CFD INVESTIGATION ON HEAT TRANSFER PERFORMANCE OF DIFFERENT PIPE GEOMETRIES AT VARIOUS REYNOLDS NUMBERS

by

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In this study, three different pipe geometries have been evaluated to investigate the effects of pipe geometry on heat transfer for incompressible flows at different Reynolds numbers. The selected geometries have been determined as dimpled, corrugated, and helical. The study performed three-dimensional analyses, and Reynolds numbers were selected as 2000, 3000, 4000, and 5000. The SST k-ω model has been used in the turbulent flow regime, while laminar flow conditions have been analyzed using the appropriate solver settings. The obtained results have been compared using heat transfer coefficient values and skin friction coefficient. The helical pipe demonstrated the highest heat transfer coefficient among all geometries, with a value of 1951 W/m²K at Re = 5000, while the dimpled and corrugated pipes exhibited values of 1910 W/m²K and 1805 W/m²K, respectively. Similarly, the helical pipe showed the lowest skin friction coefficient, with a value of 2.02 at Re = 5000, compared to 2.61 for the corrugated pipe. It has been observed that the heat transfer coefficient and the skin friction coefficient increased with the increase in Reynolds number. The wall temperature distributions on each pipe geometry for laminar and turbulent flow conditions have been obtained and analyzed. When the results were examined, it was determined that the highest heat transfer values were obtained in the helical pipe geometry at all Reynolds numbers, while the highest skin friction coefficient was observed in the corrugated pipe geometry.

Key words: heat transfer, Reynolds number, dimpled, corrugated, helical

1. Introduction

Energy demand is rapidly increasing due to technological advancements and population growth. This rise is linked to economic growth and improved living standards. However, it highlights the need for efficient energy use and adopting renewable energy solutions [1]. According to the 2021 Global Status Report for Buildings and Construction, the buildings and construction sector alone accounts for

36% of total energy consumption and 37% of energy-related carbon emissions worldwide. This shows that energy efficiency and sustainable building technologies are a critical priority [2]. The fact that fossil fuels are still largely used in energy production causes serious damage to the environment and increases greenhouse gas emissions that lead to climate change. The IPCC's 2023 Climate Change Summary Report emphasizes that fossil fuel consumption must be rapidly reduced by 2050 to limit global warming to 1.5 °C. Carbon dioxide released because of burning fossil fuels not only increases the greenhouse effect in the atmosphere but also causes air pollution and health problems [3].

In addition, the limited reserves of fossil fuels cause fluctuations in energy prices, which puts a great burden on the economic structures of countries. Countries that are dependent on energy imports may face economic crises due to increasing costs. At this point, the International Energy Agency's (IEA) World Energy Outlook 2023 report reveals Europe's efforts to reduce fossil fuel dependency and emphasizes the importance of introducing renewable energy resources in terms of ensuring energy security [4]. Energy efficiency and saving strategies are of vital importance in terms of both environmental sustainability and economic development. The IEA Renewables 2023 Report predicts that renewable energy resources have increased rapidly in recent years and will have a significant share in global energy production by 2028. While renewable resources, especially solar and wind energy, play a critical role in the energy transition, it is stated that technological investments should be increased for the storage and integration of these resources [5].

As a result, with the increasing energy demand, efficient use of energy resources, accelerating the transition from fossil fuels to renewable energy, and expanding energy-saving measures have become a necessity in terms of both environmental sustainability and economic development. The future depends on the applicability of innovations in energy technologies and the transformations in countries' energy policies [6].

Energy efficiency and the reduction of greenhouse gas emissions are critical global challenges. Innovative solutions are needed to address these issues, particularly in thermal systems, where significant energy is consumed. One promising approach is the optimization of energy consumption through advanced pipe designs. Traditional straight pipes, while widely used, offer limited surface area and are less effective in enhancing heat transfer. Helical, dimpled, and corrugated pipes have been shown to increase energy efficiency by providing larger surface areas and inducing turbulence flow, which improves heat transfer rates without requiring additional energy input.

The methods used to provide energy efficiency are divided into two basic categories. These are active and passive methods. While active methods increase heat transfer by providing additional energy to the system, passive methods aim to increase the efficiency of existing systems without using an additional energy source. Passive methods are the preferred approaches in systems that prioritize energy saving [7]. The development of these methods is of critical importance to reduce energy consumption. In particular, providing thermal comfort stands out where thermal systems require intensive energy. Maintaining the temperature balance in residential and commercial buildings industrial facilities, and other living spaces is essential to maintaining quality of life and increasing work efficiency. However, the high-energy consumption of these systems increases the energy import of states and negatively affects their economic balance [8]. Therefore, one of the most effective ways to reduce energy consumption in thermal systems is to increase the thermal performance of these systems.

Innovations in the geometric structures of pipes used in thermal systems are an important way to increase heat transfer performance. Using more complex pipe geometries instead of traditional straight pipes can increase heat transfer and enable systems to operate with less energy consumption. Compared to straight pipes, helical, dimpled, and corrugated pipes have a significantly higher internal surface area for heat transfer within the same length. Additionally, corrugated pipes exhibit a higher external surface area, which can further enhance heat transfer performance.

This increased surface area allows these geometries to achieve higher heat transfer rates, making them ideal for compact systems where space is limited. Moreover, these geometries enhance turbulence flow near the pipe wall, disrupting the thermal boundary layer and further boosting heat transfer performance. Additionally, these geometries can achieve similar energy efficiency with shorter pipe lengths within the same volume, which is particularly beneficial for compact systems, such as smaller-volume heat storage units [9]. In this context, studies on helical, dimpled and corrugated pipe geometries show that they have great potential in terms of energy saving. The performance increase provided by these pipes is due to the turbulence and instability formed in the boundary layer due to the interaction between the fluid and the pipe wall. Turbulent flow structures obtained using different pipe geometries positively affect heat transfer and enable systems to operate more efficiently.

There are many studies in literature using different tube geometries. Kishan et al. have conducted numerical analyses to investigate the effects of heat exchangers with different tube designs on heat transfer coefficient. Their studies used three different designs: straight, S-shaped and zigzag tubes. As a result, it was seen that zigzag tubes have the best heat transfer performance [10]. Karuppa et al., because of their study to compare straight tubes and helical tubes in terms of heat transfer, found that helical tubes reduce the boundary layer effect by increasing the turbulence in the flow. It was also observed that the Nu number increases with the curved line spacing in helical tubes [11]. Rabby et al. used numerical methods to investigate the effect of tube design on Nu number using hybrid corrugated, trapezoidal and sawtooth tube designs. As a result, it was observed that the hybrid corrugated design gives better results than the others and that the Nu number increases by 40-60% with its use [12]. In the study conducted by Rabby et al. to compare the effect of straight and corrugated pipes on heat transfer, it was seen that corrugated pipes provided effective results, especially in laminar flows. However, it was observed that the pressure drops increased as the heat transfer increased. While these advanced geometries offer significant advantages, they also pose challenges under high Reynolds number conditions. At higher flow rates, the increased turbulence and the formation of vortices can lead to non-uniform flow patterns and a decrease in the overall heat transfer coefficient. This trade-off between enhanced turbulence and efficient heat transfer must be carefully managed to optimize performance. For this reason, it was stated that the corrugated heights and locations should be configured [13]. As a result of the numerical analysis conducted to examine the effect of pipe geometries on heat transfer, it was observed that twisted and helical pipes increased heat transfer by up to 3.15 times compared to straight pipes. However, it was found that the friction factor increased significantly as the heat transfer increased [14].

Al-Obaidi et al. found that the flow structure, pressure drop, and heat transfer increased significantly in corrugated pipes. The highest performance was obtained in corrugated pipes with narrower ring gaps [15]. Virgilio et al. investigated the effects of dimple structures on heat transfer in pipes during turbulent flow. It was observed that the dimple structure increased heat transfer by 80% in the flow and improved the skin friction coefficient values [16]. Al-Obaidi et al. determined in their studies that the interrupted grooves in corrugated pipes increased the heat transfer performance by disrupting the boundary layer of the flow. It was stated that using corrugated pipes instead of straight pipes in any heat exchanger design provides a great advantage in heat transfer [17]. Azman et al. observed that the Nusselt number increased to 74 % at high Reynolds values during flow in sawtooth corrugated pipes. However, it was added that there was also a great increase in the friction factor [18]. Heat transfer was increased by 45-49% compared to straight pipes with different configurations tried for corrugated pipes by Al-Obaidi et al. It was stated that this situation can be used in industrial applications [19]. Al-Haidari et al. found that dimple structures increase heat transfer by 28-38% but also increase pressure drop by up to 65 %. It was found that dimple diameter, number, and placement directly affect heat transfer performance [20]. In their study, Raj et al. aimed to optimize the helical tube heat exchanger using numerical analysis. Heat transfer and flow parameters were studied using the CFD method, with SST k-ω employed as a turbulence model. The results obtained from the analysis were verified with experimental data. It was stated that this method is an effective approach for calculating heat transfer and pressure drop in helical tube systems [21]. Sivasubramaniam et al. reported that inserting plain tapes with specific geometries significantly enhances heat transfer rates in double-pipe heat exchangers with a marginal increase in pressure drop. These findings underline the impact of internal flow disturbances on heat transfer performance [22].

This study investigates the effects of different pipe geometries (helical, dimpled, and corrugated) on heat transfer performance under various flow conditions through theoretical and numerical analyses, and their potential for providing energy efficiency is discussed in detail. Despite the advancements in pipe design, there is still a lack of comprehensive understanding regarding how different geometries impact heat transfer and flow dynamics under varying Reynolds numbers. This paper aims to address these gaps by evaluating the performance of these geometries through numerical simulations, focusing on their heat transfer characteristics, friction factors, and maximum wall temperatures. The findings of this study are expected to provide valuable insights for optimizing heat exchanger designs in industrial applications. In this direction, numerical analyses were performed using three different pipe geometries, and the results were compared. The Reynolds numbers (2000, 3000, 4000, and 5000) were selected to cover both laminar ($Re < 2300$) and turbulent ($Re > 4000$) flow regimes. $Re = 2000$ represents a near-laminar regime, while the higher values represent different degrees of turbulence. This range allows a detailed investigation of heat transfer and flow characteristics across regimes. In engineering applications, such as HVAC systems, heat exchangers, and substations in district heating systems flow conditions frequently operate within or near this Reynolds number range, where both laminar and turbulent regimes are of practical significance. This ensures the study findings align with typical engineering scenarios and provide actionable insights. The k-ω SST turbulence model has been preferred in turbulent flow analyses for accurately modeling flow behaviors. The data obtained from numerical analyses have been examined and evaluated in detail to determine the effects of pipe designs on heat transfer.

2. Material and Methods

This section provides an overview of the geometric designs of the evaluated pipe configurations, the mesh structure employed for the numerical simulations, and the solution methodology. Additionally, the boundary conditions and the numerical techniques utilized for the analysis are explained in detail to ensure the reproducibility and reliability of the study.

2.1. Geometry Design

The pipes used in the CFD analyses had a length of 300 mm and an inner diameter of 50 mm. These dimensions were chosen to allow the flow to fully develop while maintaining computational efficiency. The design of the pipe geometries has been carefully optimized due to their significant impact on flow dynamics and heat transfer performance. Helical, dimpled, and corrugated pipe geometries were selected because they enhance heat transfer by increasing the internal surface area and inducing turbulence. Helical pipes create a swirling flow that promotes better mixing of the fluid, while dimpled pipes generate localized turbulence near the dimples, disrupting the boundary layer. Corrugated pipes amplify turbulence through their irregular surface structure, which increases both the heat transfer coefficient and flow resistance. These mechanisms collectively improve heat transfer efficiency compared to smooth pipes. The performance of these geometries is important, especially in industrial applications where high heat transfer is required, and space for heat exchangers is limited. The three-dimensional pipe models used in this study have been created using CAM software and analyzed according to the determined dimensions to ensure geometric accuracy and achieve more reliable and accurate simulation results. The appearances of the pipe geometries created are given in Figure 1.

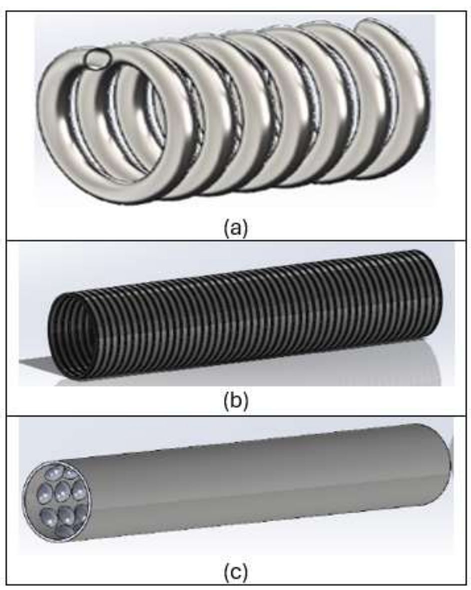

Figure 1. Appearances of designed pipes; a) Helical, b) Corrugated, c) Dimpled

2.2. Meshing

To ensure the better accuracy of the numerical analyses, each pipe geometry has been divided into small grids and meshed. It was used hexahedral mesh to increase accuracy and computational efficiency. Hexagonal cells provide more precise results in fluid dynamics and heat transfer analyses and superior performance in boundary layer analyses [23].

A mesh dependence study was conducted to ensure the accuracy and reliability of the simulation results for the helical pipe geometry, which was analyzed at a Reynolds number in 2000. The varying mesh quality involved observing its impact on key parameters such as the surface heat transfer coefficient, maximum wall temperature, and skin friction coefficient. Computational time was also chosen to evaluate the trade-off between accuracy and efficiency. The results are summarized in Table 1.

Table 1. Comparison of analyses performed according to mesh dependence

Mesh quality value	Surface heat transfer coefficient	Max. wall temperature	Skin coefficient	Computational Time
0,75	1836	254.61	1,82	50 min
0,80	1870	259.78	1,85	1-hour 20 min
0,85	1872	259.82	1,85	4-hour 30 min

As the mesh quality improved from 0.75 to 0.85, the surface heat transfer coefficient increased from 1836 to 1872, while the maximum wall temperature rose from 254.61°C to 259.82°C. The skin coefficient also stabilized at 1.85 for higher-quality meshes. These observations indicate that further refinement beyond a mesh quality value of 0.80 yields negligible differences in key parameters, suggesting that the simulation results are mesh-independent at this level. However, computational time increased significantly, from 50 minutes at a mesh quality of 0.75 to 4 hours and 30 minutes at 0.85. Considering this trade-off, a mesh quality of 0.80 was selected as the optimal configuration for this geometry, balancing computational efficiency with simulation accuracy. It is worth noting that while this mesh dependence analysis was specifically performed for the helical pipe geometry at a Reynolds number of 2000, the same mesh configuration was used for other pipe models and Reynolds numbers without additional mesh dependence studies. This approach was deemed sufficient to ensure consistency across the simulations while maintaining computational efficiency.

The appearances of the created mesh of different pipes are given in Figure 2.

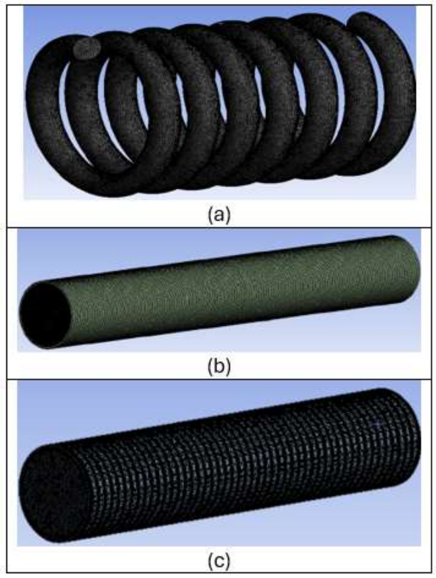

Figure 2. Appearances of pipe mesh structures; a) Helical, b) Corrugated, c) Dimpled

2.3. Numerical Solution

The SST k−ω turbulence model was selected for turbulent flow conditions because it provides accurate and reliable solutions, particularly near the wall regions, where boundary layer effects are significant. This model combines the advantages of the k−ω formulation in the near-wall region with the k−ϵ formulation in the free stream, enabling a detailed and comprehensive examination of turbulence along the pipe geometry [24]. SST k−ω has been used as a turbulence model for Reynolds numbers of 3000, 4000, and 5000 during the pipe flow.

Calculations have been made according to laminar flow conditions for Re = 2000. Fluid motion and heat transfer equations were solved using CFD software, and approximately 300,000 mesh structures were used in the analyses. The numerical simulations were performed on a system with an Intel Core i7-13700H processor, 64GB RAM, 1TB SSD, and an NVIDIA GeForce RTX 3050 GPU (6GB VRAM). Numerical solution processes were performed using the finite volume method throughout the study. The initial temperature of the pipe surface was accepted as 300 °C, and the ambient temperature was accepted as 25 °C. These values were chosen to represent typical operating conditions in industrial applications where significant temperature gradients are present, ensuring that the results are relevant for practical heat transfer scenarios.

It was assumed that the pipe material is steel. Steel has been chosen as the pipe material due to its high thermal conductivity and resistance to thermal pressure, and its thermophysical properties were considered in the heat transfer calculations. Steel has been chosen as the pipe material due to its high thermal conductivity and resistance to thermal pressure. Additionally, the air has been chosen as the working fluid, and the properties of both the air-fluid, such as density and viscosity, and the steel have been considered in calculations.

3. Results

In this section, the results obtained from numerical analyses are presented and discussed in detail. The analyses focus on the effects of different pipe geometries on heat transfer, skin friction coefficient, maximum wall temperature, and temperature distribution under various Reynolds number conditions. Each result is supported by graphical representations and numerical data, providing insights into the thermal and flow characteristics of the studied geometries.

3.1. Surface Heat Transfer Coefficient

The heat transfer coefficient (h) of different pipe designs is shown in Figure 3.

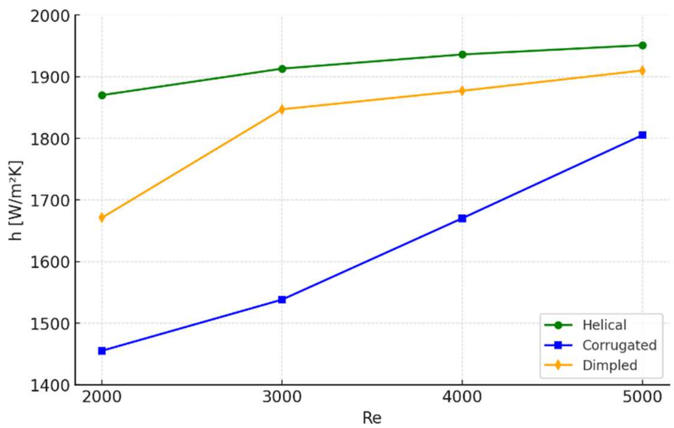

Figure 3. Comparison of heat transfer coefficients of different pipe designs according to Reynolds number

Figure 3 shows the variation in the heat transfer coefficient (h) for different pipe geometries over a Reynolds number (Re) range from 2000 to 5000. It is observed that helical pipes exhibit the highest heat transfer coefficient at all Reynolds numbers, followed by dimpled pipes, while corrugated pipes perform relatively poorly.

The heat transfer coefficient for all pipe designs increases with an increase in Reynolds number, highlighting the strong influence of turbulence on enhancing heat transfer. Specifically, the heat transfer coefficient in helical pipes increases from 1870 W/m²K at Re = 2000 to 1951 W/m²K at Re = 5000. Dimpled pipes demonstrate a significant increase from 1671 W/m²K at Re = 2000 to 1910 W/m²K at Re = 5000. For corrugated pipes, the heat transfer coefficient increases from 1455 W/m²K at Re = 2000 to 1805 W/m²K at Re = 5000.

Among the geometries, the highest gradient of heat transfer coefficient is observed in corrugated pipes, indicating that this design is more sensitive to the effects of increasing Reynolds number. This behavior can be attributed to the enhanced turbulence caused by the corrugated surface, which amplifies the heat transfer at higher flow rates.

For dimpled pipes, a high gradient is observed between Re = 2000 and Re = 3000, where the heat transfer coefficient increases significantly due to the formation of localized vortices and turbulence near the dimples. However, in the range of Re = 3000 to Re = 5000, the gradient decreases slightly, suggesting a stabilization in the turbulent flow field as the Reynolds number increases further.

In contrast, the helical pipes show a relatively consistent and moderate increase in the heat transfer coefficient across the entire range of Reynolds numbers. This behavior reflects the uniform mixing and stable flow patterns induced by helical geometry, which contribute to its superior heat transfer performance without drastic changes across different flow rates.

These results emphasize the role of pipe geometry in influencing heat transfer characteristics and demonstrate how different designs respond uniquely to variations in flow conditions. Further investigation into the flow dynamics for each design could provide deeper insights into the observed behaviors.

3.2. Skin Friction Coefficient

The results of the friction coefficient analysis are given in Figure 4.

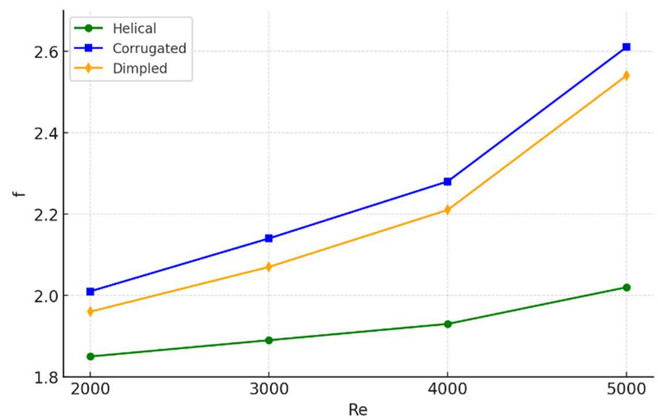

Figure 4. Comparison of skin friction coefficient values of different pipe designs according to Reynolds number

According to Figure 4, the highest friction coefficient value at each Reynolds value has been obtained from corrugated pipes. This value is lower in dimpled pipes than in corrugated pipes but higher in helical pipes. While the skin friction coefficient has been 1.85 in helical pipes at Re = 2000, this value became 2.02 at Re = 5000. While the skin friction coefficient has been 2.01 in corrugated pipes at Re = 2000, this value became 2.61 at Re = 5000. While the skin friction coefficient has been 1.96 in dimpled pipes at Re = 2000, this value became 2.54 at Re = 5000.

Also, it can be observed that the corrugated and dimpled designs show a higher increase in the range of Reynolds numbers (Re = 2000–5000) compared to the helical design. This can be attributed to the enhanced turbulence generated by the corrugated and dimpled geometries, which increases flow resistance and, consequently, the friction factor. In contrast, the smaller increase in the friction factor for the helical design is due to its smoother and more streamlined geometry, which reduces flow resistance while maintaining effective heat transfer characteristics. This behavior highlights the trade-off between heat transfer performance and pressure drop in different pipe designs.

3.3. Maximum Wall Temperature

The maximum wall temperature results and the range of Reynolds numbers used to evaluate heat dissipation in different pipe designs are given in Figure 5.

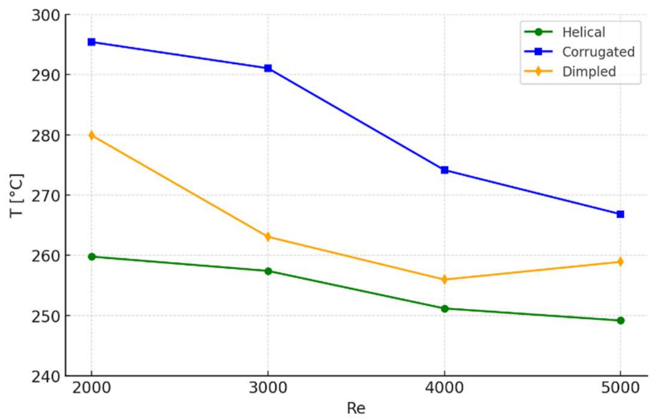

Figure 5. Comparison of maximum wall temperature values of different pipe designs according to Reynolds number

According to Figure 5, when the maximum wall temperatures are examined, it is observed that the outer surfaces of the corrugated pipes reach the highest temperatures, while the helical pipes show the lowest temperature values. This indicates that heat dissipation is weaker in corrugated pipes, whereas more efficient heat transfer occurs in helical pipes. For the helical pipes, the maximum wall temperature decreases from 259.78 °C at Re = 2000 to 249.17 °C at Re = 5000. Similarly, for the corrugated pipes, the temperature decreases from 295.41 °C at Re = 2000 to 266.83 °C at Re = 5000. For the dimpled pipes, the temperature decreases from 279.91°C at Re = 2000 to 258.91 °C at Re = 4000 but then slightly increases to 260.00 °C at Re = 5000.

This slight increase in the wall temperature for dimpled pipes between Re = 4000 and Re = 5000 can be attributed to the flow dynamics unique to this pipe design. At higher Reynolds numbers, the dimpled geometry may cause localized turbulence and eddy formations near the wall, reducing the overall effectiveness of heat dissipation. These turbulent zones could limit the heat transfer coefficient's increase, leading to a slight temperature rise compared to other pipe designs. On the other hand, the helical and corrugated pipes maintain more uniform flow patterns, allowing for continued improvement in heat dissipation as Re increases.

These findings emphasize the complex relationship between pipe geometry and heat transfer performance, particularly under turbulent flow conditions. The results also suggest that optimizing dimpled pipe designs may require further investigation to mitigate such localized effects.

3.4. Temperature Contour Analysis

Temperature contour results obtained from numerical analysis clearly show the temperature distribution along the flow for each geometry. At Re = 2000, where the turbulence effect is more limited, and the flow is generally laminar, the temperature profiles for each geometry are given in Figure 6.

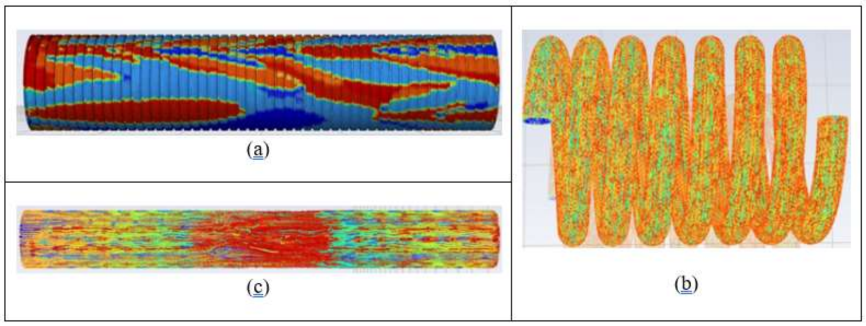

Figure 6. Temperature contours calculated by the k-ω SST turbulence model at Re = 2000: (a) corrugated pipe, (b) helical pipe, (c) dimpled pipe

In these results, the temperature profile of the corrugated pipe is the most irregular and draws attention to its high-temperature differences. The flow is more regular in the helical pipe. The temperature distribution is more homogeneous in the recessed pipe due to the effect of the surface structure. At Re = 5000, where the effect of turbulence increases and the flow becomes more complex, the temperature profiles of each geometry are given in Figure 7.

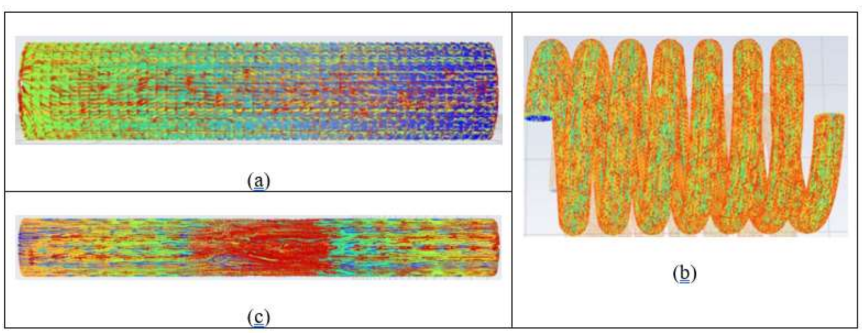

Figure 7. Temperature contours calculated by the k-ω SST turbulence model at Re = 5000: (a) corrugated pipe, (b) helical pipe, (c) dimpled pipe

It was observed that the temperature differences in the corrugated pipe were greater at Re = 5000, and the temperature distribution became more uneven. In the helical pipe, the temperature profile was generally more homogeneous and showed a regular distribution along the surfaces. High-temperature differences and turbulence effects characterized the recessed pipe.

The temperature contours in Figures 6 and 7 display the distribution of temperature values along the flow for each geometry. Each color in the contour maps corresponds to a specific temperature range. For example, in Figure 6, the red areas represent temperatures close to 300°C, indicating regions with minimal heat dissipation, while the blue areas indicate lower temperatures, approximately 25°C, corresponding to areas with efficient heat transfer. Similarly, in Figure 7, the yellow and green regions show intermediate temperature ranges, highlighting areas where heat transfer efficiency varies depending on the pipe geometry and Reynolds number.

4. Conclusions

Numerical analyses have been performed using the computational fluid dynamics method for four different Reynolds numbers (Re = 2000, 3000, 4000 and 5000) in pipes with different pipe geometries (helical-helical, corrugated-corrugated and dimpled-dimpled). The study aims to compare the effects of pipe geometry on the heat transfer coefficient, wall temperature, and friction coefficient, focusing on the heat transfer between the pipe wall and the fluid. The results obtained can be summarized under the following headings:

- The highest heat transfer coefficient in all Reynolds numbers has been achieved using helical pipes. These pipes increase heat transfer by significantly enhancing the contact area between the fluid and the pipe walls due to their unique geometric structures, which promote better interaction and turbulence within the flow. Also, the secondary flows generated by twisted geometries are critical in enhancing heat transfer performance compared to smooth pipes. Findings in the literature also support this conclusion. Dimpled pipes had the second highest heat transfer after helical pipes, while corrugated pipes showed the lowest heat transfer performance.
- Corrugated pipes had the highest wall temperatures, showing higher heat accumulation. Helical pipes, on the other hand, had the lowest wall temperatures, providing more effective heat dissipation.
- The highest friction coefficient has been obtained from corrugated pipes. This shows that surface friction in corrugated structures increases more than in other shapes. The lowest friction coefficient has been obtained from helical pipes. It has been determined that spiral structures do not increase surface friction as much as other designs.

The findings of this study suggest that helical pipe geometry is the most suitable choice for applications requiring efficient heat transfer across a wide range of Reynolds numbers. Specifically, for systems operating at higher Reynolds numbers (e.g., Re = 5000), the helical pipes demonstrated the highest heat transfer coefficients and the lowest wall temperatures, making them optimal for high-performance thermal systems where heat dissipation is critical.

While dimpled pipes showed moderate performance, they may be considered for applications where moderate heat transfer efficiency is sufficient and reduced friction coefficients are desired compared to corrugated designs. On the other hand, corrugated pipes, due to their high wall temperatures and friction coefficients, are not recommended for applications prioritizing thermal efficiency.

These findings indicate that heat transfer performance varies significantly depending on pipe geometry. The differences in heat transfer performance between the pipe geometries can be attributed to variations in flow characteristics, such as velocity distribution and turbulence intensity. The enhanced convective heat transfer observed in some geometries is likely due to the promotion of secondary flows and increased turbulence levels, which improve thermal mixing. These factors play a crucial role in determining the overall efficiency of heat transfer in different configurations.

These results provide a basis for selecting pipe geometries in practical engineering applications, such as heat exchangers and fluid transportation systems, where both heat transfer efficiency and energy savings are key considerations.

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