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Manyetik alan altında nanoakışkanların akış karakteristiklerinin incelenmesi

Investigation of flow characteristics of nanofluids under magnetic field

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Investigation Of Flow Characteristics of Nanofluids Under Magnetic Field

Highlights

- *The flow characteristics and velocity profile of distilled water, alumina nanofluid, and cobalt ferrite ferrofluid in a horizontal cylindrical heat pipe flowing in a laminar regime and being exposed to an external magnetic field are investigated.*
- *It is concluded that an external magnetic field causes a deterioration in the velocity profiles of the nanofluid, especially in cobalt ferrite, while it does not have a significant effect on water.*
- *When the magnitude of the magnetic field is increased by 2 times, it is seen that the velocity of the fluid decreases by 6%.*
- *Increasing the magnetic field from 0 to 50 Tesla causes a deceleration rate of 9%.*
- *It is concluded that application of a magnetic field for the first time has a more significant slowing effect when comparing it to increasing the magnetic field.*

Graphical Abstract

The current study presents the investigation of the flow characteristics and velocity profile of distilled water, alumina nanofluid, and cobalt ferrite ferrofluid in a horizontal cylindrical heat pipe flowing in a laminar regime and being exposed to an external magnetic field.

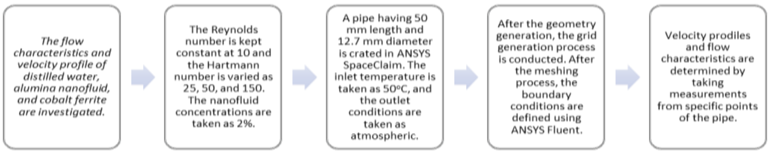

Figure. 1

Aim

In the present study, the flow characteristics and velocity profiles of water, alumina nanofluid, and cobalt ferrite nanofluid in a horizontal cylindrical pipe flowing in a laminar regime are investigated under an external magnetic field with varying magnitudes.

Design & Methodology

After the modelling of the geometry, the grid generation was conducted, follwed by the analyses in Fluent. The results were invesigated in terms of velocity values and flow behaviours.

Originality

In order to pave the way for the utilization of nanofluids in aerospace applications, it is critical to determine the behavior of the flow characteristics and hat transfer performance under an external magnetic field. In the light of this purpose, this study investigates numerically the effect of magnetic field on the velocity and pressure distributions of water, and two different nanofluids; magnetic nanofluid $CoFe_2O_4$/water, and non-magnetic nanofluid Al_2O_3.

Findings

The magnetic field does not have a significant effect on the flow characteristics and velocity profile of water, whereas it causes the flow to slow down apparently for alumina and cobalt ferrite, having a sharper effect on cobalt ferrite as it is a ferrofluid. For alumina and cobalt ferrite, the velocity decreases with an increasing magnetic field intensity. With an applied/existing external magnetic field, the flow characteristics and velocity profile of nanofluids are apparently deteriorated, and magnetic nanofluids like cobalt ferrite is affected more compared to non-magnetic nanofluids.

Conclusion

Increasing the magnitude of the magnetic field by 2 times causes the velocity of the fluid to decrease by 6% and increasing the magnetic field from 0 to 50 Tesla causes a deceleration rate of 9%. When a magnetic field of 50 Tesla is considered, the maximum velocity of alumina is lower than that of water by 5.10%, and the maximum velocity of cobalt ferrite is lower by 28.57%.

Declaration of Ethical Standards

The authorof this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

The Investigation of Flow Characteristics in Nanofluids Under Magnetic Field

Araştırma Makalesi / Research Article

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ÖZET

The existence/application of an externally induced magnetic field, like in satellite cooling applications, causes a decrement in heat transfer when used with nanofluids. This study investigates the flow characteristics and velocity profile of distilled water, alumina nanofluid, and cobalt ferrite ferrofluid in a horizontal cylindrical heat pipe flowing in a laminar regime and being exposed to an external magnetic field. All of the simulations were performed with ANSYS Fluent MHD module, for a concentration of 2%, Reynolds number of 10, and Hartmann numbers of 25, 50, and 150. The velocity profiles, pressure drops, and flow characteristics are examined by varying the magnetic field intensity while keeping all other parameters constant. It is concluded that an external magnetic field causes a deterioration in the velocity profiles of the nanofluid, especially in cobalt ferrite, while it does not have a significant effect on water. When the magnitude of the magnetic field is increased by 2 times, it is seen that the velocity of the fluid decreases by 6% and increasing the magnetic field from 0 to 50 Tesla causes a deceleration rate of 9%, which leads to the conclusion that application of a magnetic field for the first time has a more significant slowing effect when comparing it to increasing the magnetic field. In addition, when a magnetic field of 50 Tesla is considered, the maximum velocity of alumina is lower than that of water by 5.10%, and the maximum velocity of cobalt ferrite is lower by 28.57%.

Keywords: Nanofluid, ferrofluid, magnetohydrodynamics, computational fluid dynamics.

Manyetik Alan Altında Nanoakışkanların Akış Karakteristiklerinin İncelenmesi

ABSTRACT

Uydu soğutma uygulamalarında olduğu gibi, harici olarak indüklenen bir manyetik alanın varlığı/uygulanması, nanoakışkanlarla kullanıldığında ısı transferinde bir azalmaya neden olur. Sunulan çalışma, laminar rejim altında dış bir manyetik alana maruz kalan su, alumina nanoakışkanı ve kobalt ferrit nanoakışkanının akış davranışlarını ve hız profillerini incelemektedir. Analizler ANSYS Fluent MHD modülü kullanılarak gerçekleştirilmiştir. Nanoakışkanların konsantrasyonları %2, Reynolds sayısı 10, ve Hartmann sayısı da 25, 50, ve 150 olarak alınmıştır. Hız profilleri ve akış karakteristikleri, manyetik alan büyüklüğü dışındaki tüm değişkenler sabit tutularak incelenmiştir. Sonuç olarak, dış bir manyetik alan uygulamasının nanoakışkanların, özellikle de kobalt ferrit nanoakışkanının, hız profillerinde bozulmaya sebep olduğu, ancak su üzerinde kritik bir etkisinin bulunmadığı görülmüştür. Manyetik alan büyüklüğü 2 katına çıkarıldığında akışkan hızının %6 azaldığı, 0 Tesla olan manyetik alan büyüklüğü 50 Tesla'ya çıkarıldığında ise akışkan hızının %9 azaldığı görülmüştür. Bu doğrultuda, manyetik alan büyüklüğünü artırmanın etkisinin, manyetik alanı ilk kez uygulamanın etkisinden daha az olduğu saptanmıştır. Ayrıca, 50 Tesla için kıyaslama yapıldığında, elde edilen maksimum hızın alumina nanoakışkanı için suyunkinden %5.1, kobalt ferrit nanoakışkanı için de %28.57 daha az olduğu görülmüştür.

Anahtar Kelimeler: Nanoakışkan, manyetik nanoakışkan, manyetohidrodinamik, hesaplamalı akışkanlar dinamiği.

1. INTRODUCTION

Enhancing heat transfer has been one of the main design goals for thermal systems such as cooling and heating applications, gas power cycles, chemical engineering applications, etc. Nevertheless, conventional fluids like water and oil have low thermal conductivity values which results in insufficient heat transfer amounts leading to lower thermal efficiencies. The concept of nanofluids, which has been firstly proposed by [1], offers a solution to this drawback by having an enhanced thermal conductivity. Nanofluids are user-generated fluid mediums which are prepared by dispersing solid nanoparticles in a selected base fluid. Base fluids are conventional fluids, whereas solid nanoparticles can be metal or nonmetal particles [2]. It is numerically and experimentally proven that nanofluids provide a significant enhancement for heat transfer by increasing the thermal conductivity of the working fluid, as the thermal conductivity of a solid metal is higher than that of a base fluid, by increasing the thermal capacity and surface area of the working fluid, by causing the flow turbulence and turbulence intensity to increase, and by causing the transverse temperature gradient of the fluid to flatten [3]. However, in contrast to the enhancement in heat transfer by an increased thermal conductivity, nanofluids have also higher viscosity values than that of the base fluid, which in turn increases the amount of

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required work for fluid transfer [4]. Moreover, they are uniform and stable resulting in a higher thermal performance [5]. Magnetic nanofluids are fluid mediums that has magnetic nanoparticles such as cobalt, iron, nickel constituting the solid part, suspended in the chosen base fluid. The most specific property of the magnetic nanoparticles is that they can be manipulated by using a magnetic field. Magnetic nanofluids serve to the purpose of utilization as they act like a functional working fluid under magnetic field [6]. Due to the required design parameters, the properties of the magnetic nanofluid can be altered by arranging the external magnetic field. Therefore, they have a wide area of utilization like the airplane brakes, biomedical applications, data storage applications, satellite cooling, which makes them the focus of numerous research.

Most of the research concerning the application of magnetic field on nanofluids found in literature is theoretical and numerical, considering that it is out of bounds of any study in terms of expenditure and applicability [7]. From the conducted laboratory studies, it is known that external magnetic field. has a significant effect on the properties and hence the fluid flow behavior of nanofluids, especially on nanofluids with magnetic nanoparticles. Wang et al. [2] investigated the heat transfer enhancement of nanofluids under an electric or a magnetic field by conducting a comprehensive literature review. They concluded that although there is not an agreement on the effect on heat transfer mechanism, application of an electric or a magnetic field strongly affects the heat transfer amount. Li and Xuan [8] performed an experimental study to investigate the heat transfer features of magnetic fluid flow over a fine wire under an external magnetic field. They have found out that external magnetic field application can be used as a flow control mechanism, and an oppositely applied magnetic field suppresses the heat transfer between the nanofluid and the wire. Sundar et al. [9] conducted an experimental study to determine the thermal conductivity and viscosity of Fe_3O_4/water. nanofluid. They proposed theoretical equations for thermal conductivity and viscosity, which are found to be in good agreement with the experimental results. Giwa et al. [10] searched for the hydromagnetic behaviors of nanofluids in square-shaped enclosures by performing an experimental and a numerical study. They investigated the effect of boundary conditions, utilized parameters, magnetic field, nanofluid type, etc. on the natural convection behaviors of nanofluids. They pointed out that application of magnetic field has a negative effect on heat transfer mechanism except several cases where it improved at specific values. Contrarily, due to experimental results, application of magnetic field augments the heat transfer. Hariri et al. [11] numerically investigated the effect of a non-uniform magnetic field on a magnetic nanofluid inside a tube. They found out that the non-uniform magnetic field caused a significant increment in Nusselt number. Gorjaei et al. [12] simulated the Fe_30_4/water nanofluid inside a circular tube by using the Euler-Lagrange method. The findings of their results showed that the region with the magnetic field has a lower temperature than the rest of the tube, and the velocity of the nanoparticle shows a decrement in the central region. Hatami et al. [6] experimentally investigated the effect of magnetic field on heat transfer of a Fe_3O_4/water nanofluid flowing in a horizontal tube in a laminar regime under constant heat flux. They found out that an increment in Hartmann number caused the Nusselt number to decrease. Several researchers have focused on the convection heat transfer of magnetic nanofluids under magnetic field in enclosures having various shapes [13-19], and there are previous studies investigating the application of an external magnetic field on various nanofluids to enhance thermophysical properties such as thermal conductivity, viscosity, density, etc. [20-26]. Zhao et al. [27] performed a numerical study to investigate the interaction between an electrically conducting fluid and an externally applied magnetic field. Zeeshan, Ellah, and Hassan [28] conducted a study proving that an external magnetic field deteriorates the temperature and velocity distributions of the nanofluid compared to the base fluid. Malvandi and Ganji [29] showed that with an increment in the magnitude of the magnetic field, the near-wall velocity increases, whereas the peak value of the velocity distribution along the axis decreases. In Bhatti et al.'s study [30], the entropy generation of Carreau nanofluid near a plate being exposed to thermal radiation is investigated. They concluded that by increasing the intensity of the magnetic field, a drastic decrement in velocity profile is obtained, and the entropy profile exhibits an increment for all physical parameters. Asirvatham [31] stated in his study that although utilization of nanofluids in heat pipes for satellite cooling applications could improve the heat transfer performance by reducing the thermal resistance, it is seen that particle aggregation and deposition have a negative effect on heat transfer performance.

In order to pave the way for the utilization of nanofluids in aerospace applications, it is critical to determine the behavior of the flow characteristics and hat transfer performance under an external magnetic field. In the light of this purpose, this study investigates numerically the effect of magnetic field on the velocity and pressure distributions of water, and two different nanofluids; magnetic nanofluid $CoFe_2O_4$/water, and non-magnetic nanofluid Al_2O_3.

The concentrations of the nanofluids are 2% and the magnetic fields are taken as 50, 100, and 300 Tesla. Although there are many studies concerning different concentration rates, it is seen that 2% concentration is found to be the optimum value because of sedimentation problems. Therefore, the concentration value used in the analyses is 2%, and the magnetic fields are taken as 50, 100, and 300 Tesla. The results attained from different magnetic fields and the utilized working fluids are presented in order to reveal the effect of magnetic field clearly.

2. MATERIAL and METHOD

This study focuses on the numerical investigation of velocity and temperature distributions of water, a magnetic and a non-magnetic nanofluid flowing in a pipe under the application of an external magnetic field. It is known that the experimental procedure for such a problem is disadvantageous in terms of expenditure, effort, and time. Computational Fluid Dynamics provides many benefits to researchers and designers under the condition that the problem is simulated using the correct numerical assumptions and inputs, such as modeling the boundary conditions properly, choosing the right turbulence model or the discretization scheme, etc. In addition, utilization of CFD enables the researchers to obtain the results more concisely and detailed, providing several parameters that cannot be even measured. As the experimental modeling of such a problem is challenging and high-priced, it is seen that most of the previous studies are conducted numerically. ANSYS Workbench 2020 is used for the modeling and solution of this case, generating the 3D model in SpaceClaim, preparing the mesh in ANSYS Meshing, setting up and solving the case using ANSYS Fluent, and conducting the post-process in CFD-Post.

2.1. Problem Description

A standard aluminum pipe having a length of 50 mm and a diameter of 12.7 mm is used for the analyses. The generated geometry is given in Figure 1.

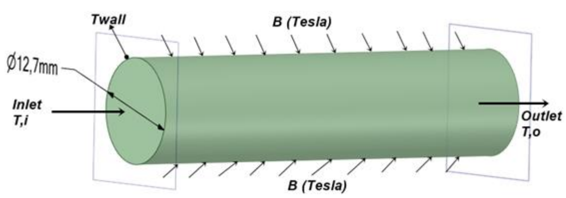


Figure 1. The 3D model of the utilized pipe and the boundary conditions

The temperature of the wall, Twall, is chosen to be 30°C whereas the fluid inlet, Ti, is at 50°C. The outlet conditions are taken as atmospheric. The magnetic field is applied at the outer layer of the pipe with a direction normal to the fluid flow, varying as 50, 100, and 300 Tesla. The flow regime is assumed to be laminar. The created magnetic field and the flow direction are perpendicular to each other.

2.2. Grid Generation

The attained results in a numerical study are strongly dependent on the generated grid structure. Therefore, it is of vital importance that the generated mesh provides the required quality conditions such as skewness, orthogonal quality, aspect ratio, etc. Vassberg, DeHaan, and Sclafani [32] stated that the aspect ratio, skewness, and maximum corner angle of the utilized mesh are critical in terms of analysis. On the other hand, it is also important to keep the computational effort as minimum as possible. Therefore, the designers should ensure that the generated grid structure uses the minimum computational effort while providing that the structure does not affect the attained solution. In other words, a mesh independence study should be conducted before deciding the final mesh structure since it can cause significant differences in the obtained output [33]. For the present study, the velocity of the fluid at the center of the pipe is used as the control point. After the difference between the two fine mesh structures providing the required conditions are found to be below 1%, the grid having smaller number of elements is chosen to be the final structure. The generated grid structure is given in Figure 2, and the results of the grid independence study is presented in Figure 3.

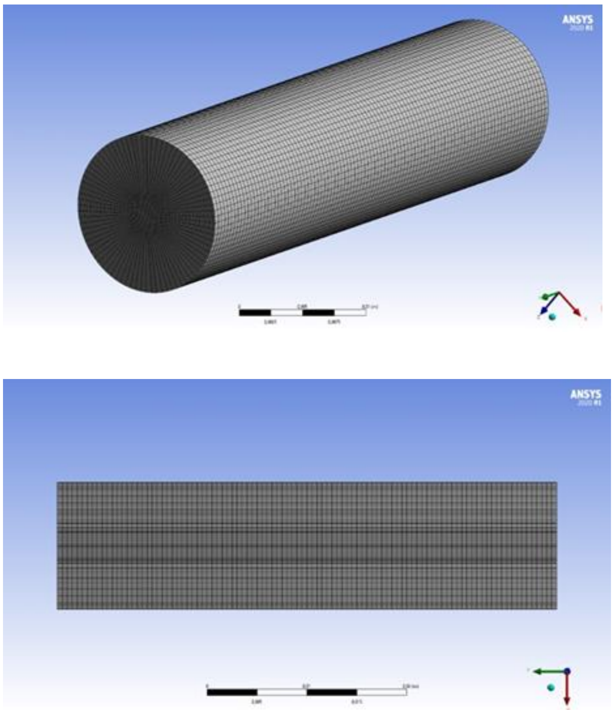


Figure 2. The utilized mesh

The utilized mesh has approximately 264000 elements having an average skewness of 0.18. ANSYS Fluent Theory Guide [34] states that the average skewness value should be maximum 0.33, otherwise the prepared mesh structure is not appropriate to be used in the analyses. In addition, increasing the number of elements did not have a significant effect on the mentioned velocity value. Hence, the mesh structure providing the required conditions and causing the minimum computational effort is chosen to be used in the study.

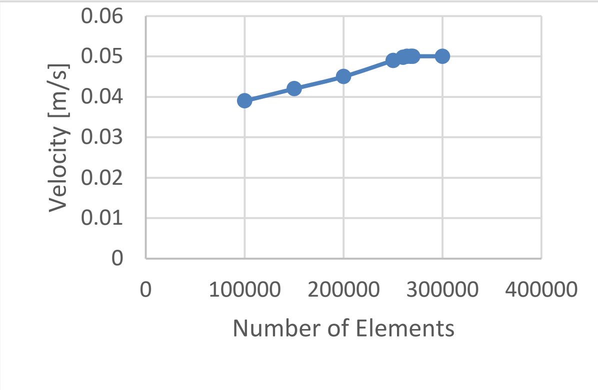


Figure 3. Mesh independence study

2.3. Numerical Analysis

After the meshing process is completed, the simulations of the analyses are conducted using ANSYS Fluent. The working fluids in the present study are $CoFe_2O_4$, Al_2O_3, and water. The properties of water are existing in ANSYS Fluent's library, and the properties of the nanofluids are described using the relationships proposed by [31] given in Equations 1-3.

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

$$(\rho C_p)_{nf} = (1 - \varphi)(\rho C_p)_{bf} + \varphi(\rho C_p)_{np} \tag{2}$$

$$\mu_{nf} = \mu_b(123\,\varphi^2 + 7.3\varphi + 1) \tag{3}$$

These properties are calculated according to 2% concentration, and the calculated values are given in Table 1.

Table 1. Properties of the utilized nanofluids

	$CoFe_2O_4$	Al_2O_3
Density [kg/m3]	1076.18	1053.69
Specific Heat [J/kgK]	3812.813	3937
Thermal Conductivity [W/mK]	0.6413	0.645
Dynamic Viscosity [Pa.s]	0.0010637	0.0011987

Following the properties of fluids, the boundary conditions are defined. The inlet region is defined with velocity-inlet, and the outlet with pressure-outlet; assuming the outlet has atmospheric conditions. The inlet and outlet conditions are kept constant throughout the study, with a laminar flow inside the pipe. The fluids are taken as Newtonian and incompressible, and the analyses are conducted as single phase, neglecting the nanoparticles as they are very small. The magnetic field is varied as 50, 100, and 300 Tesla for each of the fluids by using the Magnetohydrodynamics module (MHD) of Fluent. Magnetohydrodynamics concerns the interaction between a magnetic field and a conductive fluid (ANSYS MHD Module, 2019). This model enables the user to simulate the behavior of a conducting fluid flow exposed to a constant (DC) or oscillating (AC) electromagnetic field. The relationship between the fluid flow field and the magnetic field can be defined on the basis of two fundamental effects. The first one is the induction of electric current due to the movement of conducting material in a magnetic field, and the other one is the effect of Lorentz force as the result of electric current and magnetic field interaction. Generally, the induced electric current and the generated Lorentz force tend to behave in the opposite manner to the mechanisms creating them. Therefore, movements that result in an electromagnetic induction are braked by the resulting Lorentz force. Magnetic induction method with a constant electromagnetic field is used in this study, and the related equations are given through Equations 4-10 [35].

The magnetic induction equation is derived using Ohm's law and Maxwell's equation basically. Ohm's law can be written as Equation 4 for a fluid velocity of U with a magnetic field B.

$$\vec{j} = \sigma(\vec{E} + \vec{U} \times \vec{B}) \tag{4}$$

The induction equation can be written as Equation 5 by using the Ohm's law and Maxwell equation.

$$\frac{\partial \vec{B}}{\partial t} + (\vec{U} \cdot \nabla)\vec{B} = \frac{1}{\mu\sigma}\nabla^2\vec{B} + (\vec{B} \cdot \nabla)\vec{U} \tag{5}$$

With the help of Maxwell's equations, the externally imposed field B_0 can be calculated using Equation 6.

$$\nabla^2\overrightarrow{B_0} - \mu\sigma'\frac{\partial \overrightarrow{B_0}}{\partial t} = 0 \tag{6}$$

Here σ' is the electrical conductivity of the media in which field $\overrightarrow{B_0}$ is generated.

The flow is modeled as 3D and is solved with Navier-Stokes equations given in Equations 7 and 8.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\vec{v}) = S_m \tag{7}$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho\vec{g} + \vec{F} \tag{8}$$

Here p is the static pressure, $\bar{\bar{\tau}}$ is the stress, $\rho\vec{g}$ the gravitational body force, and $\vec{F}$ is the resultant of external body forces.

Fluent Magnetohydronamics module introduces additional terms due to the external magnetic field to the momentum and energy equations. To implement the effect of Lorentz force to the momentum equation, user defined functions are used. Lorentz force is the total force that a particle moving with velocity U is exposed to as a result of an electric field E and magnetic field B. This force provides the fluid to move and is expressed as Equation 9 [36].

$$F = \overrightarrow{g_y}(\sigma\beta)_{nf}(T - T_0) + J \times B \tag{9}$$

By using the magnetic field intensity, characteristic length scale, electrical conductivity and dynamic viscosity of the fluid, Hartmann number is calculated with Equation 10.

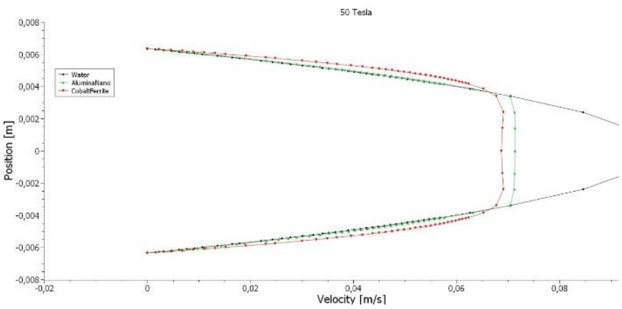
$$\text{Ha} = B_0 L \sqrt{\frac{\sigma}{\mu}} \tag{10}$$

The utilized Hartmann numbers are 25, 50, and 150 in the presented study, corresponding to 50, 100, and 300 Tesla of magnetic fields, respectively.

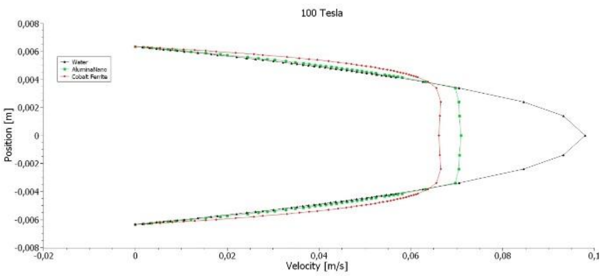
3. RESULTS and DISCUSSION

The effect of the externally induced magnetic field for water, Al_2O_3, and $CoFe_2O_4$ working fluids has been investigated for 50, 100, and 300 Tesla. The concentration rates of the nanofluids are taken as 2% and the flow is assumed to be laminar and steady state throughout the study.

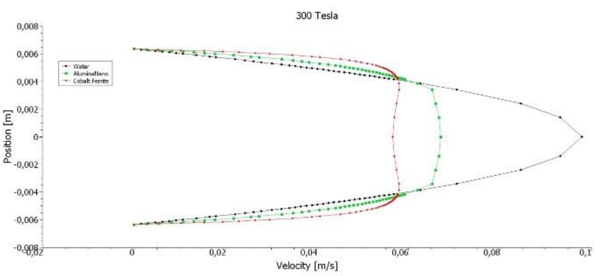
The obtained velocity profiles under 50, 100, and 300 Tesla are presented in Figure 3 (a), (b), (c).



(a)



(b)



(c)

Figure 4. The velocity profiles for (a) 50, (b) 1000, (c)300 Tesla

Figure 4 (a) represents the velocity profiles of the working fluids under a magnetic force of 50 Tesla. The velocity profiles are measured from the mid-plane of the pipe, starting from the top wall moving through the bottom wall. Magnetic field causes the velocity gradient to change, and this variation will be the most distinct in a magnetic working fluid. Cobalt ferrite is a magnetic nanofluid (ferrofluid) having both fluid and magnetic properties [36]. It can be seen from Figure 4 that an applied magnetics force affects cobalt ferrite the most regardless of the magnitude of the applied magnetic field, causing it to reach the smallest maximum velocity among the others. The magnetic field does not have an evident effect on the velocity profile of water, and the effect on alumina is significant although it is not as much as that of cobalt ferrite. In accordance with the results of the study [28], it is seen that the velocity distributions of the nanofluids are significantly negatively affected.

Concerning the shape of the velocity profiles, cobalt ferrite is different from the others by having a "valley" in the neighborhood of the central region. The profile of water shows a sharp behavior in that location, and alumina is more similar to cobalt ferrite. The maximum velocity in the center does not exhibit a "valley", but its increment is stonewalled significantly.

It is clear from Figure 4 that the maximum velocity that alumina and cobalt ferrite reach is decreasing with the increment in magnetic field. In all cases, water has the maximum central velocity, followed by alumina and then cobalt ferrite. In addition, the distinction between the boundary layers is getting more evident as the magnitude of the magnetic force increases. In accordance with the findings of Asirvatham's study [31], it is seen that the magnetic field in outer space cause a significant deterioration in the velocity profiles of the nanofluids, especially in cobalt ferrite as it is a ferrofluid.

The pressure drops along the pipe are presented in Figure 5.

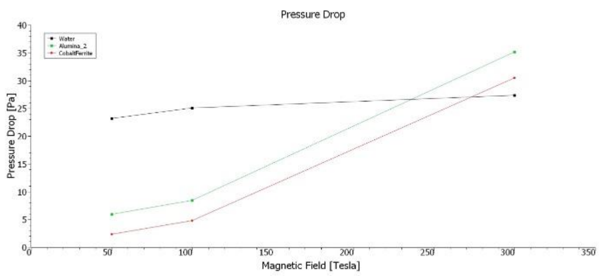
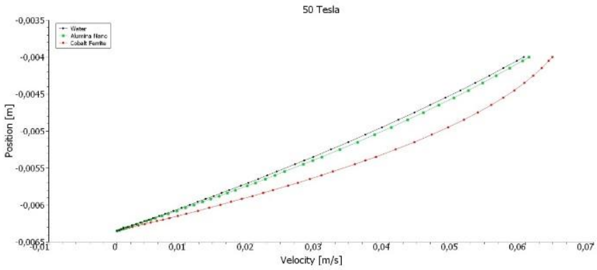


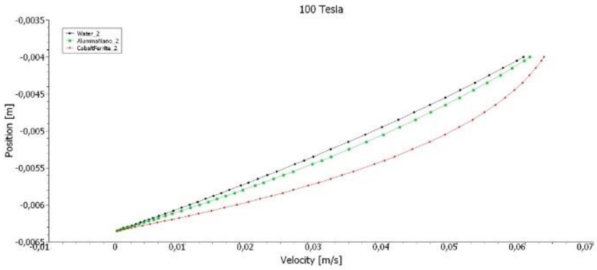
Figure 5. Pressure drops along the pipe

It is clear from Figure 5 that the change in magnetic field does not have a significant effect on the pressure drop of water; the pressure drop values are very close to each other for 50, 100, and 300 Tesla. Contrarily, it has a direct effect on the nanofluids, increasing with the increment in magnetic field. The increment in pressure drop exhibits a drastic behavior as the magnetic field increases. This is an expected result as the differences between the velocity profiles and the maximum velocity values are getting more distinct as the magnitude of the magnetic field increases.

Figure 6 (a), (b), (c) presents the variation of the velocity profiles in the boundary layer region for 50, 100, and 300 Tesla, respectively.



(a)



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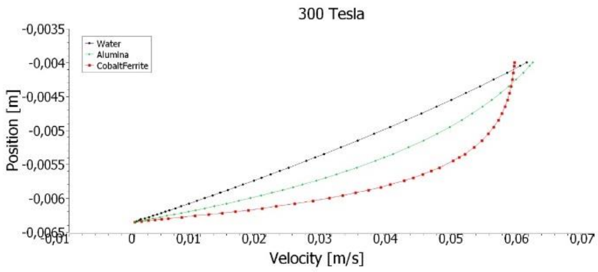


(c)

Figure 6. The variation of velocity profiles in the boundary layer for (a) 50, (b) 100, (c) 300 Tesla

Figure 6 shows the difference between the velocity profiles in the boundary layer region in detail. Cobalt ferrite, which is the most affected working fluid from magnetic field, exhibits a flatter behavior in this region, i.e., it sticks to the wall more strongly. However, water is released from the effects of the boundary layer very earlier, and the velocity starts to increase more significantly even when measured from the near-wall region. The distinction between the velocity profiles is getting clearer with the increment in the magnetic field. Therefore, it can be said that velocity gradients in the near-wall regions increases with increased magnetic field. For the rest, the velocity profile gets flatter in nanofluids, whereas it has no significant effect on water. This stems from the magnetic nature of the cobalt ferrite and the difference between the viscosities.

Figure 7 shows the variation of the velocity profile of alumina with different magnetic fields, and Figure 8 shows that of for cobalt ferrite to make a better comparison.

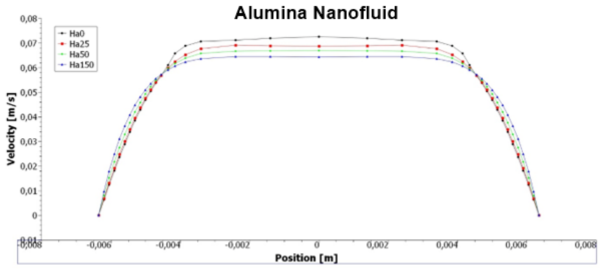


Figure 7. Velocity profiles of alumina nanofluid for 0, 50, 100, and 300 Tesla

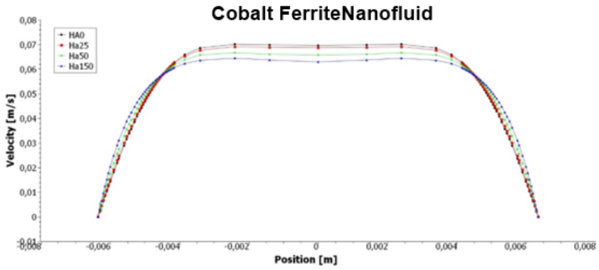
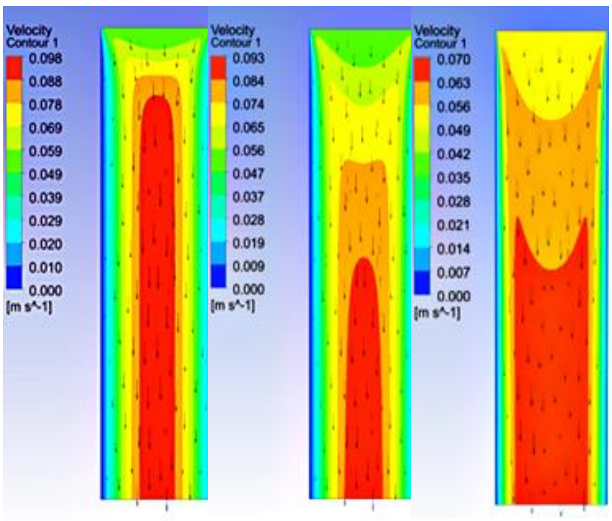


Figure 8. Velocity profiles of cobalt ferrite nanofluid for 0, 50, 100, and 300 Tesla

When Figure 7 and 8 are compared, it can be seen that the velocity profile of cobalt ferrite has a valley at the central region as mentioned previously, reaching a smaller maximum value than alumina. Also, with the increment in magnetic fields, the boundary layer thickness decreases, causing the fluid to stick to the wall more strongly. Hence, a larger magnetic field causes the near-wall velocities to increase and the peak velocity value to decrease. This effect is much more significant in cobalt ferrite.

Figure 9 presents the velocity contours and vectors when magnetic field is 50 Tesla for all of the working fluids.

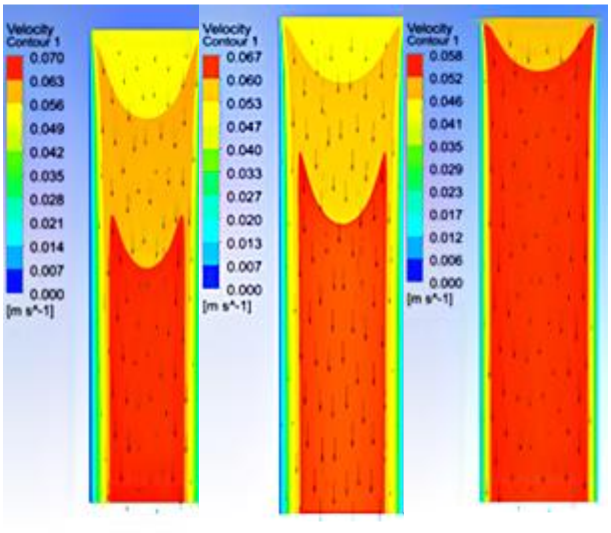


(a) (b) (c)

Figure 9. Velocity contours and vectors for 50 Tesla in (a) distilled water, (b) alumina nanofluid, (c) cobalt ferrite nanofluid

Figure 9 shows that water validates that it reaches the maximum velocity, followed by alumina and cobalt ferrite. It can be seen that the velocity profile is flatter for cobalt ferrite, exhibiting the effect of magnetic field more intensely. The transition behavior between the velocities in water and alumina are similar to each other, whereas cobalt ferrite's is different. It exhibits a behavior such that the fluid is pushed away from the center. Cobalt ferrite has the minimum peak velocity, and also the thickness of boundary layer of cobalt ferrite is the smallest as it is the most affected fluid from an external magnetic field.

Figure 10 shows the comparison between different magnetic fields for cobalt ferrite.



(a) (b) (c)

Figure 10. The velocity contours of cobalt ferrite nanofluid for (a) 50, (b) 100, (c) 300 Tesla

It is clear from Figure 10 that the obtained maximum velocity decreases as the magnetic field intensity increases. Also, it can be seen that the velocity profile in the boundary layer region sticks more strongly to the wall with the increment in magnetic field, i.e., the thickness of the boundary layer decreases as the Hartmann number increases. In addition, the hydrodynamic entrance length of the duct is increases with an increment in Hartmann number. This is because of the Lorentz force, increasing the friction of the boundary layer region, and preventing the development of the flow. Thus, it is obvious that an external magnetic field negatively affects the velocity profile of nanofluids, causing a significant decrement and deterioration in flow characteristics, which eliminates the advantages of the utilization of nanofluids.

NOMENCLATURE

CFD	*Computational Fluid Dynamics*
bf	*Base Fluid*
np	*Nano particle*
ρ	*Density [kg/m^3]*
μ	*Dynamic viscosity [Pa.s]*
C_p	*Specific Heat [J/kg. K]*
σ'	*Electrical Conductivity [1/S]*
B	*Magnetic Field*
E	*Electrical Field*

6. CONCLUSION

The present study investigates the effect of varying magnetic field for water, alumina, and cobalt ferrite flowing in a pipe with a laminar regime. It is concluded that the magnetic field does not have a significant effect on the flow characteristics and velocity profile of water, whereas it causes the flow to slow down apparently for alumina and cobalt ferrite, having a sharper effect on cobalt ferrite as it is a ferrofluid. For alumina and cobalt ferrite, the velocity decreases with an increasing magnetic field intensity. The velocity profile of the cobalt ferrite has a "valley" at the central region whereas alumina shows a flatter distribution. The Lorentz force acting on the fluid has a delaying effect, implying the most drastic effect on cobalt ferrite as expected. Increasing the magnitude of the magnetic field by 2 times causes the velocity of the fluid to decrease by 6% and increasing the magnetic field from 0 to 50 Tesla causes a deceleration rate of 9%. Therefore, it is concluded that application of a magnetic field has a more significant slowing effect when comparing it to increasing the magnetic field. When a magnetic field of 50 Tesla is considered, the maximum velocity of alumina is lower than that of water by 5.10%, and the maximum velocity of cobalt ferrite is lower by 28.57%. Although the utilization purpose of nanofluids in heat pipes is mainly to augment the heat transfer performance, it is seen that with an applied/existing external magnetic field, the flow characteristics and velocity profile of nanofluids are apparently deteriorated, and magnetic nanofluids like cobalt ferrite is affected more compared to non-magnetic nanofluids.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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