

Optimizing Thermal Performance in Triple Concentric Tube Heat Exchangers: A CFD Study on Nanofluids and Design Variations

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Abstract: The performance of Triple Concentric Tube Heat Exchangers (TCTHE) is significantly enhanced by optimizing the design and incorporating nanofluids. Through computational fluid dynamics (CFD) simulations, the study evaluates various configurations, including straight and inclined tubes, with and without baffles. The impact of different nanofluid concentrations on heat transfer efficiency was assessed, showing improved temperature distribution and better heat exchange performance at higher nanofluid concentrations. The results highlight the potential of advanced heat exchanger designs and nanofluids in optimizing energy systems for sustainable applications.

Keywords: Heat exchangers, Triple Concentric Tube Heat Exchanger (TCTHE), nanofluids, Computational Fluid Dynamics (CFD), heat transfer efficiency, energy optimization, sustainable energy systems, fluid flow, temperature distribution, and thermal performance.

I. INTRODUCTION

As global energy demands rise with population growth and industrial advancement, there is an increasing need to optimize energy systems for sustainability. Fossil fuel depletion, climate change, and the environmental impact of energy production highlight the urgent need for renewable energy solutions and more efficient systems, such as HVAC, which play a key role in regulating temperatures in buildings [1]. Despite the growing adoption of renewable energy technologies, societal and democratic challenges hinder their widespread implementation. The construction industry, which consumes vast energy resources for heating, cooling, and refrigeration, faces mounting pressure to adopt eco-friendly, energy-efficient solutions to address global concerns such as global warming, resource depletion, and rising energy consumption [2]. A heat exchanger is an essential device used to transfer heat efficiently between hot and cool fluids, often designed to last for decades. While typically free of moving parts, heat exchangers may face challenges when operating at partial loads, encountering mechanical vibrations, or being reused under changing process conditions. To address these issues, heat exchangers are often redesigned or remodeled. Improving heat transfer efficiency is crucial, with active, passive, and compound methods employed to enhance performance [3]. Passive methods, such as using inserts, are particularly beneficial for existing systems. Heat exchangers are widely used across various industries, including automotive, power plants, and refrigeration, playing a critical role in preventing overheating and improving energy efficiency. Common types include plate and shell-and-tube heat exchangers, which vary in design and application. However, these systems are exposed to environments that can lead to costly corrosion, highlighting the need for durable materials and proper maintenance to reduce operational costs [4].

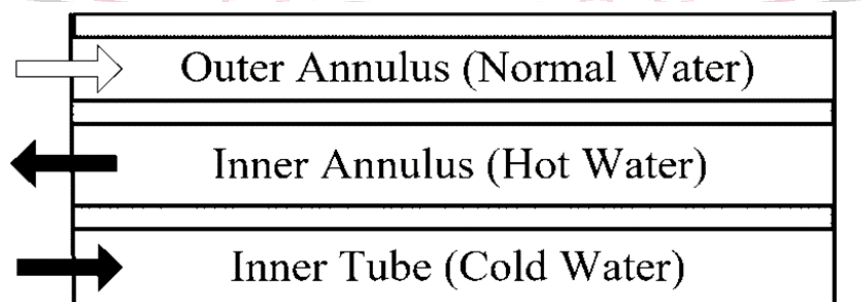


Figure 1 Three fluids in the triple concentric pipe heat exchanger flow in various directions.

The growing demand for energy has led to research aimed at improving the efficiency of thermal devices like heat exchangers. The double-tube heat exchanger, commonly used in industries, has been enhanced with the development of three-tube heat exchangers to increase the heat exchange area and reduce energy consumption. Heat exchangers work by transferring heat between two fluids, either in parallel or counterflow configurations. The Triple Concentric Tube Heat

Exchanger (TCTHE) features an inner and outer annular space along with a central tube, and its design and performance have been extensively studied, with equations developed to simplify its analysis [5].

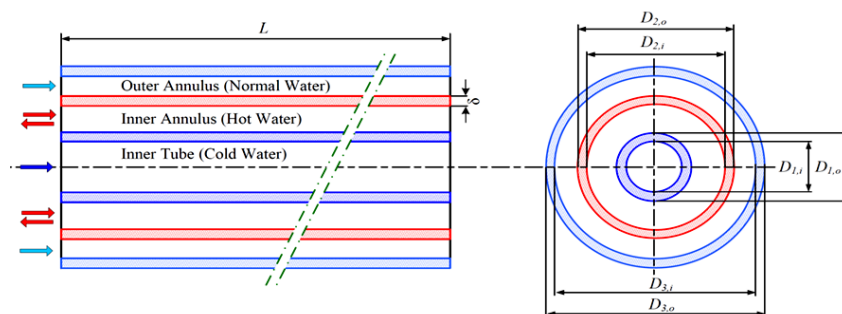


Figure: 2 Triple concentric-tube heat exchanger.

The Triple Concentric Tube Heat Exchanger (TCTHE) offers significant advantages over traditional shell-and-tube exchangers, such as a larger heat exchange area and higher heat transfer coefficient. It allows heat transfer between three fluids in a single unit, making it ideal for applications like food processing, refrigeration, and pasteurization. The use of compact, curved tubes, including helium-hardened heat transfer tubes, has improved heat transmission efficiency. Additionally, heat transfer can be enhanced using both active methods, like rotating surfaces or impinging jets, and passive techniques, such as turbulators, wire coils, or twisted tapes, which are cost-effective and easy to implement [6].

II. LITERATURE REVIEW

Ke Chen et al. (2022) [7] studied the thermal behavior of phase change materials in a vertical triple-tube heat exchanger with annular fins. By optimizing the fin distribution and size, they achieved a 29% reduction in melting time and a 37% improvement in charge rate, compared to uniformly distributed fins, improving heat storage performance.

Iman Bashtani et al. (2021) [8] investigated the effects of adding aluminum oxide nanoparticles (1%, 4%, 6%) to a water-to-water double pipe heat exchanger with turbulators. The study found that nanoparticles and turbulators significantly increased heat transfer, with enhanced efficiency at higher Reynolds numbers, improving the Nusselt number and heat transmission by about 70%.

Ashraf Mimi Elsaid et al. (2021) [9] examined heat transfer and flow characteristics in a triple-ribbed tube heat exchanger using water and hybrid nanoparticles ($\text{Al}_2\text{O}_3 + \text{MWCNT}/\text{H}_2\text{O}$). It demonstrated that hybrid nanofluids enhanced heat transfer compared to single nanofluids, with optimal rib configurations increasing heat transfer rate and effectiveness.

Amin Shahsava et al. (2019) [10] focused on an innovative latent heat storage system with triple-tube wavy channels, showing that sinusoidal waviness significantly increased charging and discharging rates by 50% and 48%, respectively, compared to smooth channels, with a 100% improvement in heat storage and recovery rates.

Nima Mazaheri et al. (2019) [11] evaluated the exergy performance of a ribbed triple-tube heat exchanger using hybrid nanofluids (Pt and graphene). It demonstrated that nanofluids reduced entropy generation and exergy destruction, while the heat exchanger's second law efficiency increased with the nanoparticle concentration.

Table 1 Comparative Analysis of Heat Exchanger Studies with Different Materials and Designs

Authors	Study Focus	Heat Exchanger Type	Nanofluid/Material Used	Key Findings
Ke Chen et al. (2022)	Thermal behavior of phase change materials in a vertical triple-tube heat exchanger with annular fins.	Triple-tube heat exchanger	Phase change material, annular fins	Optimizing fin distribution and size achieved a 29% reduction in melting time and a 37% improvement in charge rate, improving heat storage performance.
Iman Bashtani et al. (2021)	Effects of aluminum oxide nanoparticles (1%, 4%, 6%) in a water-to-water double pipe heat exchanger with turbulators.	Double pipe heat exchanger with turbulators	Aluminum oxide nanoparticles (1%, 4%, 6%)	Nanoparticles and turbulators enhanced heat transfer, improving Nusselt number and heat transmission by about 70% at higher Reynolds numbers.

Ashraf Mimi Elsaid et al. (2021)	Heat transfer and flow characteristics in a triple-ribbed tube heat exchanger using hybrid nanoparticles (Al ₂ O ₃ +MWCNT/H ₂ O).	Triple-ribbed tube heat exchanger	Hybrid nanoparticles (Al ₂ O ₃ +MWCNT/H ₂ O)	Hybrid nanofluids enhanced heat transfer, with optimal rib configurations increasing heat transfer rate and effectiveness.
Amin Shahsava et al. (2019)	Latent heat storage system with triple-tube wavy channels and its performance.	Triple-tube wavy channel heat exchanger	Water as heat transfer fluid, phase change material (PCM)	Sinusoidal waviness significantly increased charging and discharging rates by 50% and 48%, respectively, and improved heat storage and recovery rates by 100%.
Nima Mazaheri et al. (2019)	Exergy performance of a ribbed triple-tube heat exchanger using hybrid nanofluids (Pt and graphene).	Ribbed triple-tube heat exchanger	Hybrid nanoparticles (Platinum and graphene)	Nanofluids reduced entropy generation and exergy destruction, while second law efficiency increased with nanoparticle concentration.

III. OBJECTIVE

- To develop various computational models for triple concentric tube heat exchangers with straight, inclined, and no baffles.
- To perform a CFD analysis on each design with varying nanofluid concentrations.
- To compare results from different triple concentric tube heat exchanger designs.
- To study various heat exchangers and their mathematical relationships.

IV. METHODOLOGY

This study focuses on the mathematical analysis of a concentric triple-tube heat exchanger, specifically for cooling applications. In this system, cold fluids flow through the inner and outer tubes, entering at temperatures $T_{c1(in)}$ and exiting at $T_{c1(out)}$ and $T_{c2(out)}$, respectively. The hot fluid, entering the inner annulus at $T_{h(in)}$ and exiting at $T_{h(out)}$, requires cooling. The heat transfer modeling approach varies based on whether the hot fluid flows concurrently or counterflow with the cold fluid, with both configurations examined separately. Assumptions made include steady-state conditions, constant fluid properties, no phase changes, and insulation from the surroundings. The study also considers the overall heat transfer coefficients in the countercurrent flow arrangement, where the energy balance equations for the hot and cold fluids are derived.

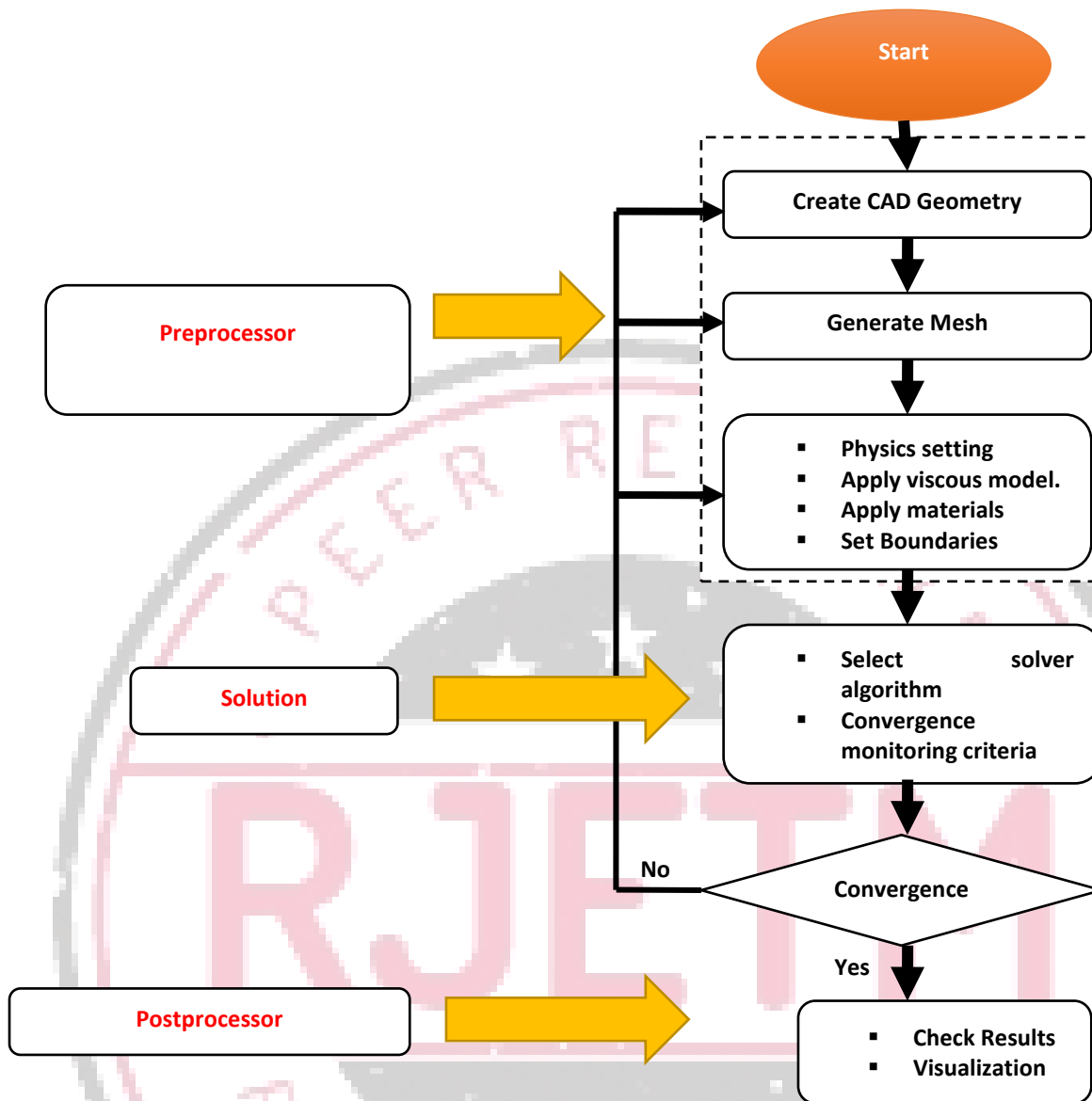


Fig. 3 Computational fluid dynamics analysis algorithm.

V. RESULT ANALYSIS

This work uses mathematical analysis and computational fluid dynamics (CFD) to evaluate various designs of concentric triple-tube heat exchangers, including configurations with or without baffles, and inclined baffles at 45°, 60°, and 75°. Two cold fluids flow through the inner and outer tubes, while a hot fluid circulates in the center tube, with nanofluid concentrations of 0, 0.02, 0.06, and 0.1%. The study employs Fluent software, solving governing equations using the finite volume method and the SIMPLE algorithm, with the RNG k-epsilon model for turbulent flow. Boundary conditions, including mass flow inlets and pressure outlets, are applied, and the effects of these design variations on heat transfer and fluid flow are analyzed.

Table 2 Comparative results of temperature distribution for concentric triple tube heat exchanger without baffle at different concentration ratio

Concentration ϕ (%)	Cold water at Temperature outlet		Nano-fluid at Temperature outlet		Normal Water at Temperature outlet		Nano-fluid at Temperature entire length	
	Min	Max	Min	Max	Min	Max	Min	Max
0.0	11.96	22.71	42.82	66.26	18.80	41.96	27.39	69.47
0.02	11.84	21.65	42.83	66.52	18.76	40.97	26.40	69.46
0.06	11.60	21.89	37.63	64.04	18.64	40.29	24.04	69.46
0.1	10.69	20.04	19.85	41.80	18.22	36.91	15.53	69.36

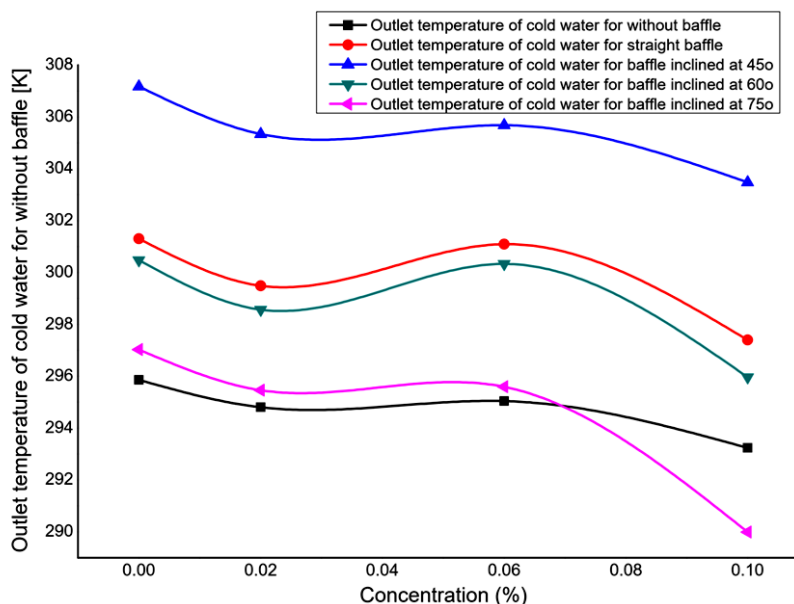


Figure 4 Comparative results of outlet temperature of cold water for concentric triple tube heat exchanger at various configuration and concentrations

VI. Conclusion

The study concludes that the TCTHE design, particularly when coupled with nanofluids, shows significant improvements in heat transfer efficiency compared to traditional heat exchangers. The inclusion of varying concentrations of nanofluids, along with different tube configurations, resulted in optimized temperature distribution and enhanced overall performance. These findings highlight the importance of innovative design strategies, such as the use of nanofluids and specialized configurations, in addressing the growing demand for energy-efficient and sustainable thermal systems across various industrial applications.

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