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Enhancing heat transfer performance in elliptical tubes with nano fluids: A numerical case study

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ABSTRACT
This study focuses on investigating the thermal performance of elliptical tubes in heat transfer applications with three different working fluids, namely water, CuO-water nano fluid, and Al_2O_3-water nano fluid. The research emphasizes the role of channel cross-sectional geometry and the utilization of nano fluids in enhancing heat transfer for four different elliptical aspect ratios with the same hydraulic diameter. To ensure fully developed hydrodynamic flow conditions and eliminate pipe outlet effects, a test section for flow analysis was identified at the midsection of the designed pipe geometry. Numerical simulations were conducted using ANSYS 2020 R2 commercial software for low Reynolds numbers, which yield laminar flow, to analyze the impact of the elliptical cross-sectional geometry and heat transfer characteristics on the flow. The effects of nano fluids and the use of elliptical pipes on heat transfer were validated against empirical formulas based on Nusselt numbers. The results indicate that nano fluids exhibit superior heat transfer performance compared to water across all elliptical aspect ratios investigated. Although the best thermal performance belongs to the CuO nanoparticle fluid, it was understood that the use of Al_2O_3 fluid would also be beneficial due to its accessibility and being more economical. Moreover, it was determined that increasing the ellipticity under the specified flow conditions improved the heat transfer efficiency. Overall, this research provides a comprehensive analysis of the interaction between channel geometry, nano fluid selection, and heat transfer performance, offering valuable insights for designing more effective heat transfer systems in various engineering applications.

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1. Introduction

Passive heat transfer enhancement studies are utilized due to their advantages such as simple configurations and direct applicability and they are constantly being developed. Improvements in pipe, tube, and channel flows are generally achieved through changes in flow geometry or fluid type [1–3]. When considering system design and device arrangement for heat transfer applications in such pipe flows, better heat transfer is expected alongside the arrangement and design of the system. These arrangements can provide significant advantages in heat exchanger applications where thermal improvements are intended [4–6]. For instance, in heating devices that require the use of wide volumes horizontally and narrow volumes vertically, compact designs would be prioritized [7,8]. Elliptical or flattened tube designs enhance compactness in heat transfer devices. Additionally, with such arrangements, heat transfer rate can be increased. Flattened tubes have

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better properties in terms of noise and vibration effects. On the other hand, the presence of nano particles in the fluid enhances the effective thermal conductivity of the fluid, thus improving its heat transfer properties [9,10]. Moreover, the parameters influencing heat transfer in fluid flow are elaborately discussed in various studies conducted by Lu *et al.*, [11–14].

Nano fluid applications have various applications ranging from solar devices to heat exchangers, boilers, turbo machinery, and cooling of electronic devices. In addition to a good systemic design, acceptable heat transfer performance is also expected. Expectations of certain applications where channel flow is organized are taken into account in such designs. Some researchers [15–17] numerically examined the heat transfer performance of CuO and Al_2O_3 nano particles in ethylene glycol and water mixture flowing through horizontal flat tubes under laminar flow conditions. The results of these studies showed a significant improvement in heat transfer coefficient along the tube in the developed and developing flow regions compared to the base fluid condition in the presence of nano fluid. Furthermore, an increase in nano particle volume fraction led to an increase in average friction factor and convective heat transfer coefficient. In a study on nano fluid applications in an automotive radiator, Peyghambarzadeh [18] demonstrated that increasing the flow circulation rate enhances heat transfer performance, despite the transient effect of inlet flow temperature, ultimately revealing that low concentrations of Al_2O_3 nanoparticles in water can improve heat transfer efficiency by up to 45% compared to pure water. Razi *et al.*, [19] examined the pressure drop and heat transfer in *CuO/Oil* nano fluid flow through flattened horizontal tubes under laminar fixed heat flux conditions. The study results demonstrated higher pressure drop and higher heat transfer coefficient compared to the base fluid. In an experimental study by When and Ding [20] on laminar flow (through a straight copper tube) with Al_2O_3 nano particles dispersed in ionized water, it was reported that an increase in nano particle concentration led to an enhancement in heat transfer, and the increase in boundary layer thickness was suggested as the reason for this improvement. Shariat and colleagues [21] performed a numerical investigation of nano fluid flow using a two-phase mixture model within a horizontal elliptical tube, revealing that an increase in nanoparticle content under fixed heat flux boundary conditions enhanced heat transfer at a constant Reynolds number, but also resulted in increased pressure drop and surface tension in laminar flow. In another study where a fixed heat flux boundary condition was applied, Dawood *et al.*, [22] investigated the flow of nano fluid within an elliptical ring. They evaluated the contributions of four different types of nano particles with different sizes in heat transfer. Numerically, it was stated that the glycerine-based nano fluid with SiO_2 nano particles exhibited the best thermal performance among the studied fluids. Nadeem and Hussein [23] numerically examined the effect of heat transfer in the flow of TiO_2 nano particle-laden nano fluid through an elliptical tube with turbulent flow, where water was the base fluid. Improved heat transfer was observed compared to pure water, with rising Reynolds numbers and nano fluid volume concentrations between 0.25% and 1% leading to increased Nusselt numbers, while smaller nanoparticle sizes further enhanced heat transfer. Guo *et al.*, [24] conducted a numerical study on the impact of a centrally placed twisted tape in laminar flow within a circular straight tube, finding that an optimal central gap could enhance thermohydraulic performance, potentially achieving thermal improvements of up to 20%, thus highlighting the effectiveness of using central tapes as a promising technique. Vaezi *et al.*, [25] examined the impact of aspect ratio on heat transfer performance in alternating oval double pipe heat exchangers through numerical simulations, demonstrating that alternating oval tubes significantly enhance heat transfer compared to circular tubes, particularly at higher Reynolds numbers, and introducing the enhancement ratio (ER) as a measure of design effectiveness, with optimal aspect ratios varying according to Reynolds number. The study confirms previous findings by Tang *et al.*, [26] regarding the benefits and tradeoffs of using alternating oval tubes for heat transfer enhancement. Furthermore, Huminic and Huminic [27] investigated the thermal performance of nano fluid flow in a flattened tube under a fixed heat flux boundary condition and laminar flow regime in a three-dimensional manner. The study results indicated that increasing concentrations of *CuO* nano particles in ethylene glycol enhanced the heat transfer coefficient. Hussein *et al.*, [28] researched investigates the impact of aspect ratio on heat transfer enhancement in alternating oval double pipe heat exchangers. Numerical simulations show that alternating oval tubes significantly improve heat transfer compared to circular tubes, especially at higher Reynolds numbers. However, the study also highlights the tradeoff between heat transfer enhancement and increased pressure drop.

Experimental and numerical studies on the flow of nano fluids in elliptical tubes are limited. Therefore, the aim of this study is to investigate the thermal performance of nano fluids in elliptical tubes that can be used in horizontal oriented heat transfer applications including heat exchanger [6,29]. This study investigates the potential of elliptical tubes for heat transfer applications in narrow cross-sectional areas, a critical aspect for contemporary trends in smart geometry and small device technologies, while evaluating their performance in comparison to circular pipes. The effect of elliptical tubes on heat transfer performance, considering hydraulic diameter, was examined alongside the use of various nano fluids. Two different nano fluids, CuO-water and Al_2O_3-water, were included in the analysis as they represent some of the most extensively studied fluids in the literature, highlighting the thermal effects of both expensive (CuO) and relatively cost-effective (Al_2O_3) nanoparticles based on their intended applications. Some previous researches [30–32] underscore the significant role of both duct geometry and nano fluid utilization in enhancing heat transfer across diverse applications. Specifically, non-circular geometries, such as alternating oval tubes, have been shown to significantly improve heat transfer performance compared to traditional circular ducts, especially at higher Reynolds numbers, although this enhancement often leads to increased pressure drop. The introduction of nano fluids -engineered suspensions of nanoparticles in base fluids- offers a promising approach to further boost heat transfer by enhancing thermal conductivity and other thermophysical properties. Ultimately, the optimal combination of duct geometry and nano fluid selection must align with specific application requirements and operational conditions, contributing valuable insights to the growing body of knowledge aimed at developing more efficient and effective heat transfer systems in various engineering applications.

2. Materials and method

2.1. Physical model

For straight pipe flow, the inlet and outlet regions may have a significant impact on the flow depending on the flow length. In standard pipe flow, it is generally assumed that there are fully developed flow conditions hydrodynamically. This assumption may lead to some variation between numerical and experimental calculations. In experimental analyses, the assumed conditions are relevant primarily when assessing the flow along the pipe. In cases where inlet and outlet conditions are directly considered, it is imperative to evaluate measurements and calculations independently. For instance, the imposition of a constant heat flux at the inlet section has a substantial impact on the heat transfer capacity of the flow within the pipe. In this study, the elliptical effect of the cross-sectional geometry was examined for pipe flow with a fixed heat flux (q'') boundary condition applied on the walls (Figure 1). The working fluid (water or nano fluids) enters the pipe through the inlet at a constant velocity (u) and standard water temperature of 20°C. After passing through the entrance section where hydrodynamic fully developed flow conditions are provided, it is subjected to constant heat flux boundary condition in the designated test zone. After the test zone, it passes through the exit section and completes the fluid flow. In the flow calculations, the changes in the inlet and outlet sections of the test zone are included in the calculations. The same process is repeated for all runs by changing the velocity conditions in

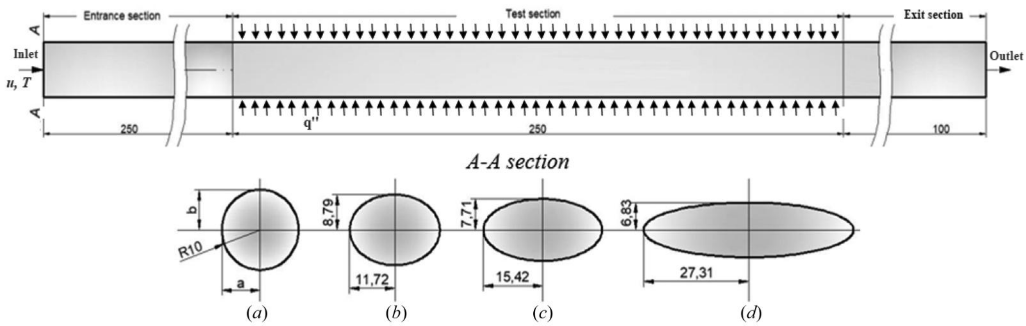

Figure 1. Pipe design for analysis.

accordance with the Re numbers in the range of 25-125. Initially, the entrance region, which was not included in the calculation to minimize the entrance effects, was determined to be longer than the calculated fully developed flow region length.

The middle portion where fully developed flow conditions occur was defined as the test section. The channel dimensions and related sections were provided in the figure. Using circular cross-sectional flow (standard straight pipe flow) as a reference, channel geometries were modeled for three different elliptical sections based on the elliptical degree of the section (Section A-A). As can be seen from Figure 1, three different elliptical sections were obtained by changing the horizontal (a) and vertical (b) radii of the ellipse while keeping the hydraulic diameter constant. In this context, the ratio of a/b defines the ellipticity of the pipe cross-section. This configuration has been established to facilitate the specification of heat transfer capabilities for various applications, including flat heat exchangers, cassette-type electronic cooling systems, and heating boilers, where the use of elliptical cross-section pipes is essential as opposed to conventional cylindrical pipes. The widest pipe cross-section with equivalent hydraulic diameters is for the fully cylindrical pipe, while the narrowest cross-section is for the cross-section arrangement with a/b ratio of 0.25.

The values obtained for the section using the selected radii and the resulting analysis cases using the Ramanujan approximation are presented in Table 1.

L_h=0.005.*100*.0,020 = 0.1 m = 100 mm (hydrodynamic entrance length =250 mm is enought for $0 < Re < 250$ [33]. For $L_{thermal}$, no need to determine a length because it is changeable in test section. Similar to the entrance section, it is also possible that the exit conditions may slightly disturb the flow in the test section. It was seen from the analysis that this disturbance can affect a region up to the length of the hydraulic diameter. Therefore, a length five times the diameter was defined as the exit section to guarantee the stability of the flow conditions in the test zone for all defined flow rates. Hydrodynamic diameter proposed by Ramanujan Approximation and Re, Nu and f proposed by Deeb and Sidenkov are defined as follows [34,35]:

Hydraulic diameter;

$$D_h = \frac{4A_c}{P} \tag{1}$$

Reynold number:

$$Re = \frac{u_m D_h}{\vartheta} = \frac{\rho u_m D_h}{\mu} \tag{2}$$

Nusselt number:

$$Nu = \frac{hD_h}{k} \tag{3}$$

f : friction factor (or Darcy friction factor); u_m : *mean velocity*

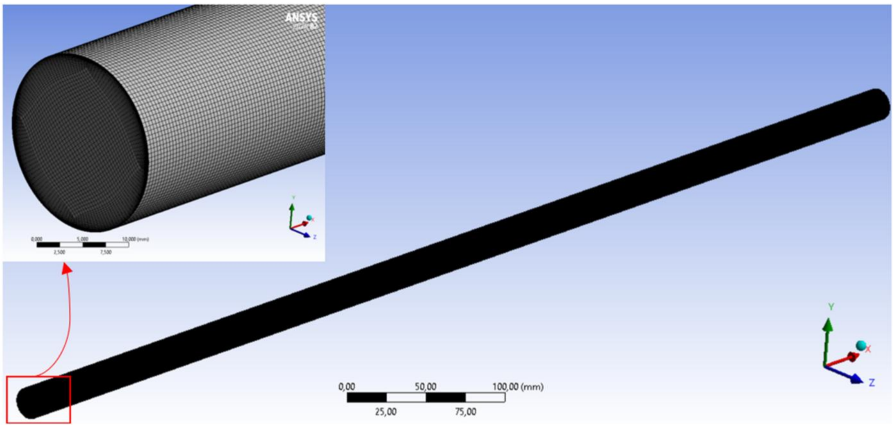

Figure 2. Mesh detail.

Table 1. Elliptical arrangement for hydraulic diameter.

	a	b	P	A	D_h	b/a
Case 1	10	10	62.8318530718	314.1592654	20	1
Case 2	11.72629	8.7947175	64.7979897723	323.9905901	20.00003959	0.75
Case 3	15.41969	7.709845	74.6964340369	373.4832784	20.00005935	0.5
Case 4	27.306	6.8265	117.1211632	585.6067219	20.00003094	0.25

C_f : friction coefficient (Fanning friction factor); μ : *dynamic viscosity*

$$C_f = \tau_s\left(\frac{\rho u_m^2}{2}\right) = \frac{f}{4} \quad (4)$$

Circular tube, laminar flow:

$$f = \frac{8\tau}{\rho u_m^2}, f = \frac{64\mu}{\rho D u_m} = \frac{64}{Re} \quad (5)$$

2.2. Governing equations

Determining the flow of fluids is a critical aspect of studying fluid dynamics and various engineering applications. Fluid flow analysis involves the examination of how liquids or gases move through different mediums, such as pipes, channels, or vessels. One essential parameter in fluid dynamics is viscosity, which characterizes a fluid's resistance to deformation. The viscosity of a fluid plays a significant role in determining the fluid flow behavior, such as laminar or turbulent flow. Understanding these flow characteristics is essential for designing efficient systems and predicting the performance of various engineering processes. Several formulas and equations have been developed to calculate and analyze fluid flow, providing engineers and researchers with valuable tools to optimize processes and ensure the reliable operation of fluid systems [36,37].

$$\rho_{nf} = \phi\rho_p + (1 - \phi)\rho_w \quad (6)$$

$$(\rho C_p)_{nf} = \phi(\rho C_p)_p + (1 - \phi)(\rho C_p)_w \quad (7)$$

$$\mu_{nf} = (1 + 2,5\phi)\mu_w \quad (8)$$

$$k_{nf} = \frac{k_p + 2k_w - 2\phi(k_w - k_p)}{k_p + 2k_w + \phi(k_w - k_p)}\ k_w \tag{9}$$

Non-Newtonian behavior and particle precipitation in nanofluid flow are prevalent challenges in various applications which includes detailed investigations, including particle behavior, and ongoing efforts are being made to mitigate these issues [38–40]. Given that all enhancements are focused on achieving stable and continuous flow conditions, it is evident that numerical flow modeling will play a significant role in addressing these challenges effectively. It is anticipated that these challenges will be further addressed, with particular consideration given to the environmental impact of nanofluid production and utilization.The problem considered is assumed to be three-dimensional, laminar, fully developed and continuous flow conditions. The flow is assumed to be a Newtonian fluid flow and the fluid thermophysical properties are assumed to be unchanged. The equations of continuity, momentum and energy in tensor form for 3D fluid flow in the channel are as follows [41,42];

Continuity equation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{10}$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{11}$$

Energy equation:

$$\frac{\partial}{\partial x_j}\left(\rho u_j C_p T - k\frac{\partial T}{\partial x_j}\right) = 0 \tag{12}$$

At the pipe inlet, constant velocity (velocity inlet) and temperature (constant temperature inlet) conditions are defined. In the test zone, fully developed flow velocity and temperature profiles are specified as given in Equations. At the exit of the test region, the pressure outlet condition is used. No-slip conditions are applied on the walls along the tube. In systems involving fluid-to-fluid or solid-to-fluid heat transfer, the flow characteristics of the target fluid significantly impact the overall performance of the system. Consequently, employing constant temperature and constant heat flux boundary conditions at the walls of pipes or ducts is essential for practical applications. Therefore, a constant heat flux is imposed on the tube wall in the test section. A constant heat flux condition is imposed on the tube wall in the test section.

$$u_m = -\frac{R^2}{8\mu}\left(\frac{dP}{dx}\right), u(r) = 2u_m\left(1 - \left(\frac{r^2}{R^2}\right)\right) \tag{13}$$

$$\Delta P = \frac{32\mu L u_m}{D^2}, \Delta P = f\frac{L}{D}\frac{\mu u_m^2}{2} \tag{14}$$

Shah equation for laminar pipe flow can be used to verify results in numerical calculations [22]:

$$Nu = \left\{\begin{array}{ll} 1,953\left(RePr\frac{D_h}{x}\right)^{1/3} & \left(RePr\frac{D_h}{x}\right) \geq 33,3 \\ 4,364 + 0,0722\,RePr\frac{D_h}{x} & \left(RePr\frac{D_h}{x}\right) < 33,3 \end{array}\right\} \tag{15}$$

Here, Nu represents the Nusselt number, Re signifies the Reynolds number, and Pr denotes the Prandtl number, all of which are dimensionless parameters. The thermo-physical properties of the fluids used vary depending on the temperature and, for nano fluids, the nanoparticle type and volumetric concentration. Table 2 shows the properties of the working fluids used in the analysis.

3. Results and discussion

3.1. Numerical procedures

In numerical computations, it is crucial to accurately determine convergence intervals for simulations. Additionally, selecting the most suitable solution model and computational settings is essential for ensuring the problem and its resolution yield accurate results. Throughout this study, results obtained from simulations where convergence levels lower than 10^{-6} were achieved have been considered. The utilization of a double-precision solver, Hybrid Initialization, and the SIMPLE solution method has been employed. Additionally, the laminar model with the enhanced wall processing function was used to solve the corresponding equation set. This model improves the ability to model strained flows, vortices, separation, and fluid recirculation. The solver has enabled the calculation of velocity, pressure, and temperature components across the entire computational domain of the elliptical tube [44]. At the inlet of the pipe, conditions of constant velocity (velocity inlet) and temperature (constant temperature inlet) are specified. Within the test zone, fully developed flow velocity and temperature profiles are defined based on given equations. Pressure outlet conditions are applied at the exit of the test region, while no-slip conditions are enforced on the tube walls. Furthermore, a constant heat flux is applied to the tube wall within the test section.

3.2. Grid independent test and model validation

After accurately defining computation methods, it is imperative that the results are not significantly influenced by the chosen number of cells. While a higher number of cells may often lead to achieving more precise values, determining the most appropriate cell count is more meaningful. Conducting simulations with the minimum meaningful number of cells—respective to saving computer memory and time for solutions—and adhering to this determined cell count is the correct approach. Such an approach has been adopted in this study as well. A grid-independent shown in Table 3 was conducted for five mesh cases (877,000, 1,251,000, 1,940,000, 2,758,000, and 6,554,000) at Re = 100. When considering the values calculated for Nu and F, changes that

Table 2. Properties of work fluids [43].

Properties	μ [kg/ms]	ρ [kg/m^3]	k [W/mC]	C_p (kJ/kgC]	Pr
Water	0.001003	998.2	0.6070	3412	5.85
CuO-water (3% vol. cons.)	0.001390	1129.69	0.7182	3580	5.80
Al_2O_3-water (3% vol. cons.)	0.001390	1181.05	0.7189	3421	5.76

Table 3. Mesh independence test.

Cell numbers.10^3	Nu	%	f	%
877	5.70608	–	0.500677	–
1251	5.56378	0.0249383	0.501068	0.000779
1940	5.36124	0.0364033	0.502312	0.002478
2758	5.34419	0.0031787	0.502288	−0.000048
6554	5.33359	0.0019850	0.502246	−0.000083

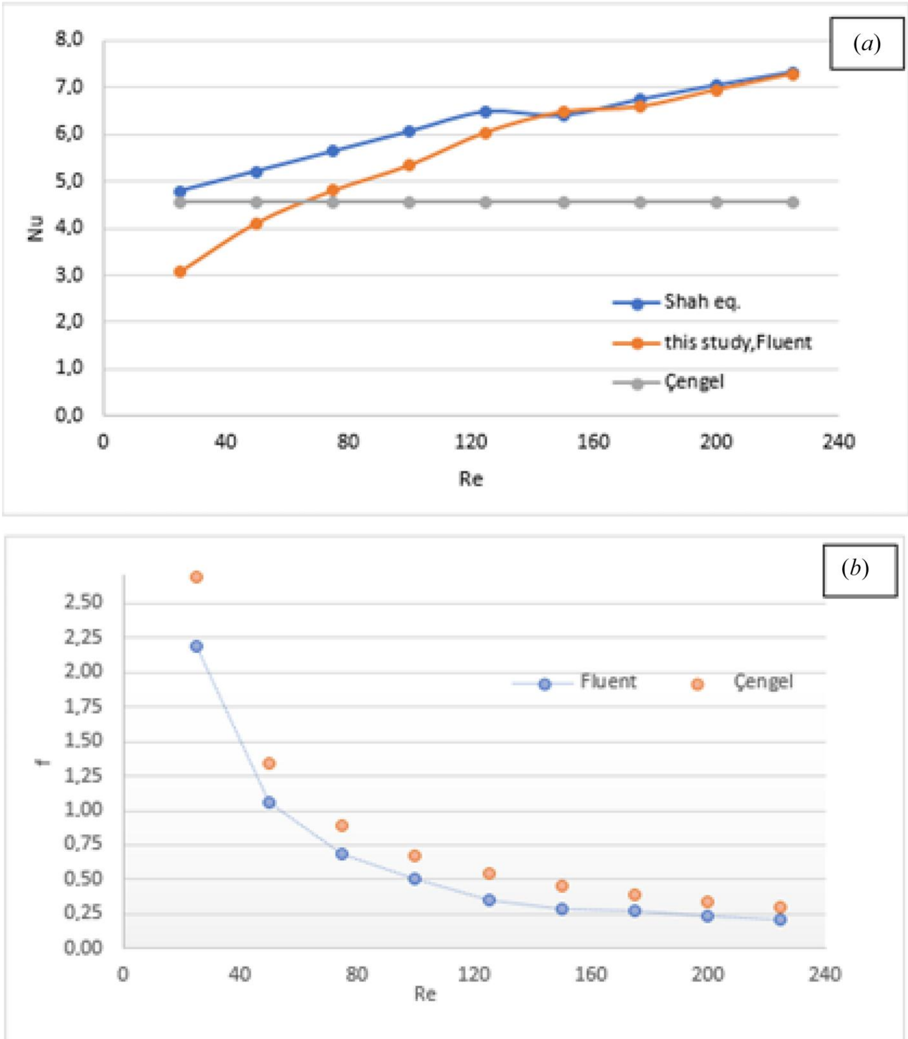

Figure 3. Model validation.

will not significantly affect the results (<5%) were taken into account. With the 2,758,000 cell count deemed sufficient for the analysis, subsequent procedures were completed at this mesh resolution.

Along with the importance of the number of cells, it is critical for the accuracy of the results that the mesh arrangement is suitable for the geometric model and flow conditions. The mesh detail is given in Figure 3. It should be noted that a linear element arrangement with smooth transition is provided along the pipe. Also, the no-slip boundary condition at the wall directly affects the flow parameters. Therefore, inflation with a finer mesh arrangement was applied in the layers close to the wall.

Figure 3 contains two plots. The top one (a) shows the Nusselt number (*Nu*) as a function of Reynolds number (*Re*). The bottom one (b) shows the friction factor (*f*) as a function of Re. The Nusselt number represents the ratio of convective to conductive heat transfer at the surface of a body. The friction factor represents the ratio of shear stress at the surface to the dynamic pressure. The top plot shows the Nusselt number calculated using three different methods: Shah Equation, this study using Fluent, and Çengel. The Shah equation given in Eq. 15 is a theoretical equation for calculating the Nusselt number. The data from this study was obtained using Fluent, a computational fluid dynamics (*CFD*) software. The data from Çengel was obtained from a textbook. The bottom plot shows the friction factor calculated using two different methods: Fluent and Çengel. The data from Fluent was obtained using ANSYS Fluent CFD software [45].

This study highlights a significant agreement between the results obtained from the Shah Equation and Çengel for Nusselt number calculations. While the Shah equation is a theoretical approach for calculating the Nusselt number, Çengel's data is sourced from a textbook [33]. The agreement between these two different sources suggests that consistent results are achieved in the fields of fluid dynamics and heat transfer. The parallelism between the Shah equation and Çengel's results further supports the reliability and accuracy of this study. This agreement demonstrates clearly that the computational methods complement each other and the results obtained are consistent.

3.3. Elliptical effect on output parameters

Figure 4 presents an evaluation of the output parameters Nusselt number (Nu) and friction factor (f) obtained through numerical simulations, considering the effect of channel aspect ratio (a/b) on heat transfer and fluid flow characteristics.

The two graphs (Figure 4*a*, *b*) presented illustrate the variation of the Nusselt number and the friction factor with respect to the Reynolds number, highlighting the effects of ellipticity on fluid dynamics. In Figure 4*a*, the increase in the Nusselt number with respect to the Reynolds number is observed across all flow cross-sections. Notably, the highest Nu values are obtained for the narrowest section, characterized by an *a/b* ratio of 0.25. This finding indicates a decreasing trend in Nu values, which represent the thermal capacity of the fluid, as the elliptic ratio diminishes. In other words, narrower sections enhance heat transfer capacity, thereby emphasizing the influence of the ellipticity ratio. In Figure 4*b*, it is observed that the friction factor decreases with increasing Reynolds numbers. Although the f values for different ellipticity ratios are relatively close, it is noteworthy that thermal enhancement is most pronounced in the narrowest section. This implies that the chosen ellipticity ratios do not adversely affect the heat transfer capability when selecting pipes. In conclusion, both graphs clearly demonstrate the effects of ellipticity on fluid dynamics and indicate that narrower sections can improve heat transfer efficiency.

Overall, the figure provides valuable insights into the combined influence of pipe ellipticity ratio (a/b) and Reynolds number (Re) on heat transfer and fluid flow characteristics (f). The analysis indicates that the numerical simulations using Fluent offer a reasonable representation of both Nu and f, particularly at higher Re. The observed deviations at lower Re emphasizes the need for careful consideration and potential model refinements for low-flow scenarios. This comparative study serves as a valuable tool for understanding the interplay of geometric and flow parameters in fluid dynamics and heat transfer applications.

3.4. Elliptical effect on velocity and temperature change

Velocity and temperature variations along the duct directly affect the output parameters. This effect is very important in heating and cooling systems, especially in determining the pipe length, so it is helpful to know it in advance. Figure 5 shows the temperature distributions for all cases. In the circular cross section, a uniform temperature distribution is observed from the center to the wall, while higher temperatures are reached in the expanding direction (horizontally) as the ellipticity increases. This observation reveals that the use of elliptical pipes can be utilized advantageously for narrow zones or planar designs. When the outlet temperature from the duct is considered, the highest value is observed in the circular pipe (case 1). This proves the condition that for applications with high temperature expectations at the duct outlet, the circular cross-section

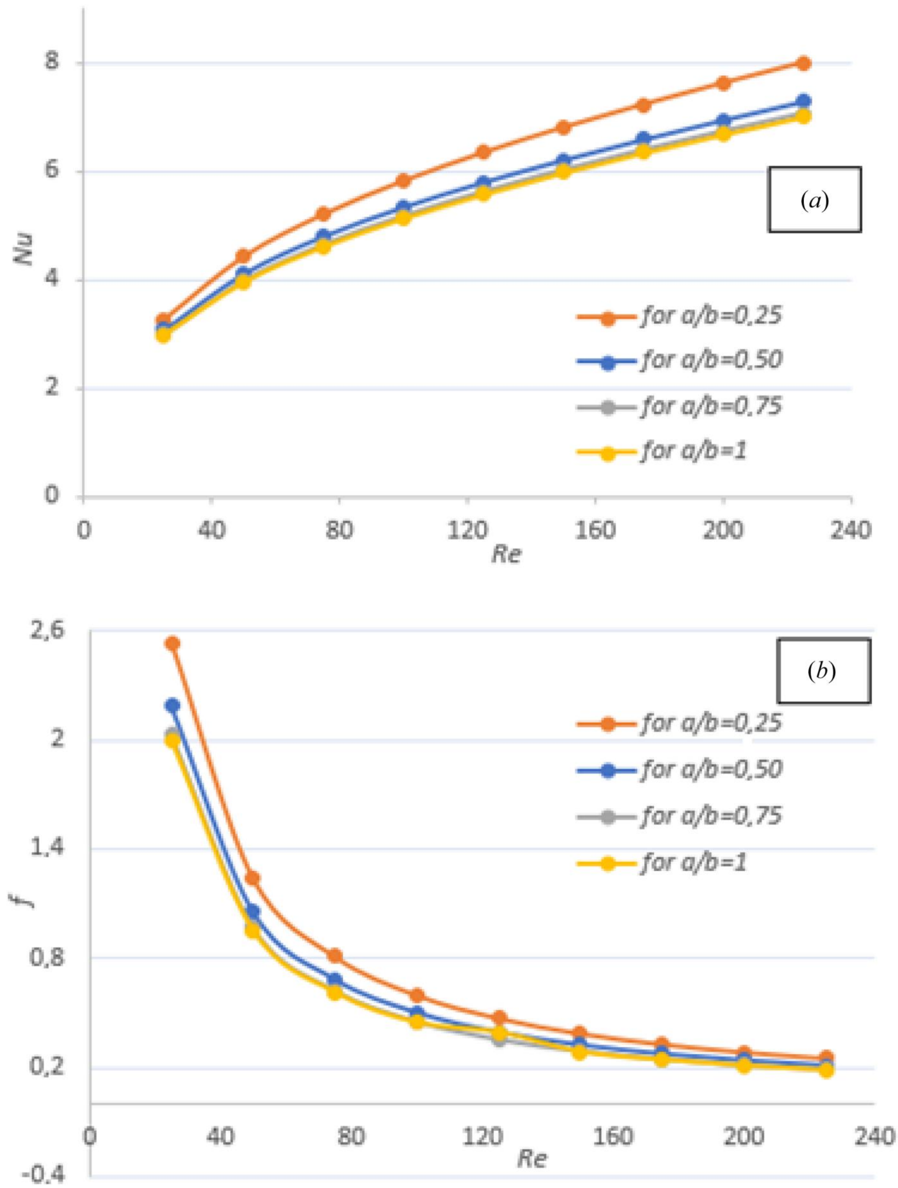

Figure 4. Evaluation of output parameters (a) Nu and (b) f.

may be the best arrangement. Here, it should be noted that for smart applications where a circular cross-section is undesirable, elliptical designs can also satisfy the expectations to a certain extent.

In this context, one of the primary factors influencing the temperature contours is the behavior of the velocity gradients. The application of heat flux from the pipe wall, combined with the presence of the no-slip boundary condition in this region, renders the development of velocity gradients that increase toward the center of the pipe cross-section inevitable. The elliptic effect further causes this gradient to extend in the elliptical direction. Consequently, elevated temperature regions are anticipated to develop in areas of low velocity. This inference is clearly demonstrated in the images across all cross-sections.

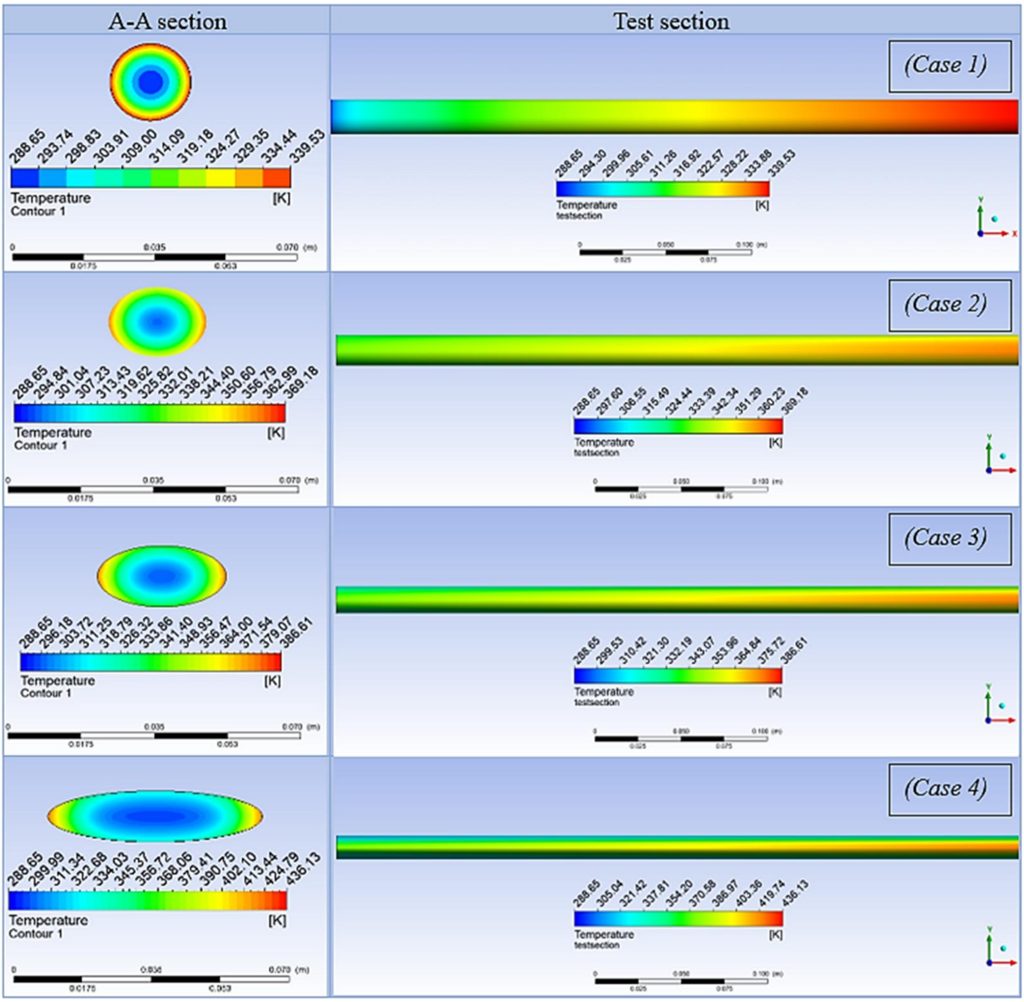

Figure 5. Temperature contours for all the cases.

3.5. Nano fluid effect

The study conducted a comprehensive analysis on the influence of different working fluids on flow and heat transfer characteristics within pipes featuring varying elliptical cross-sections (Figure 6). The investigation involved examining Nusselt Number (Nu) in relation to Reynolds Number (Re) across four distinct ellipticity ratios (a/b) – specifically, (a) $a/b = 0.25$, (b) $a/b = 0.50$, (c) $a/b = 0.75$, and (d) $a/b = 1$, representing the aspect ratio of the cross-sectional geometry. Each ratio was assessed with three different working fluids: water, CuO-water nano fluid, and Al_2O_3-water nano fluid. The results depicted a trend of Nu values increasing with rising Re, with nano fluids showcasing superior Nu values compared to water. Particularly, the Al_2O_3-water and CuO nano fluids demonstrated the highest Nu values for all ellipticity ratios, indicating their superior heat transfer performances. These results are significant with regard to the preference for Al_2O_3 among the nano fluids, owing to its readily available nature and more economical cost. The observation that CuO-water outperforms Al_2O_3-water among the nano fluids is accepted.

Thermal effects and thermo-economic comparisons of these fluids have been studied in the literature with different experimental conditions and flow modeling [46,47]. The nanofluid properties given in Table 2 according to the studied mixture concentration ratio were already expected

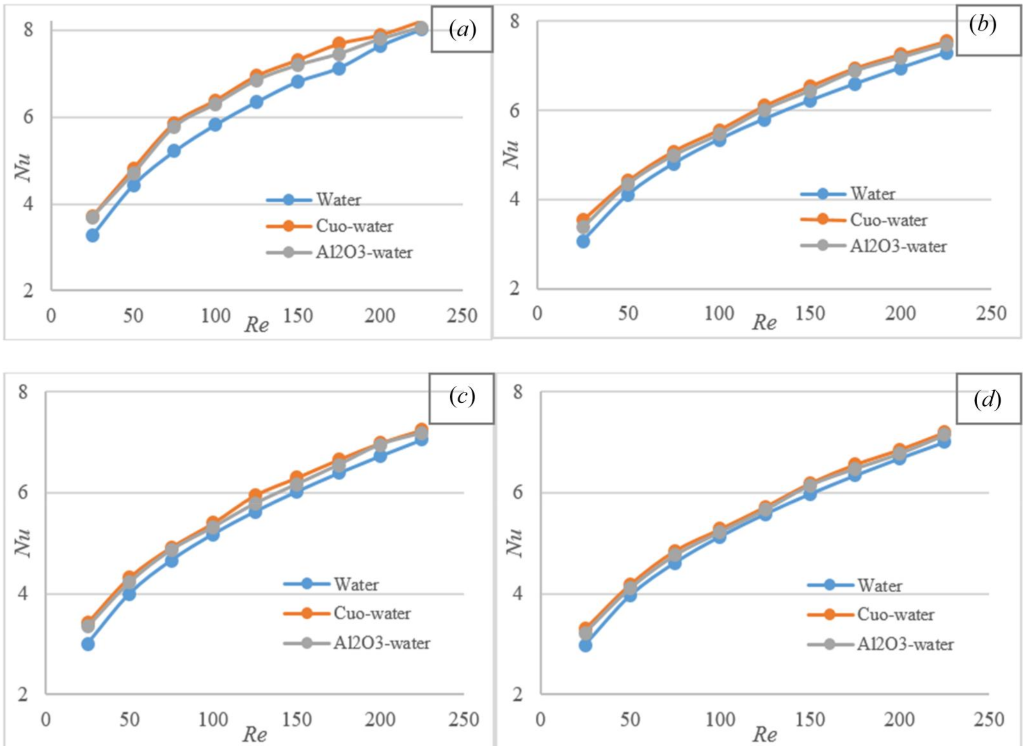

Figure 6. Effect of work fluid on flow according to ellipticity a) $a/b = 0.25$ b) $a/b = 0.50$ c) $a/b = 0.75$ and d) $a/b = 1$.

that CuO-water nanofluid would give relatively better thermal performance. However, this difference is not expected to be very large. The obtained findings confirm this literature information. Even the change in the flow cross section of the designed geometry did not change this phenomenon. The economic evaluation of the production of nanoparticles and ultimately their nanofluids can vary depending on many factors. However, the general opinion is that Al_2O_3-water nanofluid will be the more economical of the two fluids, considering that the copper element is more expensive [48,49].

The outcomes emphasized the significant impact of utilizing nano fluids on enhancing heat transfer capabilities in elliptical cross-sectioned pipes. By comparing the flow analyses of water and nano fluids, it was evident that the latter yielded notably higher Nusselt Number values, underscoring the potential for improved heat transfer efficiency. Employing both water and nano fluids across all cross-sections led to substantial advancements in heat transfer outcomes. Despite closely aligned numerical results, the Al_2O_3-water nano fluid stood out for its superior heat transfer capabilities. Incorporating these insights, it is reasonable to conclude that employing nano fluids, particularly Al_2O_3-water, can effectively enhance heat transfer performance in elliptical cross-section pipes.

4. Conclusion

The potential utilization of elliptical tubes in heat transfer devices that necessitate narrow cross-sectional geometries represents a valuable area of investigation. For such devices or applications, understanding the impact of the ellipticity ratio on overall heat transfer is essential for accurate thermal capacity calculations. Furthermore, substituting conventional water with nano fluids as the working fluid is increasingly recognized as a viable approach within active heat transfer enhancement research. Investigations that concurrently address these two critical factors yield significant advantages for practical applications, facilitating the design and optimization of more efficient heat transfer systems. Therefore, this study provides a particular investigation into the thermal performance of elliptical tubes utilizing three distinct working fluids: water, CuO-water nano fluid, and Al_2O_3-water nano fluid. The results underscore the substantial impact of channel cross-sectional geometry—particularly the ellipticity ratio—on enhancing heat transfer with equal hydraulic diameters. It was conclusively demonstrated that the incorporation of nano fluids significantly improves heat transfer performance in comparison to conventional water across all evaluated elliptical aspect ratios. Notably, the CuO nano fluid exhibited the superior thermal performance among the fluids tested, presenting the best heat transfer characteristics. In contrast, the Al_2O_3 nano fluid emerged as a compelling alternate solution due to its greater accessibility and cost-effectiveness, thereby making it particularly appealing for practical engineering applications where economic considerations are paramount. Furthermore, the analysis indicated that increasing the ellipticity ratio, under the specified laminar flow conditions, leads to a marked enhancement in heat transfer efficiency, thereby suggesting optimal design parameters for maximizing thermal performance. Overall, this research elucidates the intricate relationships between channel geometry, nano fluid selection, and heat transfer performance, providing critical insights that are essential for the design and optimization of more efficient heat transfer systems across a variety of engineering disciplines. The findings emphasize the necessity of carefully considering both fluid characteristics and geometric configurations in the pursuit of innovative and effective thermal management solutions. This study not only contributes to the existing body of knowledge but also serves as a foundation for future research aimed at advancing heat transfer technologies in practical applications.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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