquid in terms of flow and heat transfer, respectively. Mishra and Kumar [24] investigated magnetohydrodynamic (MHD) silver-water (Ag/H₂) flow and heat properties. Some of the results of the research are the magnetic parameter and the effects of thermal drift to reduce velocity profiles.

The purpose of this work is to investigate numerically MHD forced convection heat transfer for TiO₂-water nanofluid in a three-dimensional circular channel under the magnetic field. The selected nanoparticle volume-fraction and Ha numbers are 0, 0.01, 0.03, 0.05 and 25, 50 and 100, respectively. The magnetic field has applied perpendicular to the flow direction at the outside of the channel. The nano-fluid input temperature is bigger than the temperature of the wall ($\Delta T = 20$ °C). The obtained results have graphically discussed. This issue is being studied frequently in the literature today. In particular, the results related to the change in heat transfer and fluid characteristics with the addition of nanoparticles are a matter of curiosity for researchers. Therefore, in the study, it is recommended to carry out new analyzes for flow motion and efficiency of energy systems with different geometries, different boundary conditions and different methods.

2. Numerical Procedure

The pipe model used in this numerical model is shown in Fig.1. The analysis was planned by ANSYS-WORKBENCH and analyzed by means of the commercial program ANSYS-FLUENT. It is a cylindrical pipe having area with (D) mm diameter and L (mm) length and has been exposed to perpendicularly external magnetic field. The fluid enters the channel at a certain velocity and temperature. The temperature of the nanofluid entering the cylindrical channel is higher than the temperature of the pipe wall, so the fluid is under cooling conditions.

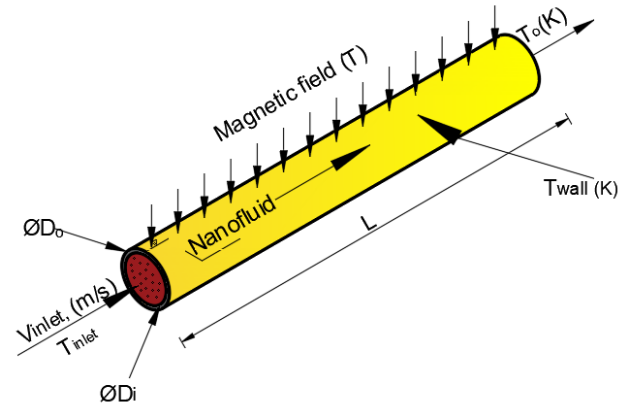


Figure 1. 3D circular channel model [20].

Fluid inlet temperature (T_i) and wall temperature (T_w) was kept constant at different temperature. Inlet temperature and wall temperature are 50 and 30°C, respectively. Thermo-physical properties were selected according to this temperature value. Thermo-physical values are taken from Ref. [21]. The divided pipe model and mesh type created for this numerical study is presented in Fig. 2. As seen in the figure, the model is divided into 5 different solid parts. Each side of the split model is divided into 10 equal parts. For the pipe geometry, making the mesh structure in this way is very important in terms of giving correct results. The Orthogonal quality and Aspect ratio obtained by this method is 0.965 and 5.72, respectively. When orthogonal quality approaches 1, the assigned mesh will be of higher quality. Mesh values in this study are quite good values according to the literature. In the literature, due to the difficulties in the application of this method in general, the solid model is created as a single piece. This may not always give the exact result. When the model is a single piece, such a clear mesh cannot be made. To see this difference in more detail, the study by Erdem [21] can be examined.

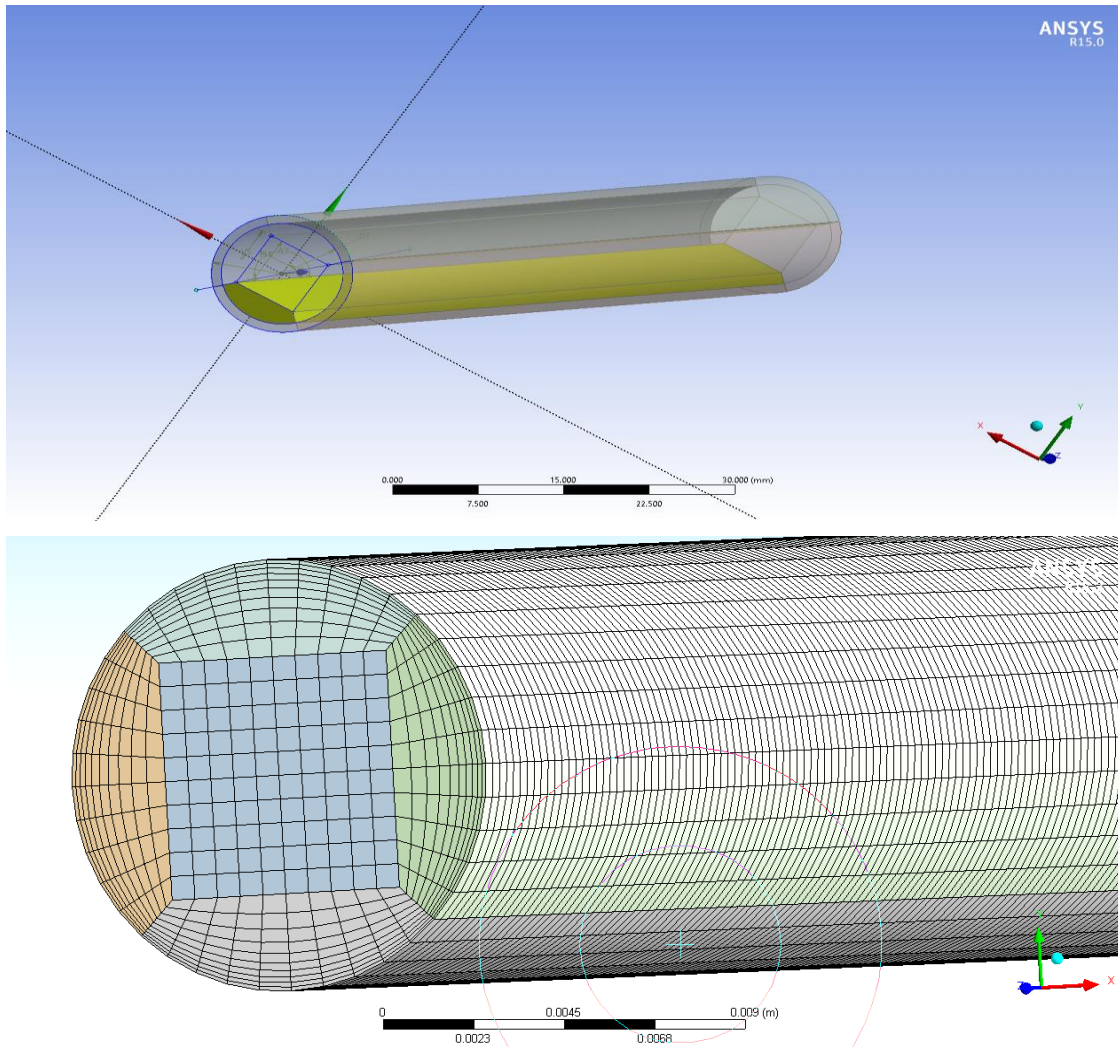


Fig. 2. Divided pipe model and mesh structure

The calculations used for this study are as follows.

With ANSYS Fluent commercial program, the numerical analysis was performed. This research uses the finite volume technique to solve the governing equations. For pressure-velocity coupling, the SIMPLE algorithm was adopted. The nano fluid in the pipe was been used as a laminar, incompressible single-phase Newtonian flow model. Here, since the nano particles are too small, the nano fluid serves as a single phase.

The dimensioned Navier-Stokes equations is calculated as follows [25,26]:

$$\nabla \cdot \vec{V} = 0 \quad (1)$$

$$(\vec{V} \cdot \nabla) \vec{V} = -\frac{1}{\rho_{nf}} \nabla P + \nu_{nf} \nabla^2 \vec{V} + \frac{1}{\rho_{nf}} \vec{F} \quad (2)$$

$$(\vec{V} \cdot \nabla) \vec{T} = \alpha_{nf} \nabla^2 \vec{T} \quad (3)$$

\vec{F} , the buoyancy force and the body force resulting from the Lorentz forces are expressed as [25, 27]:

$$\vec{F} = \vec{J} \times \vec{B} \quad (4)$$

The final term is defined in Equation (4) as the Lorentz force, which causes fluid motion.

\vec{J} , electric current density is defined by the Ohm law:

$$\vec{J} = \rho_{nf} (\vec{E} + \vec{V} \times \vec{B}) \quad (5)$$

\vec{E} , is the DC electrical current and \vec{B} , is magnetic field in the z direction. The magnetic field and the electrical current are thus perpendicular to each other, creating the x- and y-directions of the Lorentz power.

Thermo-physical properties of fluid and nanoparticles were taken from Ref. [21]. Thermo-physical properties of nano-fluid at reference temperature of $T_i = 50 \text{ }^\circ\text{C}$ are taken from ($T_w = 30 \text{ }^\circ\text{C}$):

Nano-fluids density is calculated from the following equation:

$$\rho_{nf} = (1 - \varphi)\rho_f + \varphi\rho_s \quad (6)$$

The specific heat capacity of nanofluid is found from the following equation:

$$(\rho c_p)_{nf} = (1 - \varphi)(\rho c_p)_f + \varphi(\rho c_p)_s \quad (7)$$

Heat conductivity of nanofluid (k_{nf}) is computed from the following equation:

$$\frac{k_{nf0}}{k_f} = \frac{k_s + 2k_f - 2\varphi(k_f - k_s)}{k_s + 2k_f + \varphi(k_f - k_s)} \quad (8)$$

Eq. (9) and (10) are used to calculate nano-fluid dynamic viscosity and Ha number.

$$\mu_{nf} = \frac{\mu_f}{(1 - \varphi)^{2.5}} \quad (9)$$

$$Ha = B_0 R \sqrt{\frac{\sigma_{nf}}{\rho_{nf} \nu_f}} \quad (10)$$

The local Nusselt number (Nu_x) is found from the heat balance at the edge of the hot wall as follows [1].

$$Nu_x = \frac{k_{nf}}{k_f} \frac{(\partial T / \partial r) D}{(T_w - T_i)} \quad (11)$$

The mean Nusselt number (Nu) is calculated (Eq. 12) by integrating the local Nusselt numbers along the channel length (L), (D is diameter of pipe).

$$Nu = \frac{1}{L} \int_0^L Nu_x dx \quad (12)$$

3. Results and Discussion

Local Nu and average Nu values in this study are presented comprehensively on graphs. Likewise, the average Nu values are presented in various Tables. In the results, it was aimed to better understand the effect of magnetic field, nanoscale ratio and Re number by showing them separately.

The variation of local Nu numbers with magnetic field strength along the length of the tube belonging to TiO_2 – water nano fluid is given in Fig. 3. While the fluid temperature was $50^\circ C$, the wall temperature was kept constant at $30^\circ C$. In the parameter with the lowest Re number, it was determined that the local Nu number up to about 0.04 m distance of the channel first increases with the effect of magnetic field strength and then decreases. This is one of the most interesting results obtained within the scope of this study. This is because both the fluid velocity is very low and it decreases further with the magnetic field strength. In other words, as the fluid transport is very low, it is a result of the fact that the transport event occurs very little after a certain point. It was also found that for $Re = 10$, the magnetic field increases the heat transfer, but the magnetic field strengths almost never change the heat transfer with respect to each other.

At $Re = 100$, it is seen that the magnetic field strength increases the local Nu number and is almost equal to each other towards the end of the channel. In the other three major Re (500, 1000, 2000) numbers, it was understood more clearly that local Nu numbers increased with the increase in Ha number and this increase continued at the same rate from the entrance to the exit of the channel. The improvement proportional to the increase in the Re number was greater. Values of local Nu numbers at the exact entrance of the channel prove that the addition of nanoparticle also increases the heat transfer.

In order to understand more clearly the heat transfer happening on the fluid with the addition of nanoparticles, comparisons of local Nu numbers in different nano-volumetric ratios of TiO_2 – water nano fluid are shown in Fig. 4. The results were observed for five different Re numbers with and without magnetic field effect. When the figure was examined, it is clearly seen that the nanoparticle was very effective on heat transfer.

Here, for $Re = 10$, the heat transfer first increases and then the curves is equalized. In addition, the difference between local Nu values at $Re = 100$ approaches towards the end of the channel.

Fig. 5 shows the effect of Re on TiO_2 -water nanofluid in different Ha numbers and nano volumetric ratios. As expected, the results were very effective in increasing the heat transfer of the Re number. In all the parameters studied in the study, heat transfer increased substantially as a large amount of fluid was transported with the increase in the Re number.

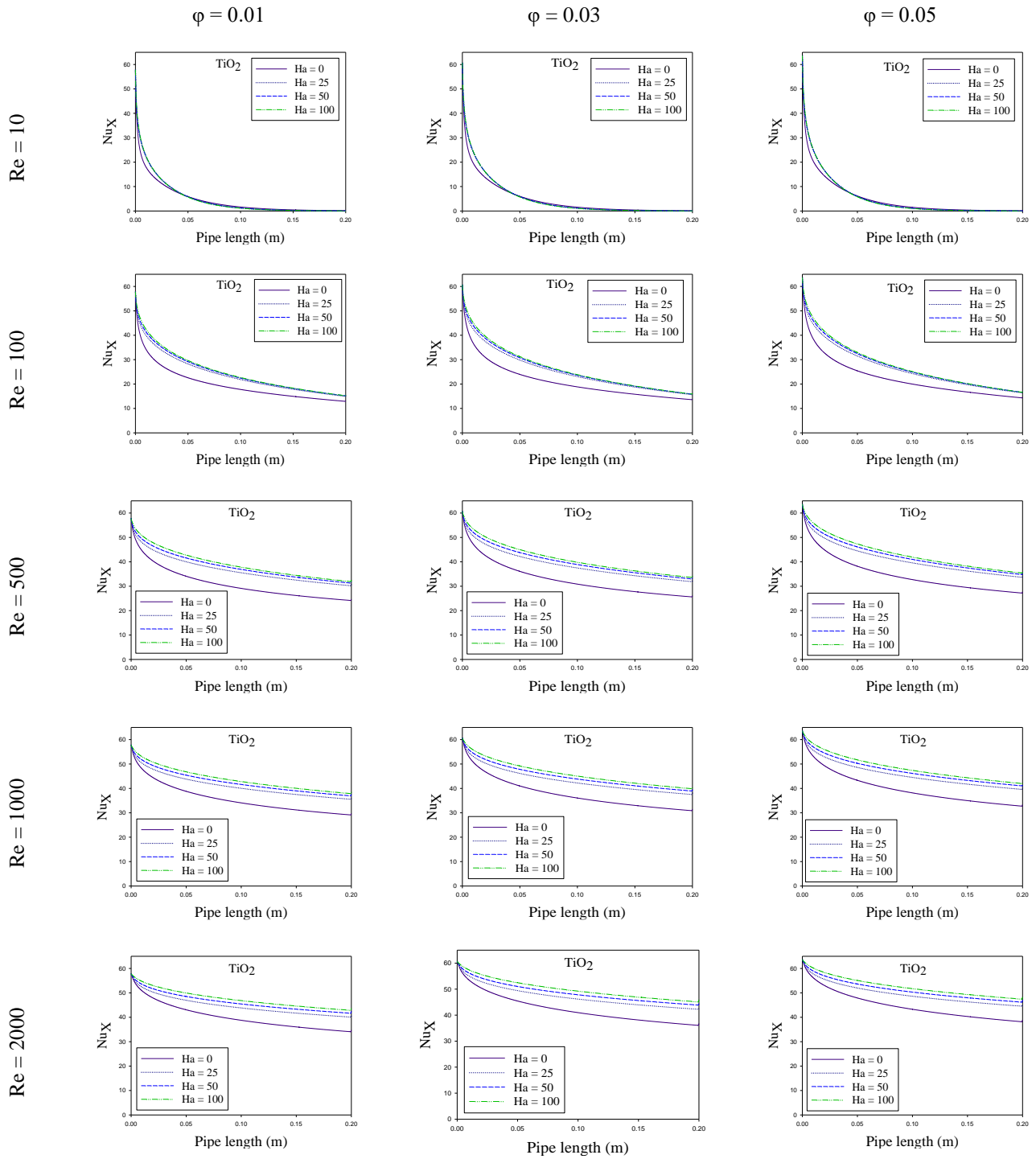


Figure 3. Variation of the local Nu number with the Ha number of the TiO_2 -water nanofluid along the length of the pipe.

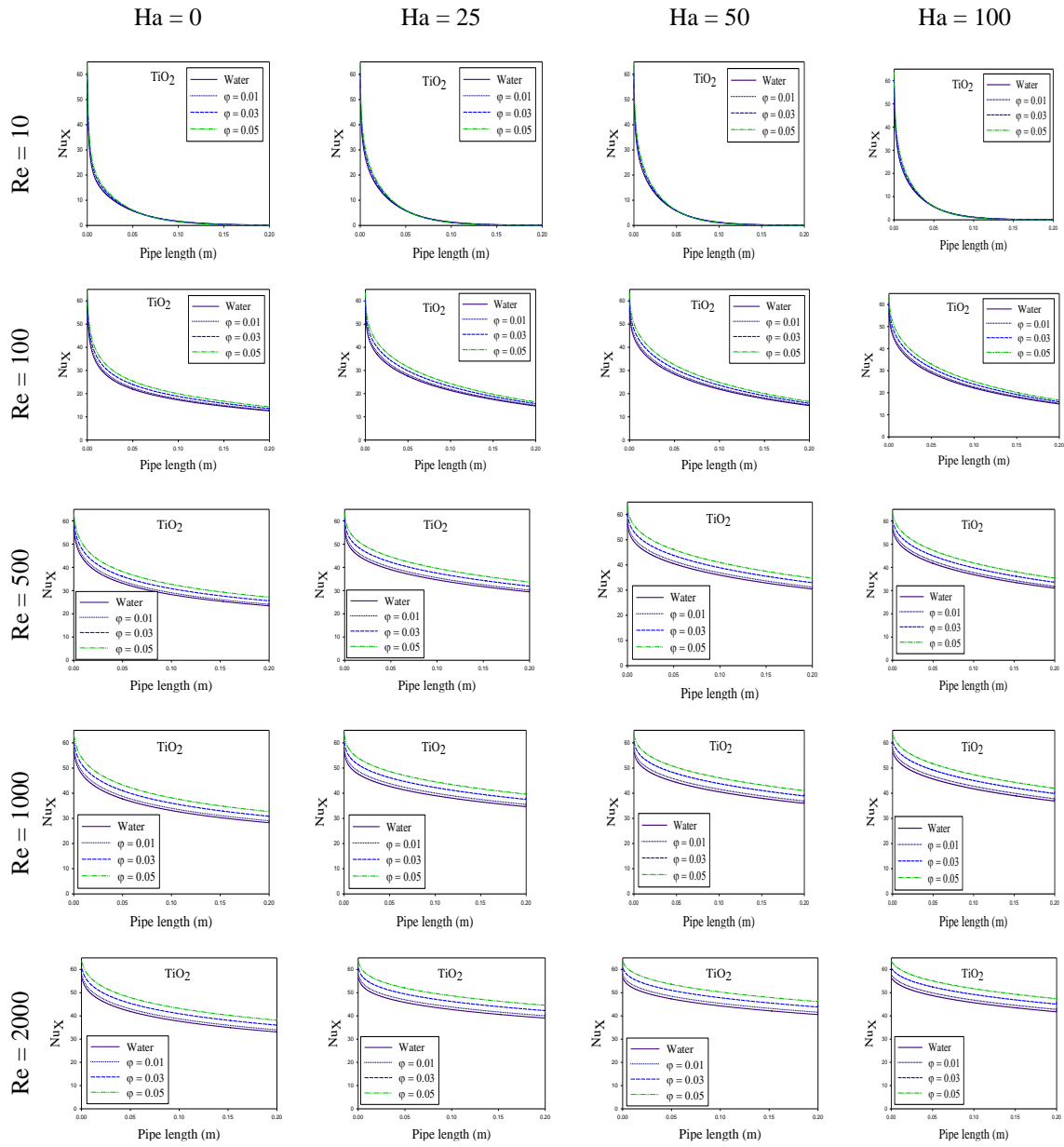


Figure 4. The variation of the local Nu numbers of TiO_2 -water nano fluid along the channel with the nano-volumetric ratio

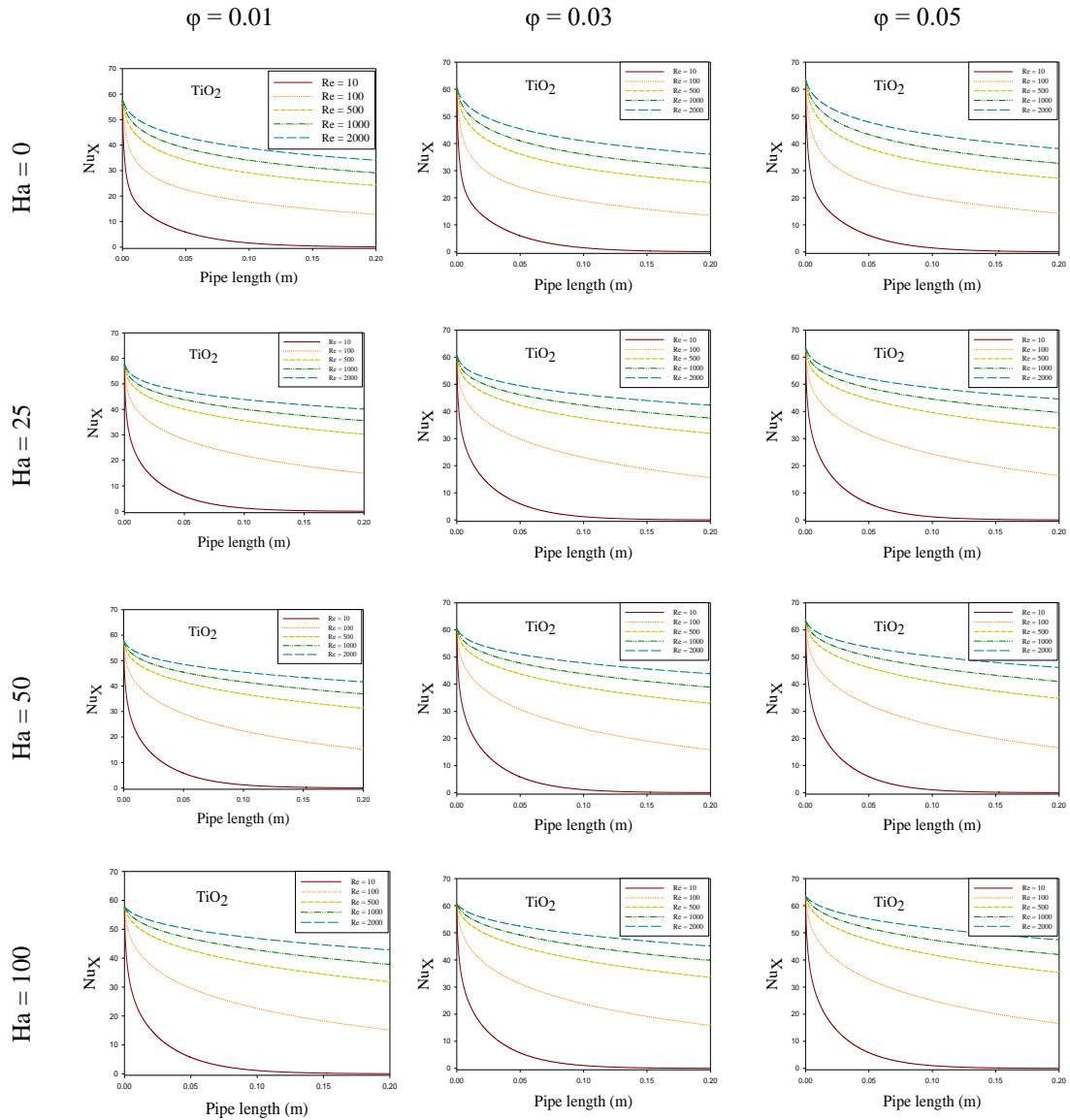


Figure 5. Variation with TiO₂-water nanofluid of local Nu numbers and Re number along the pipe.

The average Nusselt values obtained are presented in Table 1-5. Average Nu values for all operating parameters are given separately for the Ha numbers and Re numbers. These values will also be displayed graphically later. Except for some conditions at Re=10, in general the Ha number and the nanoparticle added showed an increasing effect on the average Nu number. In this section, the

average Nu values given in Table 1-5 above are graphically shown in Fig. 6. In the figure, except for Re = 10, the increase in the Re number, the Ha number and the nanoparticles showed an improvement effect on the heat transfer. These results obtained in the study were found to be compatible with the literature [28].

Table 1. Average Nu values of TiO₂ nanofluid for Re = 10.

Re = 10	Water	$\phi = 0.01$	$\phi = 0.03$	$\phi = 0.05$
Ha = 0	8.753772	8.883341	9.17462	9.509859
Ha = 25	9.351824	9.478541	9.766864	10.10293
Ha = 50	9.362623	9.488253	9.775527	10.1106
Ha = 100	9.305849	9.430679	9.71587	10.04939

Table 2. Average Nu values of TiO₂ nanofluid for Re = 100.

Re = 100	Water	$\phi = 0.01$	$\phi = 0.03$	$\phi = 0.05$
Ha = 0	37.89424	38.98119	41.26304	43.69754
Ha = 25	45.88414	47.06763	49.55331	52.20694
Ha = 50	47.11435	48.30597	50.81055	53.48589
Ha = 100	47.78854	48.98124	51.48993	54.17125

Table 3. Average Nu values of TiO₂ nanofluid for Re = 500.

Re = 500	Water	$\phi = 0.01$	$\phi = 0.03$	$\phi = 0.05$
Ha = 0	59.04561	60.75339	64.31649	68.08425
Ha = 25	70.32272	72.21303	76.14744	80.29489
Ha = 50	72.85222	74.76992	78.76041	82.96622
Ha = 100	74.70941	76.63904	80.65528	84.8892

Table 4. Average Nu values of TiO₂ nanofluid for Re = 1000.

Re = 1000	Water	$\phi = 0.01$	$\phi = 0.03$	$\phi = 0.05$
Ha = 0	68.00803	69.93387	73.9394	78.15859
Ha = 25	78.50212	80.59081	84.9245	89.47476
Ha = 50	81.32426	83.44368	87.83882	92.45144
Ha = 100	83.62099	85.75644	90.18478	94.83238

Table 5. Average Nu values of TiO₂ nanofluid for Re = 2000.

Re = 2000	Water	$\phi = 0.01$	$\phi = 0.03$	$\phi = 0.05$
Ha = 0	76.44508	78.5563	82.93435	87.52874
Ha = 25	85.35497	87.59449	92.22896	97.07928
Ha = 50	88.24054	90.51086	95.20728	100.1187
Ha = 100	90.80004	93.08984	97.82479	102.7756

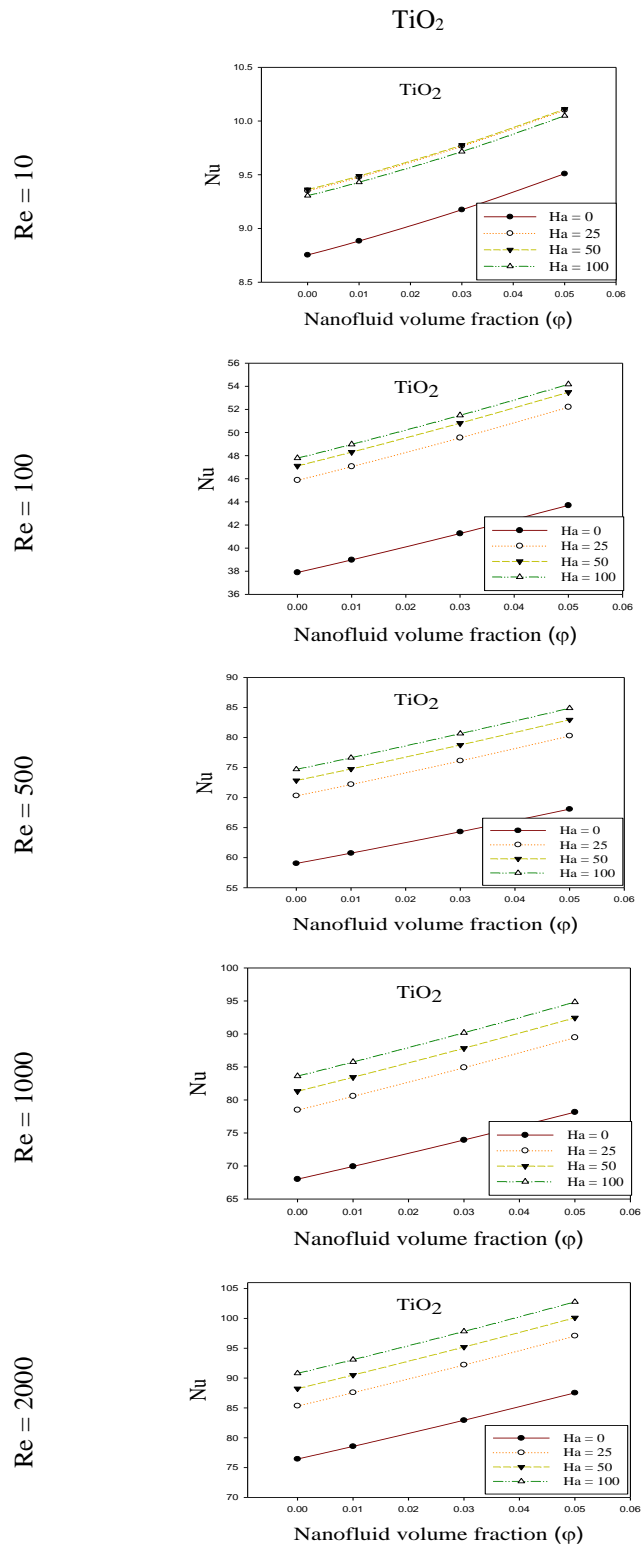


Figure 6. Effect of Nanoparticle volume ratio, Re and Ha number on average Nu number of TiO_2 -water nanofluid.

4. Conclusion

In this study, the numerical analysis of TiO₂-water-nanofluid flowing in a pipe under cooling conditions was investigated in terms of heat transfer. Analyzes were performed for different Re, Ha and nano volume ratio. Results for local Nu and average Nu numbers have been comprehensively obtained and presented. Split network structure, which is rarely encountered in the literature, was used in the study. This network structure is much smoother than the undivided network structure and gives more accurate results [21]. The results found are presented in detail below:

- ✚ At Re = 10, it was determined that the local Nu number first increased with the effect of the magnetic field strength up to about 0.04 m distance of the channel and then these values decreased.
- ✚ At Re = 100, 500, 1000 and 2000, the magnetic field have increased the Local Nu number.
- ✚ The local Nu number has increased with the nanoparticle and Re number.
- ✚ In all parameters except Re, the average Nu number have increased with both the Ha number and the nanoparticle.

As a result, heat transfer at high Re numbers increases with the nanofluid volume ratio and magnetic field strength. Additionally, the motion of the nanofluids can be kept under control by the magnetic field strength.

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