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CFD-Based Comparative Thermal Performance Analysis of a Helical Baffle Shell and Tube Heat Exchanger Using Different Tube Materials

Dr G Maruthi Prasad Yadav[a*], Mr.G.Md.Javeed Basha[b], Mr.C.Ravi[c]

[a]Professor & Head, [b]Associate Professor, [c]M.Tech Scholar

Department of Mechanical Engineering, St Johns College of Engineering & Technology (Autonomous), Yemmiganur, Kurnool (Dist), AP, India

* Corresponding author. E-mail address: maruthiprasadyadav@gmail.com

A B S T R A C T

A comparative study of the thermal performance of a shell and tube heat exchanger (STHE) with helical baffles is presented in this paper using computational fluid dynamics (CFD). The main objective is to assess how five distinct materials: aluminum, copper, steel, nickel, and titanium affects the overall heat transfer rate and shell-side temperature drop. CATIA V5 was used to model the 3D geometry, and ANSYS Fluent was used for simulations. According to the study, copper produced the higher heat transfer rate (6435.44 W) and temperature reduction (4.9°C) due to its greater thermal conductivity, whereas titanium did the least well. The results offer important new information about how material choice affects heat exchanger design and optimization.

Keywords: shell and tube heat exchanger, helical baffles, ANSYS Fluent, material comparison, heat transfer.

1. Introduction

Because of their demonstrated dependability, mechanical robustness, and versatility under a variety of operating situations, shell and tube heat exchangers (STHEs) are among the most popular types of heat exchangers in industrial operations. The effective transfer of heat between two fluids—usually one running through the tubes and the other over the shell side—is made possible by their design. Power plants, petrochemical refineries, refrigeration units, HVAC systems, chemical process industries, and many other sectors depend heavily on STHEs. They are essential in both small- and large-scale thermal systems due to their resistance to high pressures and temperatures, ease of maintenance, and design flexibility.

Despite their widespread application, there remains a continuous need to improve the thermal performance and energy efficiency of STHEs to meet modern demands for sustainability, cost-effectiveness, and environmental safety. Several strategies have been explored over the decades to enhance the heat transfer rate and reduce pressure losses, including modifications to the flow arrangement, tube geometries, and baffle design.

The arrangement of the baffles inside the shell is among the most important design elements. Even though traditional segmental baffles are good at guiding fluid flow throughout the tube bundle to improve heat transfer, they frequently cause severe pressure drops and dead zones or areas of stagnant flow, which lower efficiency and increase the risk of fouling. Helical baffles are a cutting-edge substitute that has been developed to overcome these restrictions. Helical baffles promote a more uniform and tangential flow pattern than conventional baffles by providing the shell-side fluid with a continuous helical flow route. Dead zones are greatly decreased, turbulence is increased, fluid distribution is improved, and a more effective heat transfer mechanism with fewer pressure drops results from this swirl flow. Thermal enhancement is greatly aided by geometric enhancements such as helical baffles, but the choice of material for the heat exchanger tubes is equally important. The heat transfer rate, pressure drop, structural integrity, and overall lifetime performance of the STHE are all directly impacted by the tube material's thermal conductivity, density, specific heat capacity, and corrosion resistance. Higher thermal conductivity materials typically enable faster heat transfer, increasing the efficiency of exchangers. However, it is crucial to balance mechanical strength, cost, durability, and thermal performance in a variety of fluid conditions. The purpose of this study is to assess how the parameters of the tube material affect the thermal behavior of a STHE with helical baffles. Five widely used industrial materials—aluminum, copper, steel, nickel, and titanium—are analyzed and their performances compared using computational fluid dynamics (CFD) simulations. A thorough grasp of how material selection affects shell-side heat transfer characteristics and overall exchanger performance is made possible by the wide range of mechanical and thermal conductivities that these materials offer. The goal of the study is to shed light on the best material selections for high-performance STHEs with sophisticated baffle layouts intended for a range of industrial uses.

2. Literature Survey

Several notable studies have explored performance improvements in shell and tube heat exchangers using baffle redesign and advanced materials:

Liu et al. (2010) [1] demonstrated through CFD simulations that helical baffles significantly improve heat transfer and reduce pressure drop compared to conventional segmental baffles.

Kakac and Liu (2002) [2] emphasized that material thermal conductivity plays a vital role in determining the effectiveness of heat exchangers and advocated for selection based on operational environment.

Kannadasan et al. (2017) [3] showed that the combination of helical baffles and CFD analysis provides a powerful methodology for optimizing STHE designs.
Rajashekar et al. (2020) [4] investigated the thermal characteristics of STHEs with different baffle configurations using Fluent and observed enhanced vortex formation with helical baffles.
Subramanian et al. (2015) [5] evaluated various metals for tubes in condensers and reported significant differences in heat transfer and fluid flow behavior due to material properties.
Sharma et al. (2021) [6] focused on the impact of thermal conductivity and thickness of tube materials in compact exchangers and found that thinner tubes with high conductivity materials outperform others.
Kumar and Rao (2018) [7] carried out experimental and CFD-based comparative analysis of STHEs using Aluminium and Copper, reinforcing the advantage of high conductivity materials

3. Problem Identification

Conventional segmental baffle STHEs often exhibit high pressure drop, flow maldistribution, and lower thermal efficiency. Helical baffles have shown improvement in flow distribution and turbulence. However, insufficient literature exists on the comparative performance of different tube materials in helical-baffled STHEs, especially using advanced simulation tools like ANSYS Fluent. This research addresses the knowledge gap:
"How do various tube materials affect the thermal performance metrics (temperature drop and heat transfer rate) in a helical baffle STHE?"

4. Methodology

4.1. Geometry and Design

- A 3D model of the STHE with helical baffles was created using CATIA V5.
- All geometrical parameters were kept constant across simulations.
- Tube-side fluid: water at 15°C;
- Shell-side fluid: hot water at 90°C.

4.2. Materials Used

The following materials were used to analyse the performance of shell and tube heat exchanger: Aluminium, Copper, Steel, Nickle and Titanium.

4.3. CFD Simulation Setup

- Software: ANSYS Fluent
- Solver: Pressure-based steady-state
- Energy model: Enabled
- Mesh: Fine mesh near walls, inflation layers used
- Boundary conditions:
  - Shell-side inlet temperature: 90°C
  - Tube-side inlet temperature: 15°C
  - Fixed mass flow rates
- Output parameters: Shell-side outlet temperature and total heat transfer rate

5. Results and Discussion

5.1. Numerical Results

Figures 1, 2, and 3 displayed the temperature, velocity, and pressure counters: The resulting counter attests to the presence of a pressure decrease from the flow's entrance to its exit in the direction of the shell side. Additionally, a high pressure zone was shown to form adjacent to the entrance, which is likely the result of a high pressure hot stream abruptly colliding with the cool tubes. This demonstrates how crucial the shell side entry is to achieving the intended turbulent flow in the shell. Additionally, a sharp reduction in pressure is seen near the shell's exit, suggesting that the location of the shell's exit is crucial for preventing or minimizing the majority of pressure loss. The same kind of pattern is observed in velocity counters that indicates the velocity variation throughout the flow in the shell stream and also shows that entry and exits of shell side plays key role for the sudden variation in the velocity of the flow.
Additionally, the temperature counter was examined; figure 3 illustrates the gradual temperature reduction from the shell side's entrance to departure. Higher temperatures are shown by red, which progressively changes to orange as it approaches the exit. However, because it was taken under a wider temperature band, this graphic does not provide complete and accurate information about the degree of temperature drop. Therefore, two additional counters with narrow bandwidth were taken into consideration for the shell and tube side in order to obtain local level information on the temperature decline. Figures 4 and 5 show the temperature drop and heat transfer rate at the shell side after the same process is repeated with different materials.

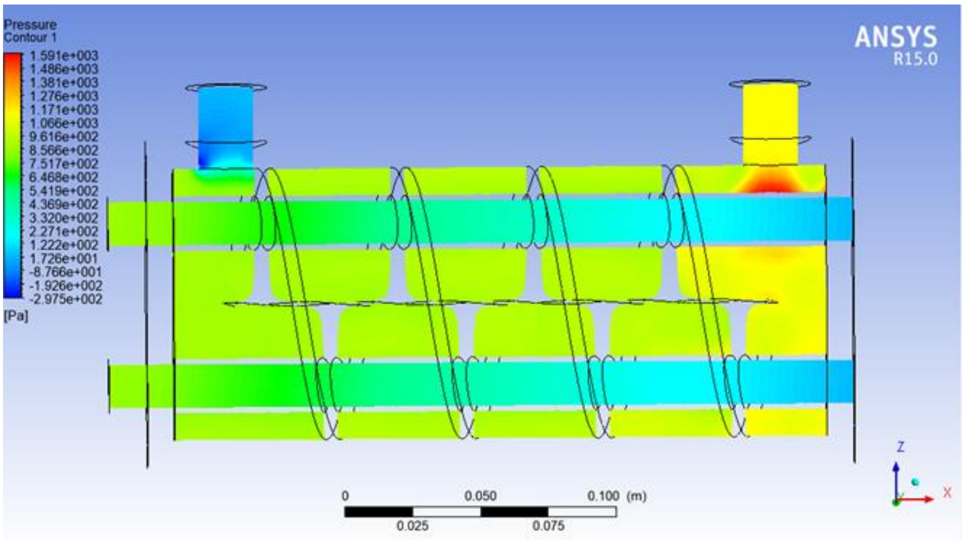

Fig 1: Pressure counter in post CFD for aluminum material

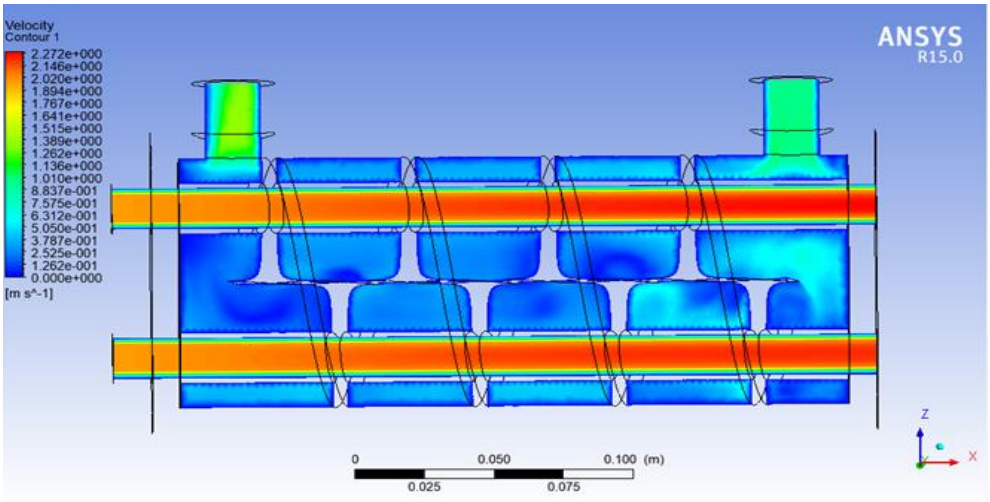

Fig 2: Velocity counter in post CFD for aluminum material

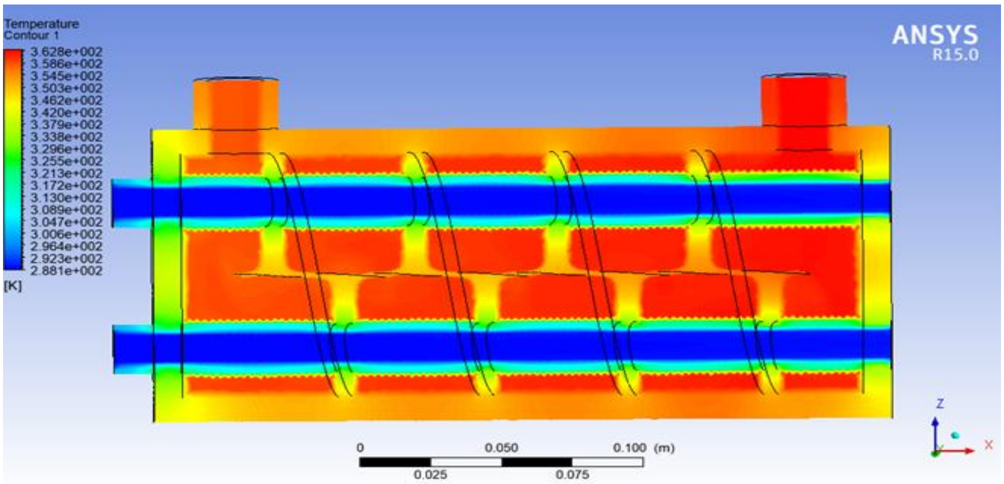

Fig 3: Temperature counter in post CFD for aluminum material

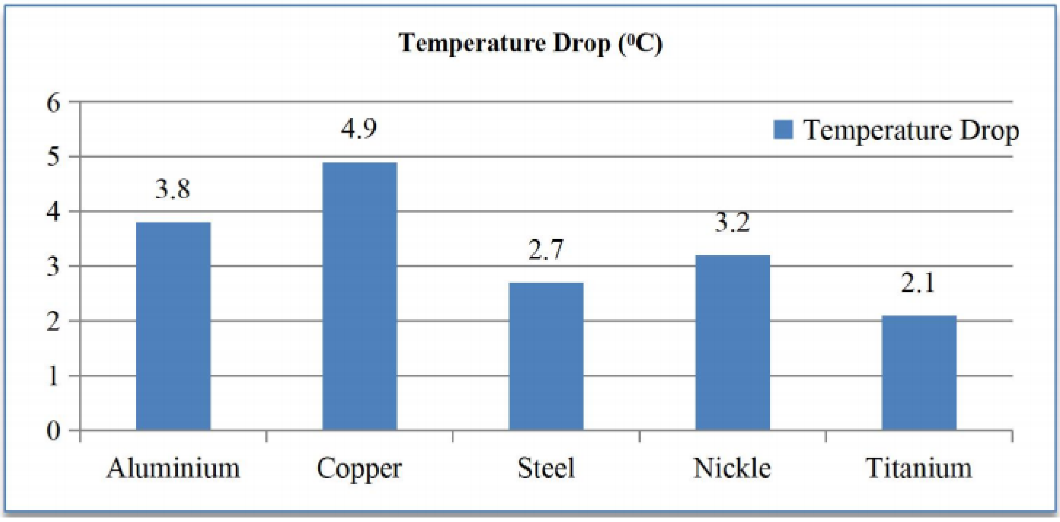

Fig 4: Temperature drop obtained using different materials

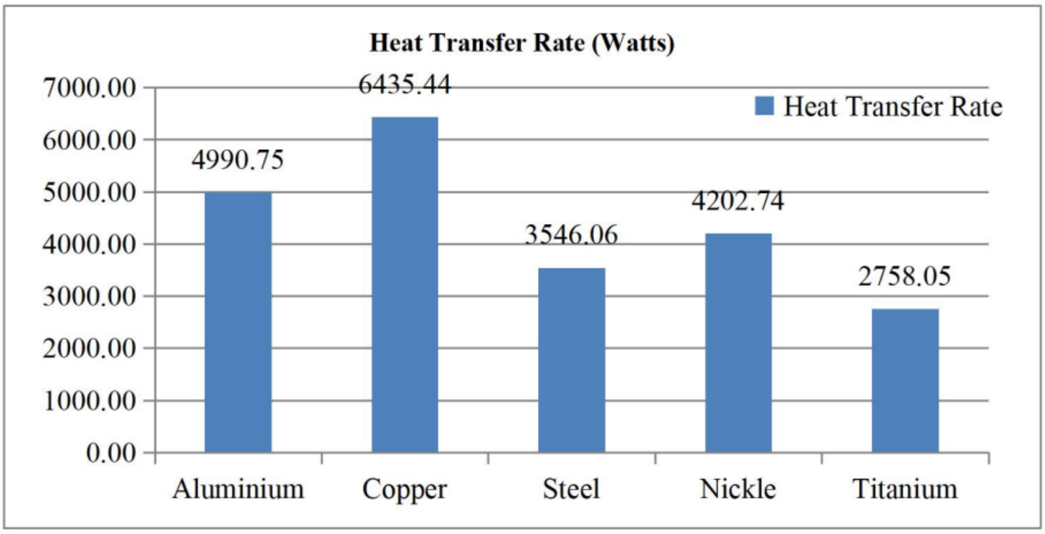

Fig 5: Heat transfer rate attained using different materials

5.2. Extended Discussion

5.2.1. Effect of Thermal Conductivity

Copper, with the highest thermal conductivity (385 W/m·K), exhibited the maximum temperature drop and heat transfer rate. Heat conduction through the solid tube wall is directly influenced by this property. The large thermal gradient across the tube material enhances heat flux, resulting in better overall performance.

Aluminium, though cheaper and lighter, performed slightly below Copper due to lower conductivity. Nickel offered moderate performance and balanced properties. Steel and Titanium underperformed due to poor thermal conductivity, confirming their limited suitability for high-efficiency exchangers unless required for specific corrosion or mechanical resistance.

5.2.2. Heat Transfer Area Utilization

The helical baffle configuration ensures better fluid contact with the tube surfaces, reducing bypass regions and stagnation. Copper and Aluminium tubes could effectively utilize this due to faster conduction, ensuring higher ΔT across the fluid-solid interface.

5.2.3. Flow Turbulence and Thermal Boundary Layer

Helical baffles induce swirl motion in shell-side flow, thinning the thermal boundary layer. For high conductivity materials, the benefit is amplified as heat can be transferred rapidly across the thin conductive wall. In low-conductivity materials like Titanium, the effect is dampened, as resistance to heat conduction within the tube wall remains a bottleneck.

5.2.4. Overall Thermal Resistance (R_total)

The total thermal resistance in a heat exchanger comprises:

$R_{total}=R_{conv,shell}+R_{cond,tube}+R_{conv,tube}$

Where $R_{cond,tube}$ is significantly reduced in Copper and Aluminium, improving $q=\Delta T/R_{total}$. Materials with low k contribute a higher $R_{cond,tube}$, reducing heat flow.

5.2.5. Engineering Implications

- **Copper** is optimal for high-performance systems but expensive.
- **Aluminium** offers a trade-off between cost, weight, and performance.

Steel and **Titanium** are suitable only for applications demanding mechanical strength or corrosion resistance, where thermal performance is secondary.

6. Conclusions

This study used five different materials: copper, aluminum, nickel, steel, and titanium to give a thorough CFD-based performance evaluation of a shell and tube heat exchanger (STHE) with helical baffles. Two important thermal parameters, shell-side temperature drop and total heat transfer rate were used to assess the performance.

It is clear from the simulation results that material thermal conductivity is a major factor in the efficiency of the heat exchanger. With the highest heat transfer rate (6435.44 W) and the maximum temperature drop (4.9°C), copper continuously performed better than the other materials. Copper's performance as a standard (100%) demonstrates the benefits of employing highly conductive materials in heat exchanger tubes.

Compared to Copper:

- **Aluminium** achieved **77.6%** temperature drop and **77.5%** heat transfer rate—making it a cost-effective and lightweight substitute with excellent thermal efficiency.
- **Nickel** showed **65.3%** of Copper's performance in both metrics—suggesting moderate efficiency with better corrosion resistance than Aluminium.
- **Steel**, although structurally robust, reached only **55.1%** efficiency—indicating it is suitable more for mechanical integrity than thermal performance.
- **Titanium**, known for corrosion resistance and strength in aggressive environments, delivered just **42.8%** of the thermal performance of Copper—rendering it suitable only for niche applications where durability outweighs heat transfer needs.

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