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Effects of secondary inlet on heat transfer of the nanofluid flow along the curved elbow: computational study

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Abstract- *The purpose of this article is to inspect the impact of singular magnetic source on the thermal efficiency of a ferrofluid containing* Fe_3O_4 *nanoparticles flowing through an elbow pipe with a junction. The study utilizes comprehensive numerical simulations to analyze the flow stream and temperature distribution, with a particular focus on the role of the generated vortex in enhancing heat transfer along the elbow pipe. The simulations are conducted using computational fluid dynamics techniques to model the flow of the ferrofluid. The thermal analysis considers various magnetic intensities and velocities of the ferrofluid. The obtained data reveals that the vortex created via singular magnetic source contributes to a rise in the average heat transfer along the elbow pipe. Additionally, the study finds that the magnetic intensity plays a more significant role when the inlet velocity of the ferrofluid is lower. Specifically, a 300% increase in the magnetic field results in an approximately 17% improvement in the thermal performance. Overall, this research sheds light on the importance of a non-uniform singular magnetic source in enhancing thermal efficiency in ferrofluids flowing through elbow pipes. The findings highlight the potential for optimizing heat transfer in such systems by controlling magnetic intensity and fluid velocity*.

Keywords: *CFD; Nanofluid; Heat transfer; Magnetic field; Numerical study*

INTRODUCTION

Ferrofluids are colloidal holdups consisting of magnetic nanoparticles suspended in a carrier liquid. These unique fluids exhibit fascinating properties when exposed to magnetic fields, making them a promising candidate for various applications. In the context of heat exchangers, different types of ferrofluids have been explored for their potential in enhancing heat transfer performance and improving thermal management systems [1-3].

Oil-based ferrofluids are the most commonly used type of ferrofluids in heat exchangers. They typically consist of magnetic nanoparticles, such as magnetite (Fe_3O_4) or maghemite (γ-Fe_2O_3), suspended in a carrier oil, such as kerosene or mineral oil [4-6]. Oil-based ferrofluids offer excellent stability, high thermal conductivity, and compatibility with conventional heat transfer fluids. When subjected to a magnetic field, these ferrofluids respond by forming chains or clusters of nanoparticles, thermal performance in heat exchangers is improved [7, 8].

Water-based ferrofluids, as the name suggests, utilize water as the carrier liquid instead of oil. They typically employ iron oxide nanoparticles coated with hydrophilic surfactants to provide stability and prevent agglomeration [9-11]. Water-based ferrofluids offer advantages such as low toxicity, environmental friendliness, and ease of handling. However, their relatively lower thermal conductivity compared to oil-based ferrofluids can limit their heat transfer enhancement capabilities. Nevertheless, ongoing research aims to optimize the properties of water-based ferrofluids for improved heat transfer performance in heat exchangers [12-14].

Hybrid ferrofluids combine the advantages of both oil-based and water-based ferrofluids [15]. These ferrofluids consist of a mixture of oil and water as the carrier liquid, along with magnetic nanoparticles [16]. Hybrid ferrofluids can offer improved thermal stability, enhanced thermal conductivity, and better control over the interfacial behavior between the nanoparticles and the carrier liquid [17, 18]. The unique properties of hybrid ferrofluids make them suitable for specific heat exchanger applications where a balance between thermal performance and other factors, such as stability or compatibility, is required [19-21].

Ionic ferrofluids are a relatively newer class of ferrofluids that exhibit both magnetic and ionic properties [22]. These ferrofluids consist of magnetic nanoparticles suspended in an ionic liquid, which is a salt that exists in a liquid state at or near room temperature. Ionic ferrofluids offer exceptional thermal stability, high electrical conductivity, and unique interfacial properties. The presence of ionic components in these fluids introduces additional mechanisms. As a result, ionic ferrofluids hold potential for advanced heat transfer applications, including heat exchangers [23, 24].

In conclusion, different types of ferrofluids, including oil-based, water-based, hybrid, and ionic ferrofluids, have been explored for their potential in enhancing heat transfer performance in heat exchangers [25, 26]. Each type of ferrofluid possesses unique properties and characteristics that can be tailored to specific heat exchanger requirements. Ongoing research and development efforts aim to optimize the properties and performance of these ferrofluids, opening up new avenues for more efficient and sustainable thermal management systems [27, 28].

The efficient exchange of thermal energy is of paramount importance in various industrial applications [29, 30]. The use of nanofluids has emerged as an intriguing approach to enhance heat transfer performance. Lately, researchers have explored the potential of nanofluids to further improve heat transfer characteristics, particularly in heat exchangers [31].

Magnetic fields have been recognized as a non-intrusive and versatile method for manipulating fluids due to their ability to induce convection and alter fluid flow patterns. When combined with nanofluids, the interaction between magnetic fields and suspended nanoparticles introduces additional mechanisms that can significantly enhance heat transfer efficiency [36].

In this context, it is important to differentiate between homogeny and non-uniform magnetic source. A homogeny magnetic field refers to a field with constant strength and direction throughout the heat exchanger system, whereas a non-homogen magnetic field exhibits spatial variations in strength or direction. Both types can influence the behavior of nanofluids and subsequently impact heat transfer performance [32, 33].

The nanoparticles distributed in the water respond to the magnetic field by reorienting themselves, which alters the thermal conductivity and convective heat transfer properties. This reorientation can lead to improved heat transfer rates, reduced thermal resistance, and enhanced overall performance of heat exchangers [34].

On the other hand, the interaction between nanofluids and non-uniform magnetic fields introduces additional complexities. Non-uniform magnetic fields induce spatial variations in the orientation and concentration of nanoparticles, resulting in non-uniform distribution of heat transfer. Understanding and optimizing the behavior of nanofluids under such conditions are crucial for maximizing the benefits of magnetic field-assisted heat transfer enhancement.

Various experimental and numerical investigations are being conducted to comprehensively understand the underlying mechanisms, and explore potential applications in industries such as energy, electronics cooling, and thermal management.

In this study, we aim to analyze thermal improvement using nanofluids within heat exchangers. By investigating the fundamental principles, exploring the behavior of nanofluids under different magnetic field conditions, and evaluating the performance of heat exchanger designs, we strive to contribute to the advancement of magnetic field-assisted heat transfer enhancement techniques.

Overall, the combination of nanofluids and magnetic fields holds great potential for improving heat transfer efficiency and performance in heat exchangers.

In this article, the hydrodynamics of the nanofluid flow is systematically investigated by CFD for the evaluation of the influences of the magnetic source on the existing ferro particles in the water base fluid. The shape of the investigated model is exhibited in Fig. 1a.

2. Governing equations and applied numerical method

The modeling of the nanofluid flow is simulated by solving Navier-stokes equations since a based fluid (water) is laminar, incompressible and steady. Since the particles with diameter less than 2 nm has no magnetic characteristic. Since its size is too tiny and homogeneity inside the base fluid (water), base water and nanoparticles act like a single fluid and a single phase model is applied for the simulation of the proposed model. The key governing equations of the 2-D stream of nanofluid [5, 26] with declared assumptions are as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\rho_m\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu_m\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+F_K(x) \tag{2}$$

$$\rho_m\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu_m\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+F_K(y) \tag{3}$$

$$\left(\rho_m C_p\right)_m\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k_m\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

These source terms (F_k) are obtained via these formulas:

$$F_K(x)=\mu_0 M\frac{\partial H}{\partial x} \tag{5}$$

$$F_K(y)=\mu_0 M\frac{\partial H}{\partial y} \tag{6}$$

In these equations, the F_K *(x)* and F_K (y) are related to the Kelvin force in x and y direction. By the presence of the magnetic field, these terms are calculated via via following equation:

$$M=\frac{6m_p}{\pi d_p^3}\left[coth(\xi)-\frac{1}{\xi}\right] \tag{7}$$

$$Mn=\frac{\mu_0\chi H_r^2 H^2}{\rho_m\alpha_m^2} \tag{8}$$

In which, α_m, H_r and H are the thermal diffusion coefficient, the constant magnetic transmitter in a vacuum, and distance from the entrance of the pipe, respectively. Table 1 presents the thermo-characteristics of nanofluid flow with 4% volumetric nanoparticles. The nanoparticles in nanofluids are typically very small and have a high surface-to-volume ratio. Due to their small size, the interparticle interactions, such as particle-particle collisions and agglomeration, are assumed to be negligible in dilute suspensions. As a result, the nanoparticles are considered as individual entities that do not significantly affect the overall flow and heat transfer behavior of the nanofluid. Thus, single phase model is reasonable for the modeling of the nanofluid heat transfer.

Table 1. Thermal properties of nanoparticles and base fluid [20]

	$\rho\left(\frac{kg}{m^3}\right)$	$cp\left(\frac{j}{kg.k}\right)$	$k\left(\frac{w}{m.k}\right)$	$\mu\left(\frac{kg}{m.s}\right)$
$Fe_3O_4(p)$	5200	672	6	-
Water (f)	998	4182	0.6	0.001

The applied boundary condition and size of the proposed model is exposed in fig. 1. The location of the wire is in front of inlet 2. There are two inlets and one outlet as demonstrated in Fig. lb. The velocity of inlet nanofluid is presented via Reynolds number in the range of 40-120. The definition of angle variation in the archived results is also demonstrated in Fig. lb.

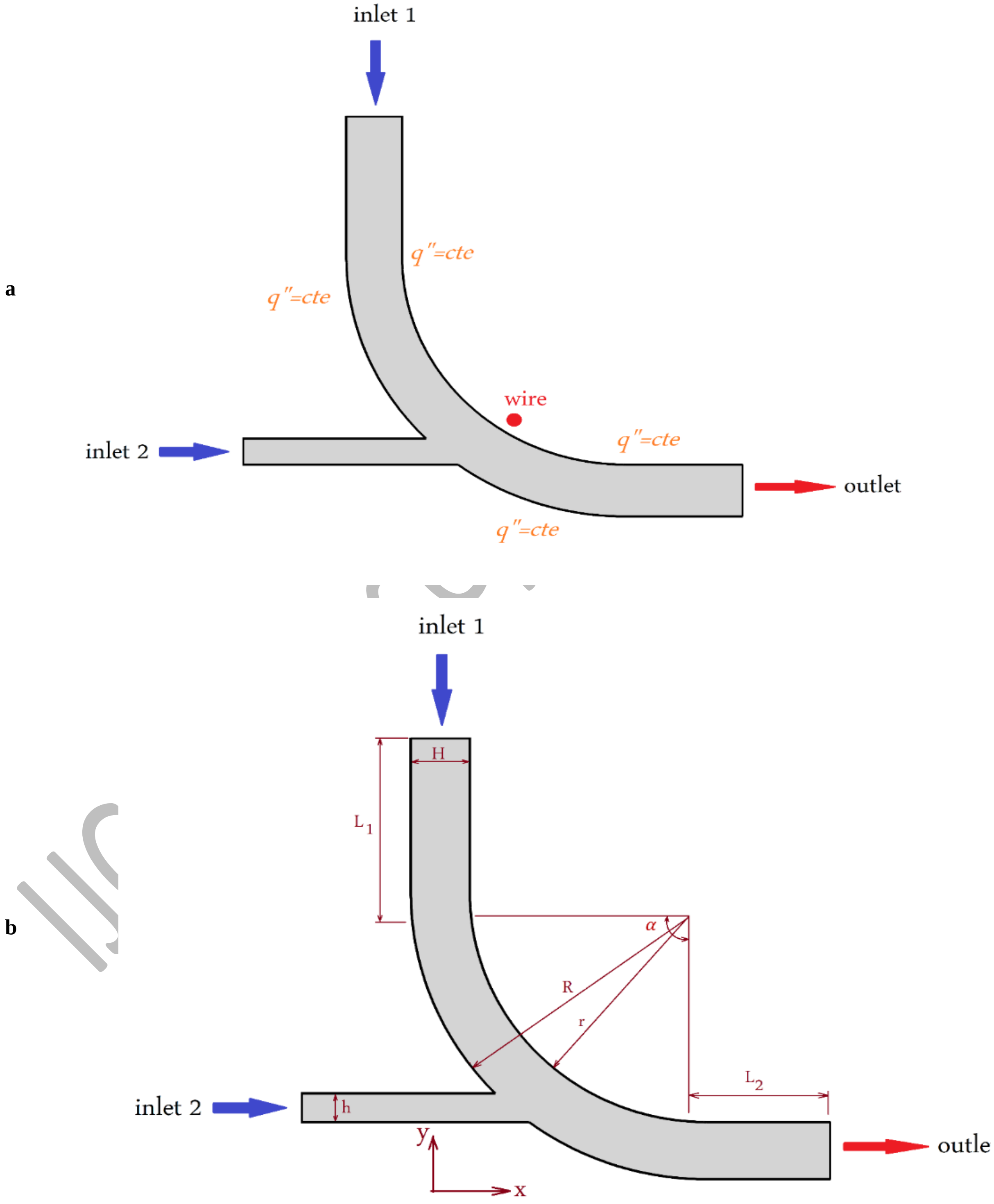


Fig. 1 model descriptions a) boundary condition b) geometry

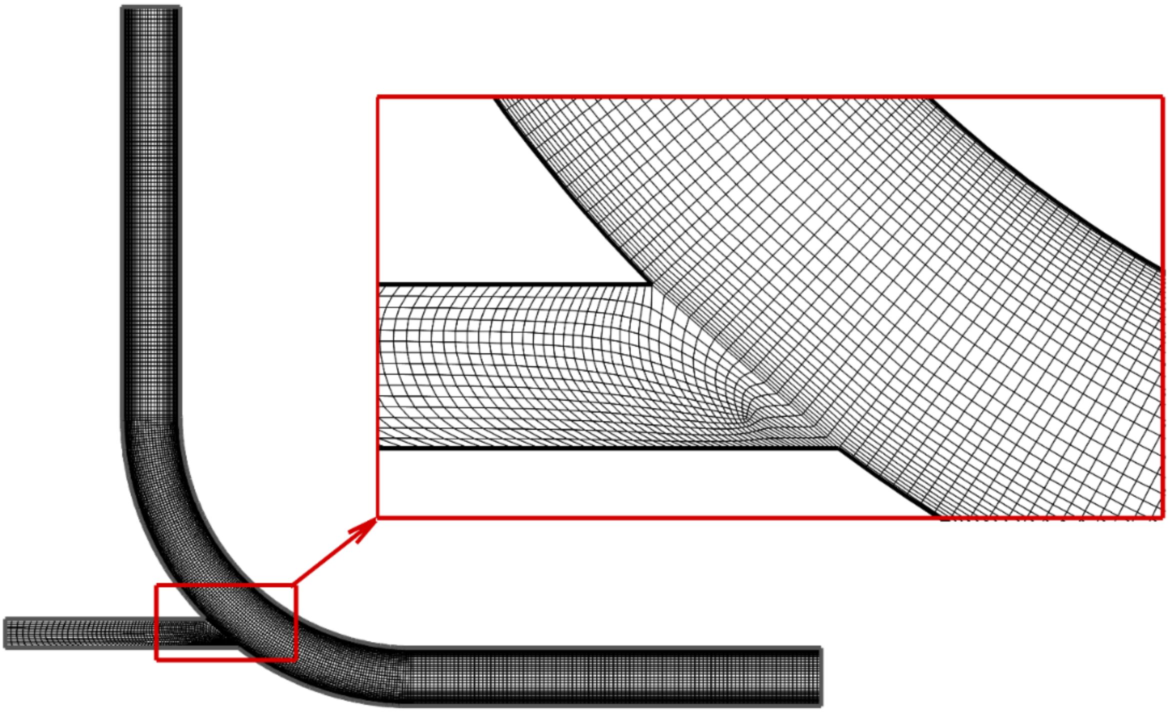


Fig. 2 Grids

Structured grid is generated for the suggested model in which grid resolution is higher near the wall as exhibited in Fig. 2. To attain grid size which is independent of results, non-dimensional temperature variations along the curve of four grids are examined and compared. As verified in Fig. 3, the grid with 26000 cells (100x260) is a reliable grid for our proposed model.

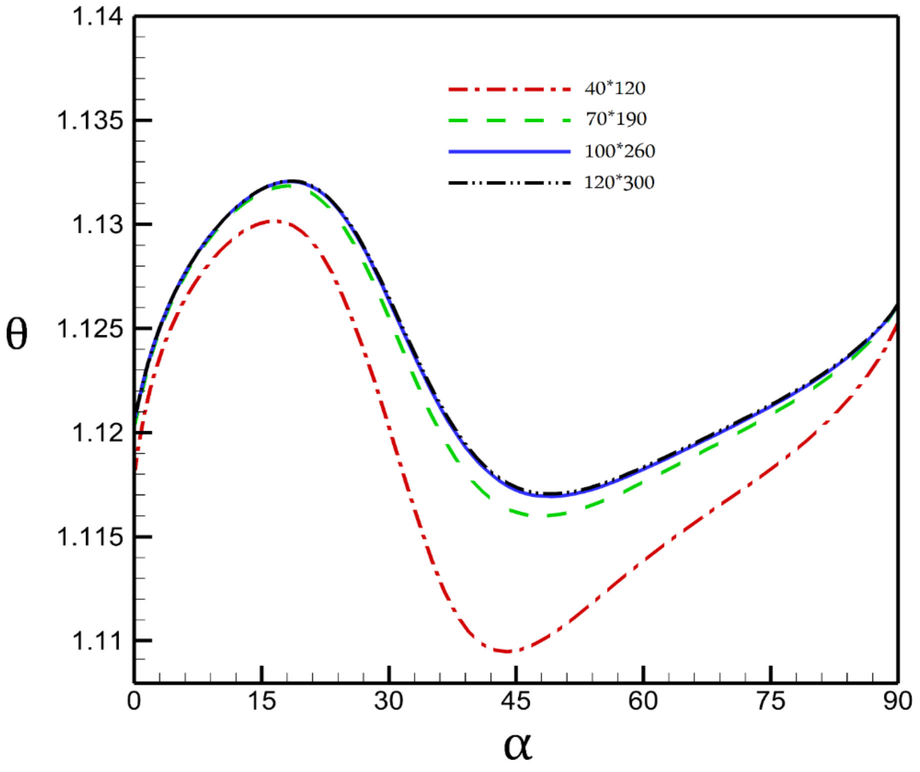


Fig. 3 grid study

3. Results and discussion

The numerical data of Aminfar et al. [35] is applied to validate the applied approach for investigation of the current model. Table 2 presents and compares the validations. The inlet Reynolds number of nanofluid flow for this comparison is 40. Evaluation of this hydrodynamic factor confirms that the chosen methodology is acceptable. In addition, Table 3 presents the validation of this work with experimental results [36]. Theoritical approaches are widely used in various engineering applications [37-41]:

Table 2. Verification of normalized velocity

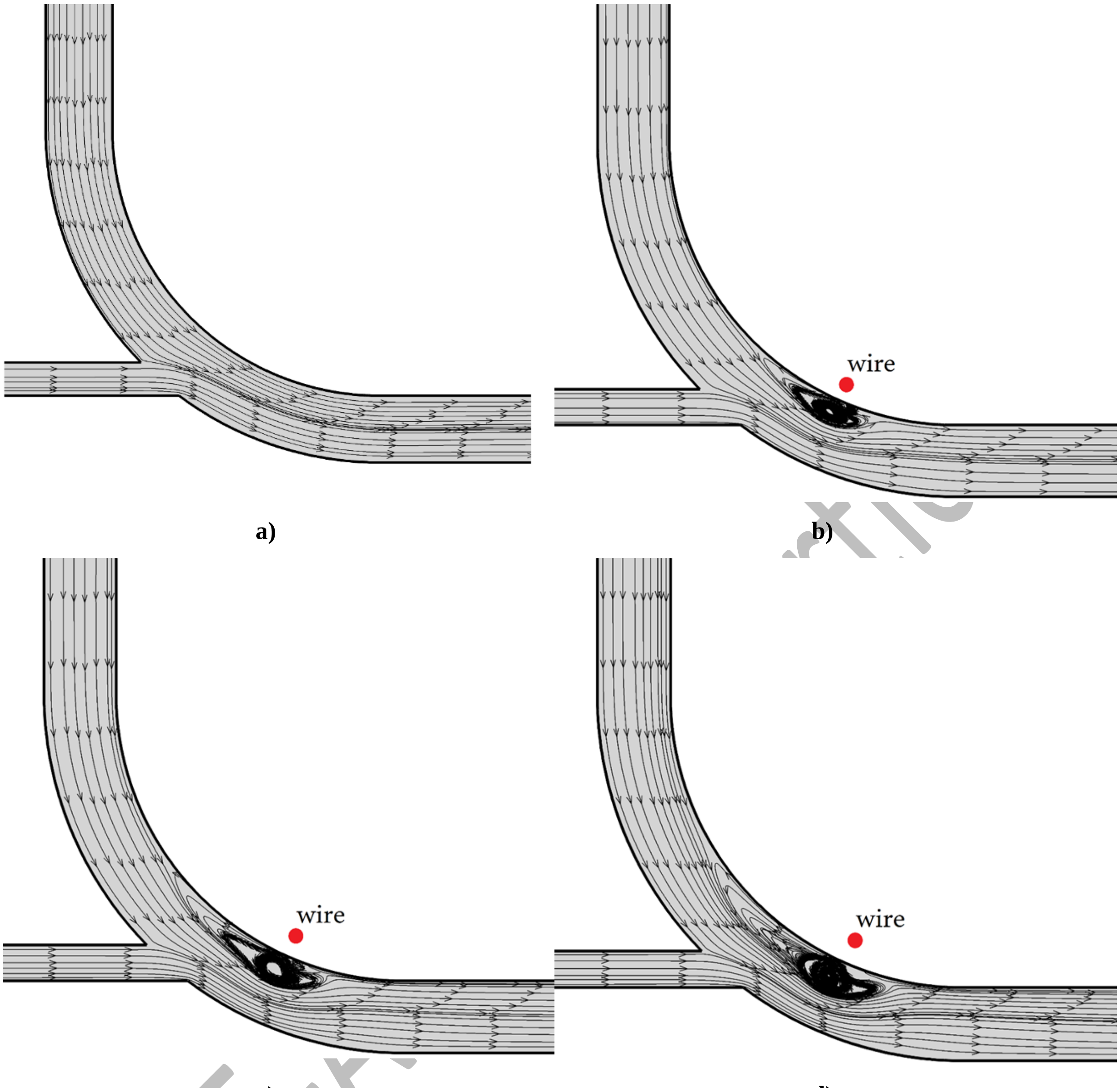
2r/D	Aminfar et al. [35]	Present data
0	1.43	1.41
0.1	1.41	1.40
0.2	1.40	1.40
0.3	1.40	1.38
0.4	1.39	1.35
0.5	1.35	1.30
0.6	1.25	1.20
0.7	1.1	1.06
0.8	1	0.96
0.9	0.4	0.38
1	0	0

Table 3. Validation of achieved Nusselt with experimental

z/D	Khanafer and Vafai [36]	Present data
0	27.1	26.5
25	14.2	13.9
50	8.2	7.9
100	7.1	6.8
125	6.2	6.1
175	5.8	5.7
225	5.5	5.4
275	5.3	5.1
300	5.2	5.0

Comparing velocity profiles between single-phase and two-phase flows can be acceptable and informative under certain circumstances. If the single-phase and two-phase flows are occurring under similar flow conditions, such as the same Reynolds number or similar geometries, fpresence of the second phase affects the flow patterns and velocity gradients. Comparing velocity profiles qualitatively can provide a visual understanding of the flow characteristics. By examining the shape, extent, and asymmetry of the velocity profiles, one can identify differences between single-phase and two-phase flows. This qualitative analysis can reveal the presence of recirculation zones, velocity gradients, and flow patterns associated with the interaction between the phases.

Figure 4 illustrates the stream of nanofluid flow inside the model with/without magnetic source at inlet Reynolds number of 50. In the model without magnetic source, the flow stream is almost laminar without any circulations. As the wire is positioned near the bending curve of the elbow, the circulation is produced near the magnetic source. This is because of the kelvin force which is induced via magnetic field. This force pushes the stream like a block body and consequently, the vortex is produced in this section. Although injection flow pushes this vortex, the power of this vortex is high enough. The circulation region easily expands as the strength of the magnetic field is increased.

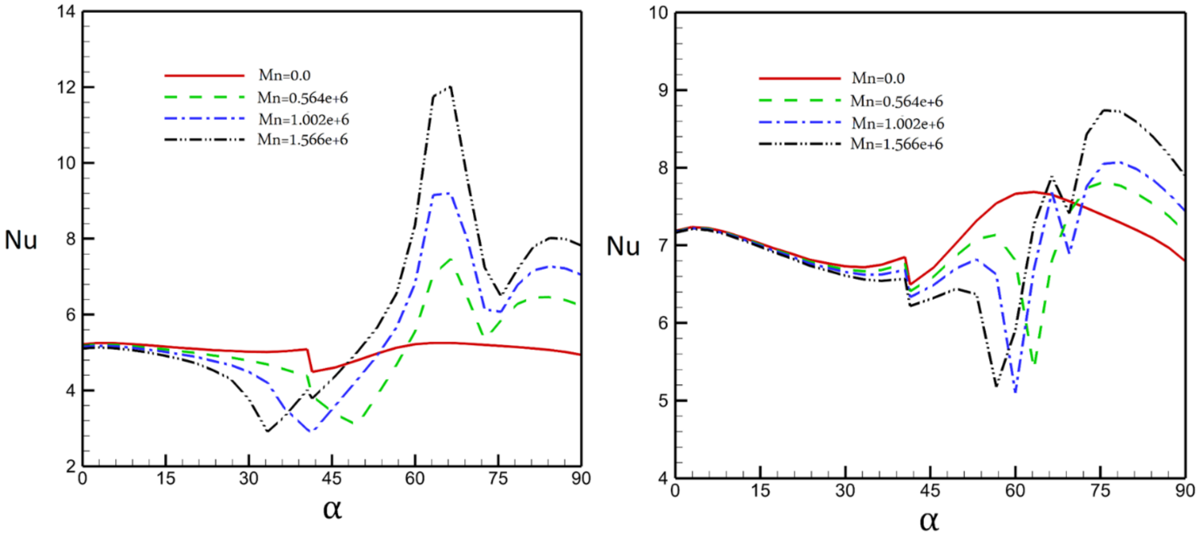


a) b)

c) d)

Fig. 4 Streamline under impacts of **a)** Mn=0 **b)** *Mn=564000* ***c)*** *1002000 d) Mn=1560000*

The change of heat transfers along the curved tube without a magnetic source is displayed in Figure 5. In fig. 5a, the inlet Reynolds number is 50 and the change of Nusselt number shows that the injection in the curve results in a drop at alpha=45 although magnetic source is not applied. In fact, the intensity of this drop in Nusselt number is higher and it moves to a lower angle. After this drop, Nusselt number surges substantially due to vortex formation especially in the model with high magnetic intensity. After circulation, the Nusselt number decreases meaningfully. As the velocity of inlet ferrofluid is increased to Re=150, the impression of the magnetic source on the heat transfer value is not substantial in comparison to the model without magnetic source. In Fig. 6, the impression of the inlet velocity on the thermal characteristic of the curved elbow without magnetic source is displayed. As mentioned before, the drop and rise of the Nusselt number at an angle of 40 degree is associated with the injection of ferrofield from the junction. Comparison of Nusselt numbers for these Reynolds numbers indicates that increasing the inlet velocity has meaningful impacts on the thermal characteristics along the curved elbow pipe with junction.



a) **b)**

Fig. 5 Heat transfer for different magnetic intensities

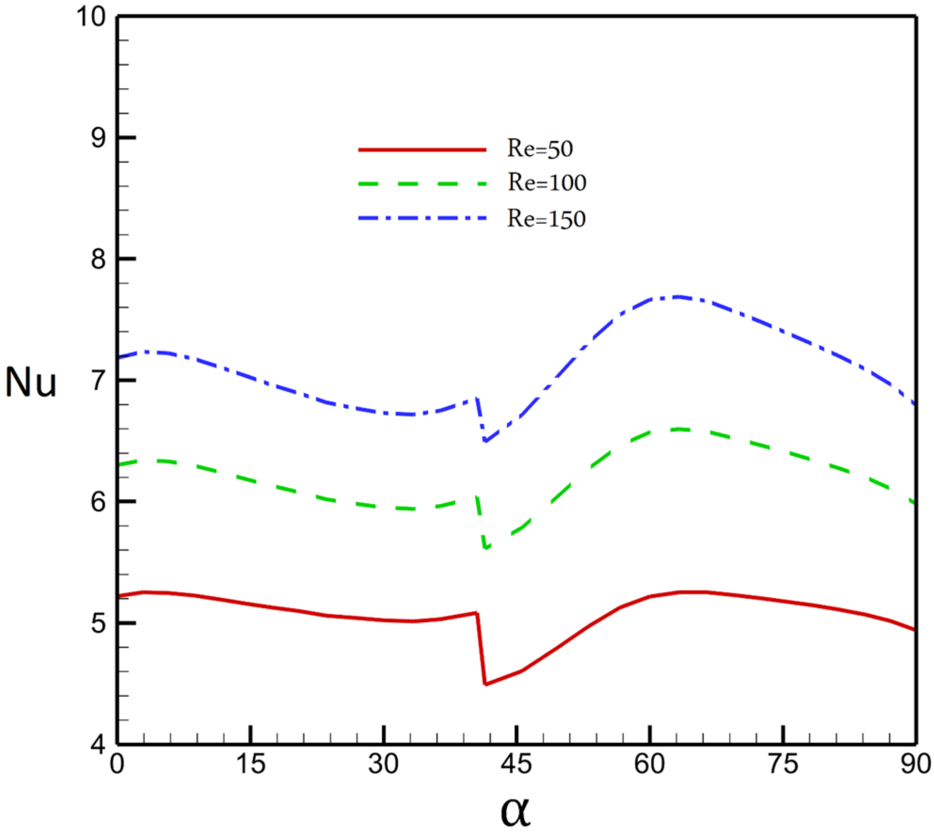
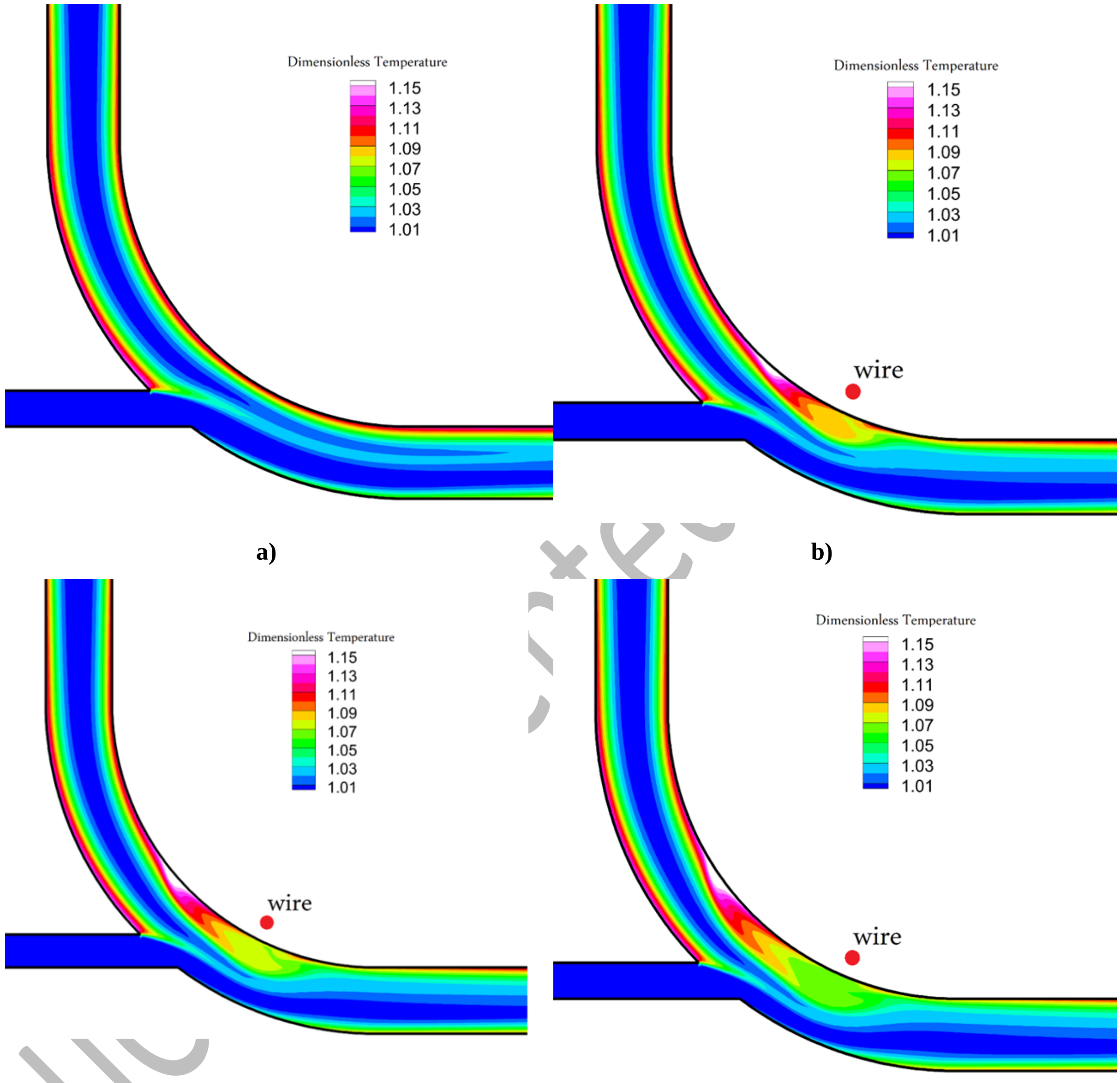


Fig. 6. Nusselt number along the angles

Figure 7 exhibits the temperature contour inside the elbow pipe with junction when different powers of magnetic source are applied near the elbow pipe with junction. In models without a magnetic source, the injection of ferrofluid declines temperature and consequently, the heat rate cuts locally near injection. The role of magnetic source on the temperature contour clearly confirms the penetration of the thermal layer into the mainstream via production of the vortex. As the intensity of the magnetic source is amplified, the expansion of the thermal layer improves.



a) **b)**

c) **d)**

Fig. 7 Temperature contour with intensity of **a)** Mn=0 **b)** *Mn=564000* ***c)*** *1002000 d) Mn=1560000*

The total heat transfer along the junction is crucial for the thermal evaluation. In this section, heat transfer improvement of the elbow pipe with secondary inlet is investigated in different magnetic intensities. Hence, the impacts of three magnetic intensities **(***Mn=564000***,** *Mn=1002000 and Mn=1560000)* on thermal efficiency of proposed configuration are compared. Figure 8 plots the change of average Nusselt number along the curved pipe for four diverse strengths of magnetic source intensity. It was expected to attain a higher average Nusselt number when the magnetic source is increased. A 300%

increase in the magnetic field increases the average heat transfer along the pipe by about 17 %. In fact, this low enhancement of the heat transfer may have related to the junction ferro flow mentioned in the previous paragraph.

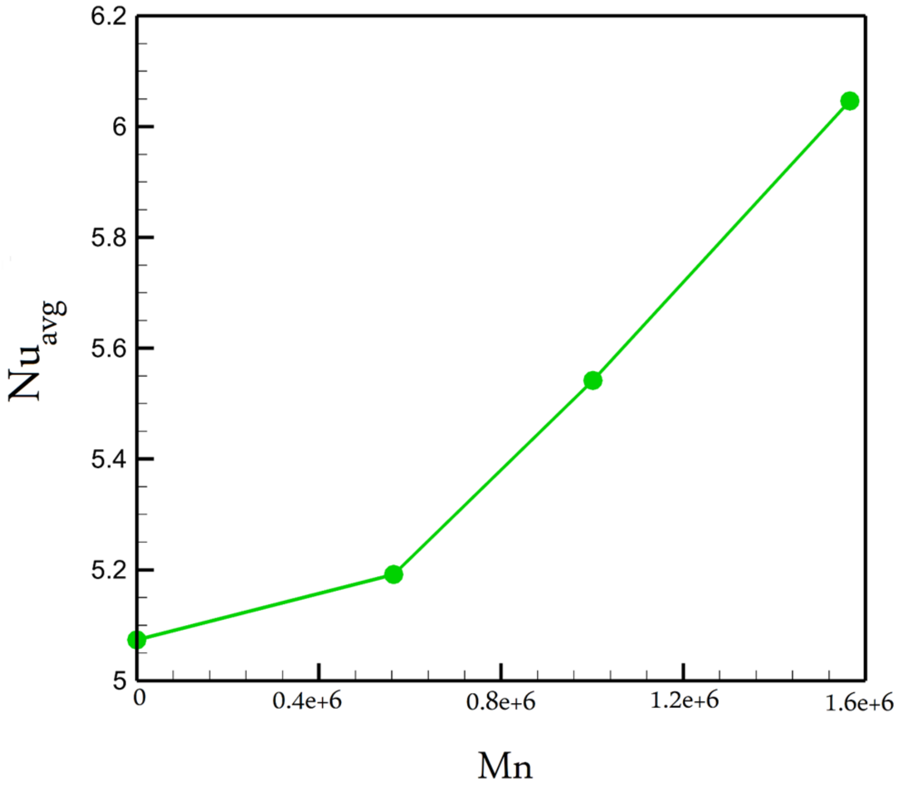


Fig. 8 variation of the Nusselt number

4. Conclusion

The chief concentration of this article is the analysis of the flow stream of a ferrofluid inside the elbow pipe under various magnetic intensities. The objective is to understand the system of heat transfer along the pipe by examining temperature contours and the vortex generated by the non-homogen magnetic field.

The results of this study reveal that the presence of a vortex initially decreases heat transfer, but as the thermal layer expands, heat transfer is subsequently enhanced. This phenomenon is observed by analyzing the change in heat transfer on the pipe wall at different angles.

Furthermore, the study demonstrates that the average heat transfer of the elbow pipe can be improved by approximately 17% as the magnetic source intensity is amplified from Mn = 0.564 x 10^6 to Mn = 1.566 x 10^6. This highlights the significant impression of magnetic intensity on thermal enhancement in the system.

Overall, these achievements pay a regular contribution to a better appreciative of the thermal behavior of ferrofluids flowing through curved elbow pipes with non-uniform magnetic fields. The results emphasize the potential for heightening heat transfer in such systems by controlling the magnetic intensity. Further research in this area can focus on exploring additional parameters and optimizing the design of magnetic sources to maximize heat transfer efficiency.

Acknowledgments

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Nomenclature

Latin symbols

E	Energy
F	force vector
g	standard gravity
h	Enthalpy, heat transfer coefficient
H	distance
Hr	constant magnetic transmitter in a vacuum
k	conductive coefficient
P	pressure
Q	Heat transfer
S	mass source term
T	temperature
t	time
v	velocity
V	volume
x,y,z	Cartesian coordinates

Greek symbols

α_m	thermal diffusion coefficient

ξ	zeta potential
μ	effective viscosity
ρ	mass density
χ	electric susceptibility of medium

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