Libyan Open University Journal of Applied Sciences (LOUJAS)
Volume 2 - Issue 1 - 2026 - Pages 127-136

Numerical Study of Triple Pipe Heat Exchanger Using Copper, Steel, and Aluminium of Varying Thicknesses

Hesham Baej [1*], Abdulhakim Abokhari Alrzzaghi [2]
[1] Department of mechanical engineering, Faculty of engineering, Libyan open University, Tripoli, Libya
[2] Department of mechanical engineering, Faculty of engineering, Gharyan University, Gharyan, Libya
***Email:** heshambaej@ou.edu.ly

دراسة عددية لمبادل حراري ثلاثي الأنابيب باستخدام النحاس والفولاذ والألومنيوم بسماكات مختلفة

هشام السني بعيج [1*]، عبد الحكيم البخاري الرزاقي [2]
[1] قسم الهندسة الميكانيكية، كلية الهندسة، جامعة ليبيا المفتوحة، طرابلس، ليبيا
[2] قسم الهندسة الميكانيكية، كلية الهندسة، جامعة غريان، غريان، ليبيا

Received: 07-01-2026; Accepted: 03-03-2026; Published: 12-03-2026

Abstract:
This study investigates the thermal performance of a triple-pipe heat exchanger constructed with copper, steel, and aluminum pipes of varying wall thicknesses. The analysis focuses on the influence of material properties and thickness on heat transfer efficiency, pressure drop, and overall exchanger effectiveness. Results indicate that copper, owing to its superior thermal conductivity, achieves the highest heat transfer rates. Aluminum provides a favorable compromise between conductivity and structural weight, while steel contributes mechanical strength but exhibits comparatively lower thermal performance. Variations in wall thickness further impact conduction resistance and fluid flow characteristics, underscoring the importance of optimising both material selection and geometric design to enhance exchanger efficiency.

Keywords: heat exchanger; triple-pipe heat exchanger Efficiency, Optimization, Strategies,

الملخص:
تتناول هذه الدراسة الأداء الحراري لمبادل حراري ثلاثي الأنابيب مصنوع من أنابيب نحاسية وفولاذية وألومنيوم ذات سماكات جدارية متفاوتة. ويركز التحليل على تأثير خصائص المواد وسماكة الجدار على كفاءة نقل الحرارة، وانخفاض الضغط، والفعالية الكلية للمبادل. وتشير النتائج إلى أن النحاس، بفضل موصليته الحرارية العالية، يحقق أعلى معدلات نقل الحرارة. ويُوفر الألومنيوم حلاً وسطاً مناسباً بين الموصلية والوزن الهيكلي، بينما يُساهم الفولاذ في المتانة الميكانيكية ولكنه يُظهر أداءً حرارياً أقل نسبياً. كما تؤثر الاختلافات في سماكة الجدار على مقاومة التوصيل وخصائص تدفق المائع، مما يُؤكد أهمية تحسين اختيار المواد والتصميم الهندسي لتعزيز كفاءة المبادل.

الكلمات المفتاحية: مبادل حراري؛ مبادل حراري ثلاثي الأنابيب، الكفاءة، استراتيجيات التحسين، الموصلية الحرارية.

Introduction
Heat exchangers are fundamental components in modern energy systems, enabling efficient thermal management across diverse industries such as power generation, chemical processing, refrigeration, and automotive engineering. Their role in transferring heat between fluids without direct mixing makes them indispensable for improving energy efficiency, reducing operational costs, and ensuring system reliability. As global energy demands rise and

sustainability becomes a priority, the optimization of heat exchanger design has become a central focus in thermal engineering research (Kareem et al., 2022)(Bux, 2021). [1]– [3].

Among the many configurations, the triple pipe heat exchanger (TPHX) has emerged as a promising design due to its ability to simultaneously handle multiple fluid streams. Unlike conventional double-pipe exchangers, the triple-pipe arrangement provides enhanced flexibility in fluid routing, allowing counterflow, parallel flow, or hybrid arrangements that improve thermal performance. This geometry also enables compact construction, making TPHXs particularly suitable for applications where space is limited but high efficiency is required, such as in aerospace systems, advanced cooling technologies, and renewable energy applications (Scholar et al., 2020)(Bux, 2021) [2], [3]. Recent studies have demonstrated that triple-pipe exchangers can achieve higher heat transfer rates compared to double-pipe designs, especially under counterflow conditions, though they also introduce challenges such as increased frictional losses and fabrication complexity (Suarta, n.d.)(Kareem et al., 2022)[6]–[8].

Material selection is equally critical in determining the performance of heat exchangers. Copper, aluminum, and steel remain the most widely used materials, each offering distinct advantages and limitations. Copper is renowned for its superior thermal conductivity (~390 W/m·K), which facilitates rapid heat transfer and makes it ideal for applications requiring high efficiency. However, its relatively high cost and density limit its widespread use in large-scale or weight-sensitive systems. Aluminum, with moderate conductivity (~205 W/m·K) and low density, offers a balance between performance and affordability. Its corrosion resistance and machinability make it particularly attractive in automotive and aerospace industries where lightweight design is essential. Steel, though possessing lower conductivity (~50 W/m·K), provides exceptional mechanical strength and durability under high pressure and chemically aggressive environments, making it the preferred choice in heavy industrial applications(Jack P. Holman, 2009) (Jack P. Holman, 2009)[4], [5]. Comparative studies consistently highlight that copper alloys excel in heat transfer efficiency, aluminum provides a cost-effective compromise, and steel dominates in contexts requiring mechanical robustness(Hussien et al., 2023)(Rasal et al., 2017) [1], [2].

Geometric parameters such as wall thickness further influence exchanger performance. Thinner walls reduce conduction resistance, thereby enhancing heat transfer, but they may compromise mechanical stability under high pressure or corrosive conditions. Conversely, thicker walls improve durability and reliability but reduce thermal efficiency due to increased conduction resistance. This trade-off underscores the importance of balancing thermal performance with mechanical reliability depending on operating conditions(Scholar et al., 2020) [6], [7]. In advanced designs, multi-pipe and concentric triple-pipe configurations have been shown to increase surface area and enable more complex fluid arrangements, thereby improving overall effectiveness. For example, concentric triple-pipe exchangers have demonstrated superior heat transfer effectiveness compared to double-pipe designs, though at the expense of higher pumping power requirements(Kareem et al., 2022) [8].

Recent research has also explored the integration of phase change materials (PCMs) into triple-pipe exchangers to enhance energy storage and exergy efficiency. (Hussien et al., 2023) reported that incorporating PCMs into TPHXs significantly improved thermal regulation and energy recovery, making them suitable for renewable energy and thermal storage applications. Similarly, Quadir et al.(M. Quadir, S. A. Khan, 2022) [2] conducted experimental and numerical investigations comparing triple-pipe and double-pipe exchangers, concluding that the triple-pipe configuration achieved higher heat transfer rates under counterflow arrangements. Reviews of triple-tube exchangers emphasize their role in optimizing heat balance among multiple fluids, making them attractive for industrial cooling and heating systems(Scholar et al., 2020) [3].

This body of research underscores the importance of carefully selecting both material and geometry when designing heat exchangers. While copper, aluminum, and steel each offer distinct advantages, their performance must be evaluated in the context of specific operating conditions, including pressure, temperature, and fluid properties. Likewise, geometric factors such as wall thickness and multi-pipe arrangements must be optimized to balance efficiency with durability. Building on these findings, the present study evaluates copper, aluminum, and steel pipes of varying thicknesses in a triple-pipe heat exchanger to provide comparative insights into their thermal and mechanical performance. By systematically analyzing material and geometric influences, this work aims to contribute to the ongoing development of high-performance, cost-effective, and durable heat exchanger designs for modern energy systems.

Material and methods

Materials Selection

Three metallic materials were modelled for the triple-pipe heat exchanger. These materials were chosen to represent high, medium, and low conductivity categories while maintaining structural feasibility as shown in the table.

Table 1 Material Thermal Conductivity.

Metal	Thermal conductivity
Copper	≈ 390 **W/(m·K).**
Aluminum	≈ 205 **W/(m·K).**
Steel	≈ 50 **W/(m·K).**

Methodology

Triple Pipe Model: The geometry of three concentric cylindrical pipes was created in SolidWorks. The inner, middle, and outer pipes were modeled with varying wall thicknesses to evaluate the impact of conduction resistance.

Material Assignment: Copper, aluminum, and steel were assigned to the pipe walls to compare their thermal conductivity and mechanical strength. The flow direction used in the simulation, along with the measurement locations, is illustrated in Figure 1.

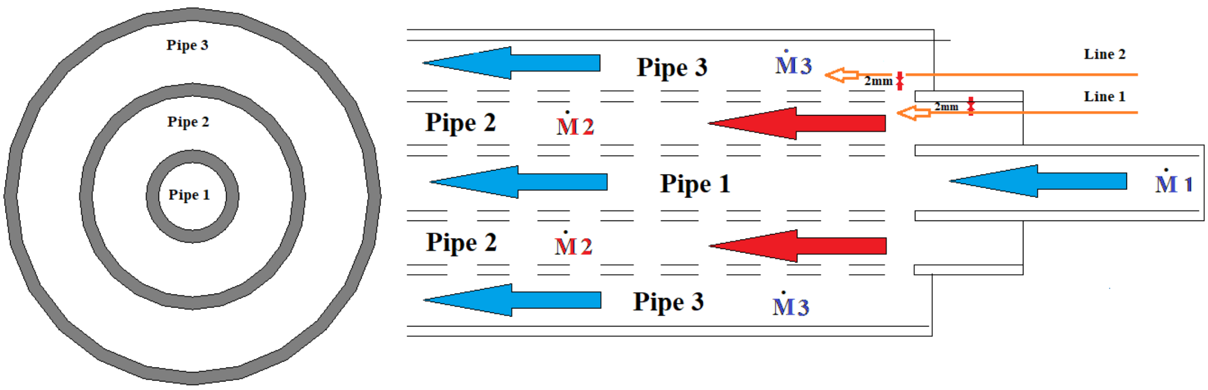

Figure 1 Heater exchanger direction diagram.

Pipe Geometry and Thickness

The triple-pipe exchanger consists of three concentric cylindrical pipes **Inner pipe** carries cold fluid, **Middle pipe** carries hot fluid and **Outer pipe** carries secondary fluid. The thicknesses were analysed for each material as shown the table below.

Table 2 Thickness dimensions in mm

0.75 mm	1.0 mm	1.5 mm	2.5 mm

The inner diameter of the innermost pipe was fixed at 13.5 mm, and intermediate pipe diameter 40 mm and outer pipe diameter 70 mm with concentric spacing maintained to ensure uniform fluid distribution as shown in the figure 2.

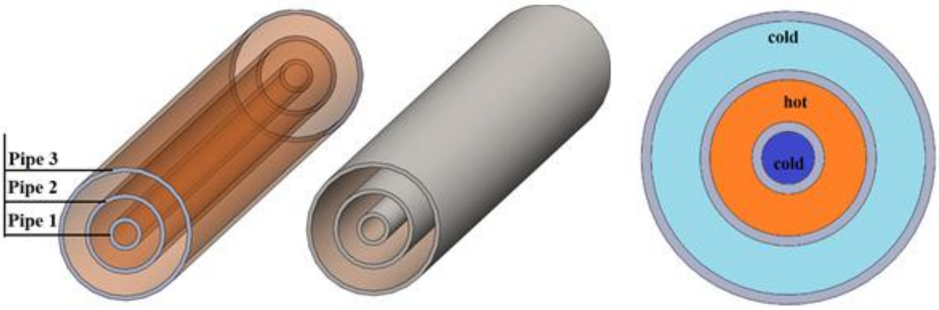

Figure 2 Geometry shape and cold and heat positions

CFD Modeling in ANSYS Fluent

Numerical Simulation Setup

Numerical simulations were conducted using ANSYS Fluent to evaluate the heat transfer and fluid flow characteristics of the triple-pipe heat exchanger. The geometry of the exchanger was created in ANSYS Design Modeler, where concentric triple-pipe arrangements were modeled to replicate the experimental setup. The schematic representation of the geometry is shown in Figure 4. The computational domain was discretized using a structured mesh to ensure accuracy in capturing boundary layer effects and fluid interactions across the three pipes. Mesh independence tests were performed to confirm that the solution was not sensitive to grid density. Boundary conditions were applied to represent hot and cold fluid streams under counterflow arrangements, with inlet temperatures and mass flow rates specified according to experimental parameters.The governing equations for mass, momentum, and energy conservation were solved using the finite volume method. The SIMPLE algorithm was employed for pressure–velocity coupling, while second-order discretization schemes were used to improve solution accuracy. Convergence criteria were set to residuals of 10^{-6} for continuity and momentum equations, and 10^{-8} for energy equations. Thermal performance was evaluated in terms of heat transfer rate, overall effectiveness, and Nusselt number correlations, while fluid flow characteristics were analysed through pressure drop and velocity distribution across the triple-pipe channels. Comparative simulations were carried out for copper, aluminum, and steel pipes with varying wall thicknesses to assess the influence of material properties and geometry on exchanger performance.This numerical approach complements the experimental studies by providing detailed insights into local flow behavior and temperature distribution, which are often difficult to measure directly. The combination of simulation and experimental analysis ensures a comprehensive evaluation of the triple-pipe heat exchanger design.

Mesh Independence Study

A mesh independence (grid convergence) study was performed to ensure that the numerical results obtained from ANSYS Fluent were not influenced by mesh resolution. Two structured meshes with increasing refinement were generated, with enhanced resolution near the walls to accurately capture boundary layer behavior, velocity gradients, and thermal fields in the triple-pipe heat exchanger.The properties of the two mesh cases are summarized in Table 3.

Table 3. Mesh properties for independence study.

Case	Nodes	Elements
1	1,072,006	6,024,738
2	3,056,379	5,851,854

Both meshes were structured with wall refinement; however, Case 2 exhibited a significantly higher nodal density throughout the computational domain. This refinement allowed for more accurate resolution of near-wall gradients and improved prediction of thermal and flow fields.Based on accuracy and convergence considerations, Case 2 was selected for subsequent simulations. Further refinement beyond Case 2 was deemed unnecessary, as it would yield negligible improvements in accuracy while significantly increasing computational expense. The comparison of Case 1 and Case 2 is illustrated in Figure 3, which demonstrates the improved resolution and stability achieved with the refined mesh.

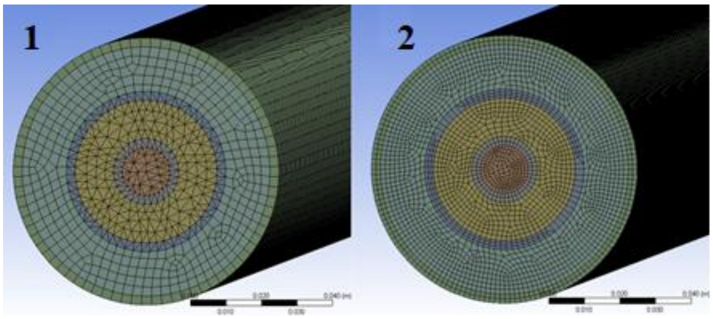

Figure 3 Mesh Independence case 1 & 2.

Boundary Conditions:

The three-tube heat exchanger was simulated under parallel flow arrangements with the following inlet boundary conditions:

Table 4. Inlet boundary conditions.

Cold fluid inlet temperature inner pipe	Hot fluid inlet temperature Middle pipe	fluid inlet temperature Outer pipe	Mass flow rate inner pipe	Mass flow rate middle pipe	Mass flow rate outer pipe
278 k	363 k	283 k	0.000859 Kg/s	0.0006 Kg/s	0.005645 Kg/s

Boundary conditions were applied to represent realistic operating conditions, with cold fluid entering the inner and outer pipes, and hot fluid entering the middle pipe. Mass flow rates were selected to ensure laminar flow regimes, consistent with experimental parameters.

Comparative Evaluation

Simulation parameters were defined to evaluate the thermal and hydraulic performance of a triple-pipe heat exchanger under different material and geometric conditions. Thermal conductivity values were assigned to copper, aluminum, and steel, while pipe wall thicknesses of 0.75, 1.0, 1.5, and 2.5 mm were incorporated into the geometry to investigate their influence on conduction resistance.

A comparative CFD evaluation was performed to analyze the effect of material selection (copper, aluminum, and steel) and wall thickness on overall exchanger performance. Pipe wall thickness is a critical design parameter, as it directly affects conduction resistance and mechanical strength. Thinner walls reduce thermal resistance and enhance heat transfer, but may weaken structural durability under operating stresses. In contrast, thicker walls provide greater mechanical stability at the expense of reduced thermal efficiency due to increased conduction resistance. By systematically examining different materials and thickness configurations, the study establishes how thermophysical properties and geometric variations interact to determine the thermal behavior of triple-pipe heat exchangers.

Performance assessment was based on key metrics including heat transfer rate, outlet temperatures (K), overall effectiveness, and pressure drop. The motivation for this research stems from the increasing industrial need for energy-efficient, cost-effective, and durable thermal systems. As energy conservation and environmental sustainability become more critical, optimizing heat exchanger design through appropriate material and thickness selection is essential. This work therefore integrates numerical analysis with a comparative material study to provide practical design guidelines for improving the efficiency and reliability of triple-pipe heat exchangers.

Results and discussion

Temperature Distribution

CFD simulations in ANSYS Fluent provided detailed temperature contours across the triple-pipe exchanger. Copper walls showed the steepest radial temperature gradients, confirming rapid heat conduction. Aluminum exhibited moderate gradients, balancing conduction with lower density. Steel displayed shallow gradients, indicating higher thermal resistance. At hot fluid inlet (**363 K**) and cold fluid inlet (**298 K**), outlet temperatures varied significantly with wall thickness:

The figures clearly show that increasing thickness leads to a greater temperature difference. Copper consistently performs as the best heat conductor, except in Case A at a thickness of 2.5 mm innthe figure 4, where aluminum surpasses it. Overall, the differences between the metals are relatively small, though copper and aluminum display the most noticeable variation in Figure A (the cold line). In this case, the temperature rises from 283°C to 298°C, resulting in a difference of 15°C.
In Figure B, the temperature distribution is highly uniform across all metals and thicknesses. Along the hot line, the temperature decreases from 355°C to 293°C, producing a consistent difference of 62°C for every material tested.

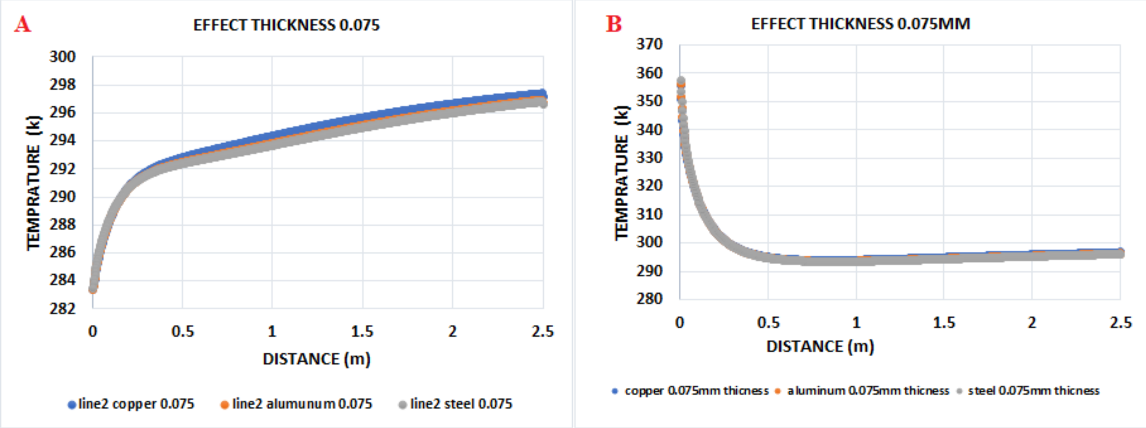

Figure 4 comparing temperature distribution for a thickness of 0.75 mm

Figure 5 shows that copper exhibits the largest temperature difference, followed by aluminum. Steel comes in third with the smallest temperature difference (c) in the cold line, where temperatures rise from 283°C to 297°C, resulting in a 14°C temperature difference for copper. For iron, the temperature rises from 283°C to 294°C, resulting in an 11°C temperature difference. Aluminum has an intermediate temperature difference, rising from 283°C to 296°C, resulting in a 13°C temperature difference.
In Figure 5 (d), there is a high degree of uniformity in the temperature distribution for all metals. The temperature drops from 360°C to 295°C along the same path for all thicknesses and metals in the hot line, resulting in a temperature difference of 65°C for copper. Iron, however, clearly exhibits the largest difference, with the temperature dropping from 360°C to 291°C, resulting in a temperature difference of 69°C

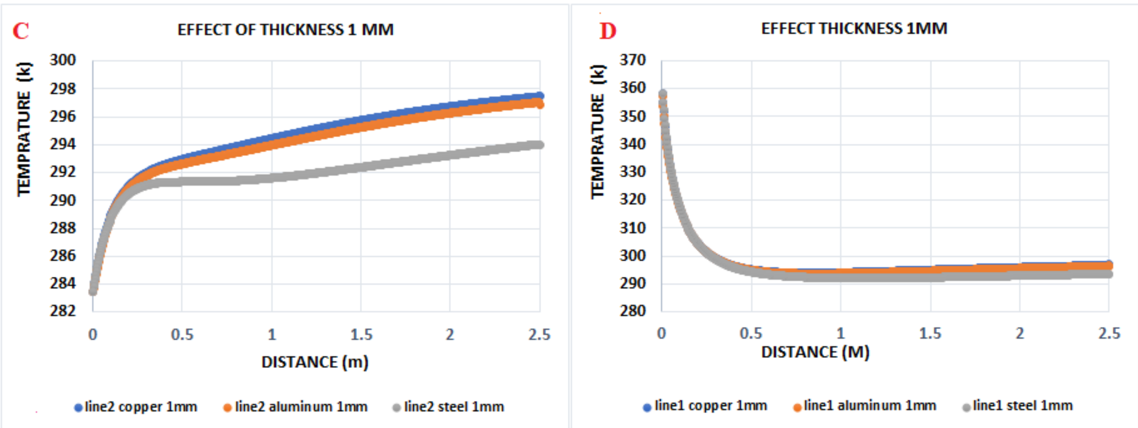

Figure 5 comparing temperature distribution for a thickness of 1 mm

Figure 6 demonstrates that copper shows the largest temperature difference, followed by aluminum, with steel exhibiting the smallest. In the cold line (E), copper's temperature increases from 283°C to 298°C, producing a difference of 15°C. Steel rises from 283°C to 294°C, resulting in an 11°C difference. Aluminum lies between the two, with a rise from 283°C to 297°C, giving a 14°C difference.

In Figure 6 (F), the temperature distribution is highly uniform across all metals. Along the hot line, copper's temperature drops from 360°C to 295°C, yielding a difference of 65°C. Steel, however, shows the largest drop, from 360°C to 291°C, resulting in a difference of 69°C.

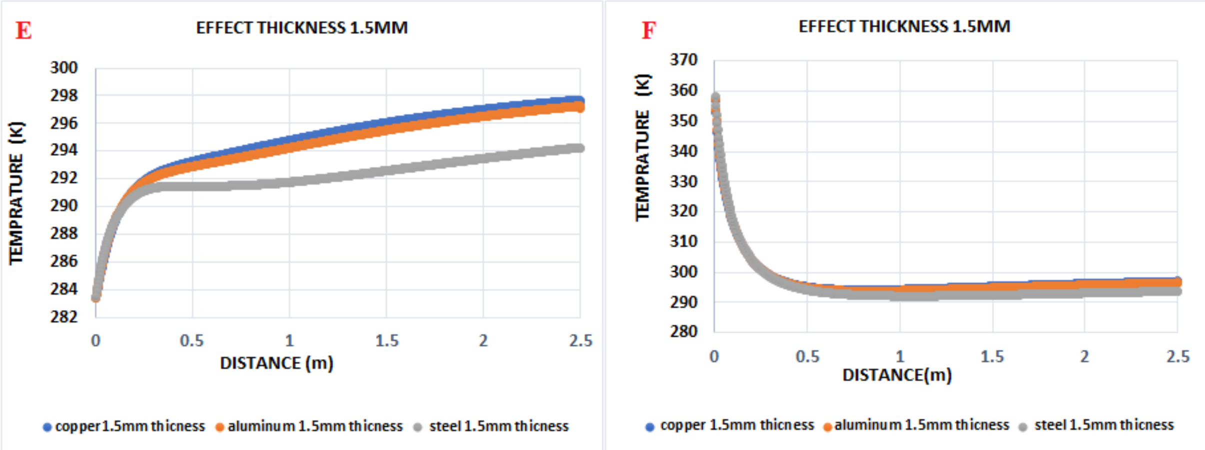

Figure 6 comparing temperature distribution for a thickness of 1.5 mm

Figure 7 indicates that aluminum exhibits the largest temperature difference, followed by iron, with copper showing the smallest. In the cold line (G), aluminium's temperature rises from 283°C to 298°C, producing a difference of 15°C. Iron increases from 283°C to 295°C, resulting in a 12°C difference. Copper records the smallest change, rising from 283°C to 289°C, which corresponds to a difference of 5°C.On the hot side figure 7 steel shows the largest temperature difference, dropping from 360°C to 289°C, a difference of 71°C. Aluminium has a moderate temperature difference, dropping from 360°C to 299°C, a difference of 61°C. Similarly, steel's temperature drops from 360°C to 295°C, a difference of 65°C.On the cold side figure 7 E , aluminium has the highest temperature rise, followed by steel , with copper showing the least change. On the hot side figure 7 H, iron undergoes the greatest temperature drop, copper a moderate drop, and aluminium the smallest. These differences highlight the varying thermal conductivities of the metals: copper equalizes temperatures quickly, aluminium moderately, and Steel more slowly, leading to larger gradients.

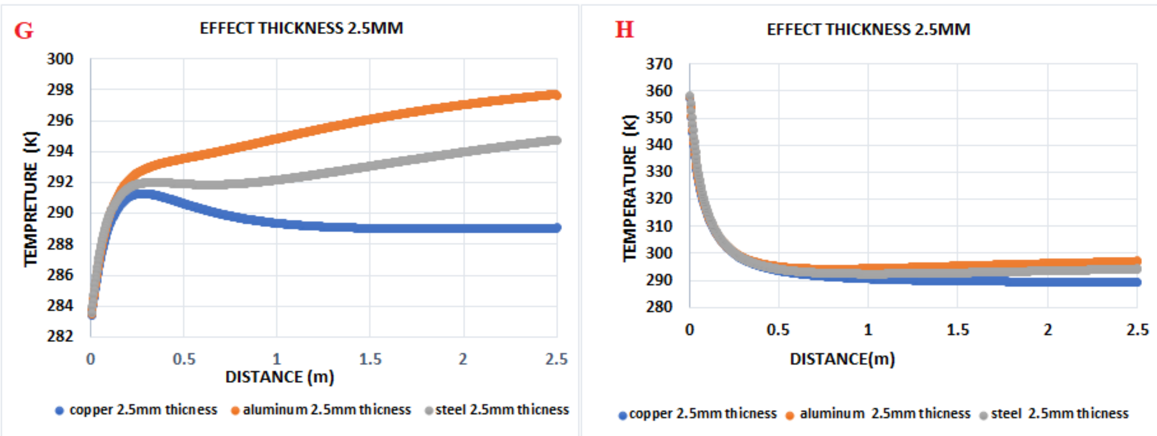

Figure 7 comparing temperature distribution for a thickness of 2.5 mm

Figure 8 illustrates the temperature distribution at the inlet and outlet of the heat exchanger. At the outlet, the fluid dissipates heat transversely across the entire exchanger, demonstrating effective thermal transfer. In contrast, at the inlet, heat dissipation is minimal and occurs only within a short distance from the entry point.

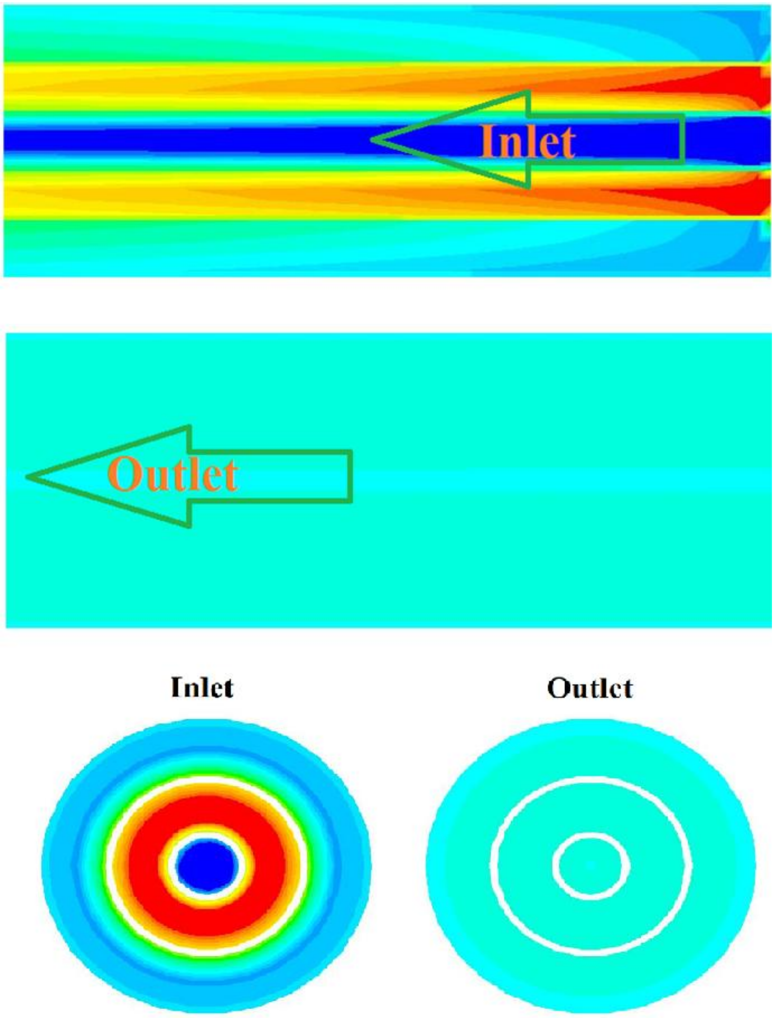

Figure 8 Temperature distribution inlet and outlet.

Conclusion

The CFD simulations in ANSYS Fluent reveal that wall material and thickness significantly influence the thermal performance of the triple-pipe heat exchanger. Copper consistently demonstrates superior heat conduction, producing the steepest radial gradients and the largest cold-side temperature rises, though aluminum occasionally surpasses it under specific thickness conditions. Aluminum provides a balanced performance, combining moderate conduction with structural advantages, while steel (or. iron) exhibits the highest thermal resistance, leading to smaller cold-side rises but larger hot-side drops.

Increasing wall thickness amplifies temperature differences across all materials, highlighting the trade-off between conduction efficiency and structural robustness. Overall, copper remains the most effective conductor for rapid thermal equalization, aluminum offers a practical compromise, and steel resists heat transfer, resulting in more pronounced gradients. These findings underscore the importance of material selection and wall thickness optimization in designing efficient triple-pipe exchangers.

References

1. Bux, S. (2021). *A Review on Triple Tube Heat Exchanger for Optimizing Heat Transfer Rate*. *June*, 4547–4549.
2. Hussien, F. M., Hassoon, A. S., & Faraj, J. J. (2023). *Performance Analysis of a Triple Pipe Heat Exchanger with Phase Change Materials for Thermal Storage*. *41*(3), 619–628.
3. Jack P. Holman. (2009). *Heat Transfer*.
4. Kareem, H. H., Hussien, F. M., & Faraj, J. J. (2022). *The Numerical Simulation of Thermal Efficiency of Triple Pipe Heat Exchanger Using PCMs (Paraffin and Lauric Acid) System*. *40*(6), 1424–1431.
5. M. Quadir, S. A. Khan, and R. I. (2022). Experimental and numerical investigation of triple pipe vs. double pipe heat exchangers. *Heat Mass Transfer*, *182*, 124–134.
6. Rasal, S., Birje, S., Pawaskar, P., Nivale, N., & Dhuri, P. (2017). *Experimental Performance Analysis of Triple Tube Heat Exchanger with Dimple Tubing*. 1–4.
7. Scholar, M. T., Technology, I., Vishwakarma, S., Technology, I., Mishra, J., & Bhopal, I. T. (2020). *A Review on Triple Tube Heat Exchanger on Optimizing Thermal Efficiency*. *6*(12), 30–32.
8. Suarta, I. M. (n.d.). *Experimental Study of Heat Transfer in Concentric Triple Pipe Heat Exchanger Experimental Study of Heat Transfer in Concentric Triple Pipe Heat Exchanger*. https://doi.org/10.1088/1757-899X/1130/1/012048