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A review on performance optimization of counter flow double pipe heat exchanger using statistical and response surface analysis

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ABSTRACT

Counter-flow double pipe heat exchangers are extensively used in industrial thermal systems due to their simple design, ease of operation, and high heat transfer efficiency. In recent years, performance optimization of these heat exchangers has gained significant attention with the application of statistical techniques and Response Surface Methodology (RSM). This review presents a comprehensive analysis of published studies focused on the optimization of counter-flow double pipe heat exchangers using statistical tools such as Design of Experiments (DoE), Analysis of Variance (ANOVA), regression modeling, and RSM. The review highlights the influence of key operating and design parameters—including hot and cold fluid mass flow rates, inlet temperatures, heat transfer area, and flow arrangement—on outlet temperatures, effectiveness, and overall thermal performance. The effectiveness of RSM in developing predictive models, identifying significant factors, and determining optimal operating conditions with minimal experimental effort is critically discussed.

Keywords: Counter-flow double pipe heat exchanger; Performance optimization; Response Surface Methodology (RSM); Statistical analysis; ANOVA; Heat transfer effectiveness; Thermal performance

1. INTRODUCTION

Heat exchangers are essential thermal devices widely used in industrial processes to transfer heat between two or more fluids at different temperatures without mixing them. They play a crucial role in industries such as power generation, chemical processing, refrigeration, petroleum refining, HVAC systems, and food processing. Efficient heat transfer not only improves energy utilization but also reduces operational costs and environmental impact [1].

A double pipe heat exchanger is one of the simplest and most used types of heat exchangers. It consists of two concentric pipes — one fluid flows through the inner pipe, while the other flows through the annular space between the inner and outer pipes [2]. This configuration is especially suitable for small-scale heat transfer applications, experimental setups, and situations requiring flexibility in operation and maintenance.

Among different flow arrangements, the counter-flow configuration is considered the most efficient. In a counter-flow double pipe heat exchanger, the hot and cold fluids flow in opposite directions [3]. This arrangement maintains a higher temperature gradient along the length of the exchanger compared to parallel flow, resulting in improved heat transfer efficiency and better thermal performance. It also allows the cold fluid outlet temperature to approach the hot fluid inlet temperature, which is often desirable in industrial applications [4].

The performance of a counter-flow double pipe heat exchanger depends on several factors, including fluid properties, flow rate, temperature difference, heat transfer coefficient, pipe material, and insulation. Proper design and analysis are essential to ensure optimal heat transfer, energy savings, and system reliability [5].

This study focuses on understanding the working principle, design considerations, and thermal performance of a counter-flow double pipe heat exchanger. It aims to analyze heat transfer characteristics, evaluate efficiency, and highlight its practical applications in engineering systems [6].

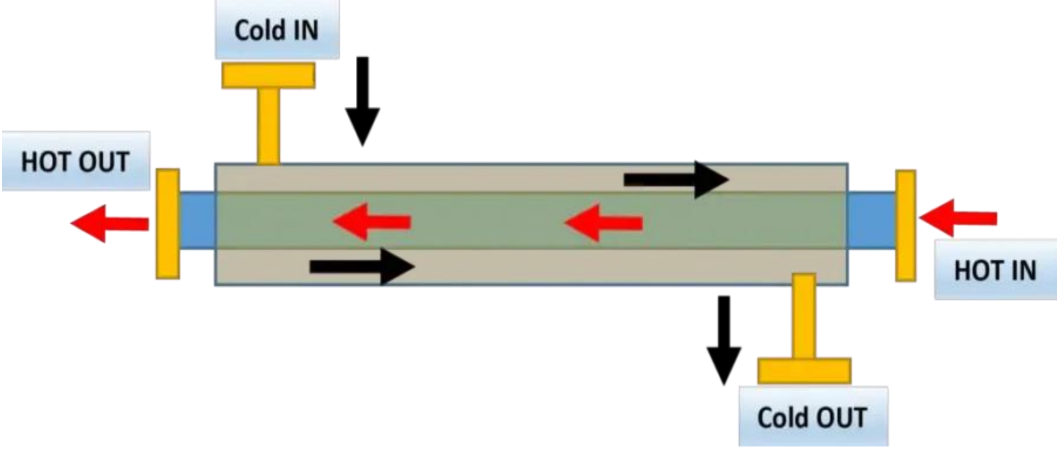

Fig. 1: Double pipe heat exchanger [7]

The figures 1 illustrate the construction and working principle of a counter-flow double pipe heat exchanger, which is one of the simplest types of heat exchangers used to transfer heat between two fluids without mixing them. It consists of two concentric pipes where one fluid flows through the inner pipe while the other flows through the annular space between the two pipes [8]. In the counter-flow arrangement, the hot fluid enters from one end of the exchanger and flows in the opposite direction to the cold fluid, which enters from the other end. Heat transfer occurs through the wall of the inner pipe due to the temperature difference between the fluids. This opposite flow arrangement maintains a higher temperature gradient along the length of the exchanger, resulting in more efficient heat transfer compared to parallel flow. Such heat exchangers are widely used in industrial applications including chemical processing, power plants, refrigeration systems, and HVAC operations due to their simple design, ease of maintenance, and effective thermal performance [9].

2. LITERATURE REVIEW

Sharifi et al. (2026) [10] examine the hydrothermal performance and entropy generation characteristics of mixed convection heat transfer in Couette–Poiseuille flow using a trihybrid nanofluid over a backward-facing step. The study focuses on improving thermal efficiency by combining forced convection (pressure-driven Poiseuille flow) with shear-driven motion (Couette flow) while incorporating advanced nanofluids containing three different types of nanoparticles. Such trihybrid nanofluids are increasingly explored because they typically offer superior thermal conductivity, heat transfer capability, and stability compared with single or hybrid nanofluids. The backward-facing step geometry is important because it induces flow separation and recirculation, conditions commonly found in heat exchangers, cooling channels, and industrial thermal systems.

Yu et al. (2026) [11] investigate the heat transfer and pressure drop characteristics during particle bed flooding through experimental visualization techniques. The study focuses on understanding how fluid flows through packed particle beds under flooding conditions, which are commonly encountered in industrial equipment such as heat exchangers, chemical reactors, filtration systems, and cooling applications. Flooding occurs when the fluid flow rate becomes high enough to disrupt normal flow patterns, causing increased resistance, unstable flow behavior, and changes in heat transfer performance. The researchers use visualization experiments to observe flow structures, liquid distribution, and thermal behavior inside the particle bed.

Hua et al. (2026) [12] investigate boiling heat transfer performance in silicon-based hybrid distributed jet-expanding microchannels, focusing specifically on how different branching numbers influence thermal efficiency. Microchannel cooling systems are widely used in advanced thermal management applications such as electronics cooling, microprocessors, power devices, and compact heat exchangers because they provide high heat removal capacity within a small footprint. The study aims to improve boiling heat transfer by combining distributed jet impingement with expanding microchannel geometries fabricated on silicon substrates. The researchers experimentally analyze how varying the number of channel branches affects fluid flow distribution, boiling characteristics, heat transfer coefficient, and pressure drop.

Ma et al. (2026) [13] analyze the flow and heat transfer characteristics of spiral microchannel heat sinks, focusing on improving cooling efficiency for high-heat-flux applications such as electronic devices, microprocessors, and compact thermal systems. Microchannel heat sinks are widely used because their high surface-area-to-volume ratio enhances convective heat transfer, and spiral channel designs are explored to further improve coolant distribution and thermal performance. The study investigates how spiral microchannel geometry influences fluid flow behavior, temperature distribution, pressure drop, and heat transfer efficiency.

Zhao et al. (2026) [14] investigate the influence of heat and mass transfer processes on the electrochemical performance of proton exchange membrane fuel cells (PEMFCs). PEM fuel cells are widely used in clean energy applications such as electric vehicles, portable power systems, and renewable energy technologies, where efficient thermal and mass transport management is essential for optimal performance and durability. The study focuses on how heat generation, water management, gas diffusion, and temperature distribution affect electrochemical reactions inside the fuel cell. Proper heat transfer is necessary to maintain suitable operating temperatures, while effective mass transfer ensures the continuous supply of reactants such as hydrogen and oxygen and the removal of byproducts like water vapor.

Rinik et al. (2025) [15] conducted a detailed study on the enhancement of heat transfer in a double pipe heat exchanger using an innovative configuration consisting of an elliptical twisted inner pipe combined with a convergent conical ring turbulator under turbulent flow conditions. The objective of the research was to improve heat transfer performance while maintaining an acceptable pressure drop, which is an important consideration in the efficient design of industrial heat exchangers. The study employs passive heat transfer enhancement techniques that do not require external energy input. The elliptical twisted inner pipe modifies the flow structure by generating swirl motion and secondary flows, which improve fluid mixing and reduce the thermal boundary layer thickness.

Shah et al. (2025) [16] investigate the development and performance of an ultra-stable counter-flow diverging minichannel heat sink integrated with microstructures designed to achieve superior cooling efficiency. The study focuses on improving thermal management systems used in high-power electronics, microprocessors, and compact energy devices where efficient heat dissipation is critical for performance, safety, and reliability. The proposed heat sink design incorporates diverging minichannels operating in a counter-flow configuration along with engineered microstructures on channel surfaces. The diverging channel geometry helps maintain stable fluid flow by reducing pressure buildup and preventing flow instabilities commonly observed in conventional parallel minichannel heat sinks.

Khaboshan et al. (2025) [17] investigate the thermal uniformity of a hybrid battery pack cooling system that integrates phase change material (PCM), metal foam, and counterflow minichannels to enhance heat dissipation and maintain safe operating temperatures. The study is particularly relevant for electric vehicles, energy storage systems, and high-power batteries, where temperature control is essential for performance, lifespan, and safety. The research proposes a hybrid thermal management system combining three cooling strategies. Phase change material is used for its latent heat storage capability, allowing it to absorb excess heat during battery operation without a significant rise in temperature.

Özenbiner et al. (2022) [18] conducted a numerical investigation of heat transfer characteristics in a nanofluid-based counter-flow heat exchanger, focusing on improving thermal performance through the use of nanofluids instead of conventional working fluids. Counter-flow heat exchangers are widely used in industrial processes because they provide higher thermal efficiency compared to parallel-flow arrangements, and incorporating nanofluids has the potential to further enhance heat transfer due to their improved thermophysical properties. The study analyzes the effects of nanoparticle addition on fluid flow, temperature distribution, heat transfer rate, and overall exchanger effectiveness.

Salameh et al. (2023) [19] conducted both experimental and numerical investigations to evaluate heat transfer enhancement in a concentric counter-flow tube heat exchanger using different nanofluids. The primary aim of the study was to improve heat exchanger performance by utilizing nanofluids with superior thermophysical properties compared to conventional fluids. Counter-flow heat exchangers are already known for their higher thermal effectiveness, and the addition of nanofluids further enhances their heat transfer capabilities. The study examined several types of nanofluids prepared by dispersing nanoparticles into base fluids such as water or other liquids.

Li et al. (2022) [20] conducted an experimental investigation on flow boiling heat transfer in a bidirectional counter-flow microchannel heat sink, focusing on improving cooling performance for high-heat-flux applications such as electronic devices, microprocessors, and compact thermal systems. Microchannel heat sinks are widely used because they offer high surface-area-to-volume ratios, which enhance heat removal efficiency, especially when phase-change heat transfer such as boiling is involved. The study examines a bidirectional counter-flow configuration where coolant flows in opposite directions within adjacent microchannels. This arrangement helps maintain a strong temperature gradient along the heat sink length, promoting efficient heat transfer and more uniform temperature distribution.

3. CONCLUSION

Despite significant advancements in heat transfer and thermal management technologies, several research gaps remain in the development and optimization of advanced heat exchangers and thermal systems. Many studies focus on improving heat transfer performance through nanofluids, microchannel designs, advanced geometries, and additive manufacturing techniques; however, integrated analysis combining thermal performance, hydraulic efficiency, cost, and long-term operational stability is still limited. Most research emphasizes laboratory-scale experimentation or numerical simulation, while real-world industrial validation and large-scale implementation remain insufficiently explored.

Additionally, although nanofluids and advanced materials show promising heat transfer enhancement, issues such as stability, viscosity increase, pressure drop, maintenance requirements, and economic feasibility require further investigation before widespread industrial adoption. Similarly, emerging technologies such as 3D-printed compact heat exchangers, TPMS structures, and microchannel cooling systems offer improved thermal performance, but their durability, manufacturability, and long-term reliability under varying operating conditions need more comprehensive study.

Another gap exists in optimizing heat exchanger designs to balance heat transfer enhancement with energy consumption, pressure drop, and sustainability considerations. Many enhancement techniques improve heat transfer but simultaneously increase pumping power or operational complexity. Furthermore, integrated thermal management strategies for modern applications such as renewable energy systems, electric vehicles, and high-power electronics are still evolving and require multidisciplinary research approaches. Therefore, further research is needed to develop cost-effective, energy-efficient, and practically viable heat transfer enhancement solutions that address performance, reliability, and sustainability simultaneously.

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