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Comparative Analysis of the Performance and Efficiency of Heat Transfer in Heat Exchangers

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ABSTRACT

This study investigated the comparative analysis of the performance and efficiency of heat transfer in parallel flow and counter flow double tube heat exchangers. The research adopted a laboratory-based experimental design in which a concentric tube heat exchanger was operated under controlled conditions to evaluate the influence of flow configuration on thermal performance. Hot and cold water were used as working fluids, and key parameters such as inlet and outlet temperatures, heat transfer rate, log mean temperature difference, overall heat transfer coefficient, and thermal effectiveness were determined for both configurations. The results revealed that the counter flow arrangement consistently exhibited superior thermal performance compared to the parallel flow configuration. This improvement was attributed to the sustained temperature gradient along the length of the heat exchanger, which enhanced heat transfer efficiency and effectiveness. In contrast, the parallel flow configuration showed a rapid reduction in temperature difference, leading to lower heat transfer performance. The findings of the study are consistent with established heat transfer theories and previous empirical studies. Overall, the study concludes that counter flow double tube heat exchangers provide better energy utilization and are more suitable for applications requiring high thermal efficiency.

Keywords: *Double Tube Heat Exchanger; Parallel Flow; Counter Flow; Heat Transfer Performance; Thermal Effectiveness; Overall Heat Transfer Coefficient; Pressure Drop*

INTRODUCTION

Heat exchangers play a critical role in mechanical and process engineering by enabling efficient thermal energy transfer between fluids at different temperatures. They are widely applied in power generation, refrigeration, chemical processing, petroleum refining, and HVAC systems. Efficient heat exchanger design is essential for reducing energy consumption, improving system performance, and supporting environmental sustainability (Incropera et al., 2017). Consequently, flow configuration and design optimization remain central concerns in heat exchanger performance evaluation.

The double tube heat exchanger (DTHE) is among the simplest and most commonly used heat exchangers due to its compact structure, ease of maintenance, and suitability for laboratory and industrial applications. Heat transfer in a DTHE occurs between two fluids flowing through concentric tubes, and its performance is strongly influenced by flow arrangement, fluid properties, and operating conditions (Kakaç, Liu, & Pramuanjaroenkij, 2020). The two primary flow configurations are parallel flow and counter flow, each exhibiting distinct thermal characteristics.

In a parallel flow arrangement, both fluids enter the exchanger at the same end and flow in the same direction. Although simple, this configuration experiences a rapid reduction in temperature difference along the exchanger length, leading to lower thermal effectiveness (Çengel & Ghajar, 2019). In contrast, counter flow arrangements allow fluids to move in opposite directions, maintaining a higher average temperature gradient and thereby enhancing heat transfer performance. Previous studies have shown that counter flow exchangers generally provide superior thermal effectiveness and outlet temperature control compared to parallel flow systems (Bejan & Kraus, 2020).

Recent experimental and numerical studies have further confirmed that counter flow DTHEs typically achieve higher overall heat transfer coefficients, although they may be associated with increased pressure drops (Gupta & Patel, 2022; Alwi et al., 2023). Given the growing emphasis on energy efficiency and sustainable thermal systems, especially in renewable energy and waste heat recovery applications, a clear comparative assessment of these flow configurations is essential. This study therefore investigates and compares the heat transfer performance of parallel and counter flow double tube heat exchangers under varying operating conditions.

Problem Statement

Despite the extensive application of double tube heat exchangers, inefficiencies related to flow configuration selection continue to limit their thermal performance. Parallel flow arrangements often suffer from reduced heat transfer effectiveness due to rapid temperature equalization, while counter flow configurations, although more efficient, may introduce higher pressure losses and operational challenges (Çengel & Ghajar, 2019; Bejan & Kraus, 2020). Existing studies have not sufficiently addressed the comparative performance of these configurations under practical operating conditions relevant to small- and medium-scale applications. This study addresses this gap by providing a systematic comparison of parallel and counter flow DTHEs to identify the configuration that offers optimal thermal performance and operational efficiency.

Aim and Objectives

The aim of this study is to comparatively evaluate the heat transfer performance of parallel flow and counter flow double tube heat exchangers.

The specific objectives are to:

1. Compare the rates of heat transfer in parallel and counter flow DTHEs.
2. Evaluate the thermal effectiveness and overall heat transfer coefficients of both configurations.
3. Examine the influence of flow arrangement on pressure drop and temperature distribution.
4. Identify the configuration that provides the best balance between thermal efficiency and operational stability.

LITERATURE REVIEWS

Heat Transfer Fundamentals

Heat transfer is the process of thermal energy exchange between media as a result of temperature differences. The predominant heat transfer modes in heat exchangers include conduction, convection, and, to a minimal extent in enclosed systems, thermal radiation. According to Cengel and Ghajar (2022), conduction occurs due to molecular interaction with heat transfer rate expressed by Fourier's Law:

$$q = -kA\left(\frac{dT}{dx}\right) \qquad eq\ (1)$$

Where:

q = heat transfer rate (W)

k = thermal conductivity (W/m·K)

A = area normal to heat flow (m²)

$\frac{dT}{dx}$ = temperature gradient (K/m)

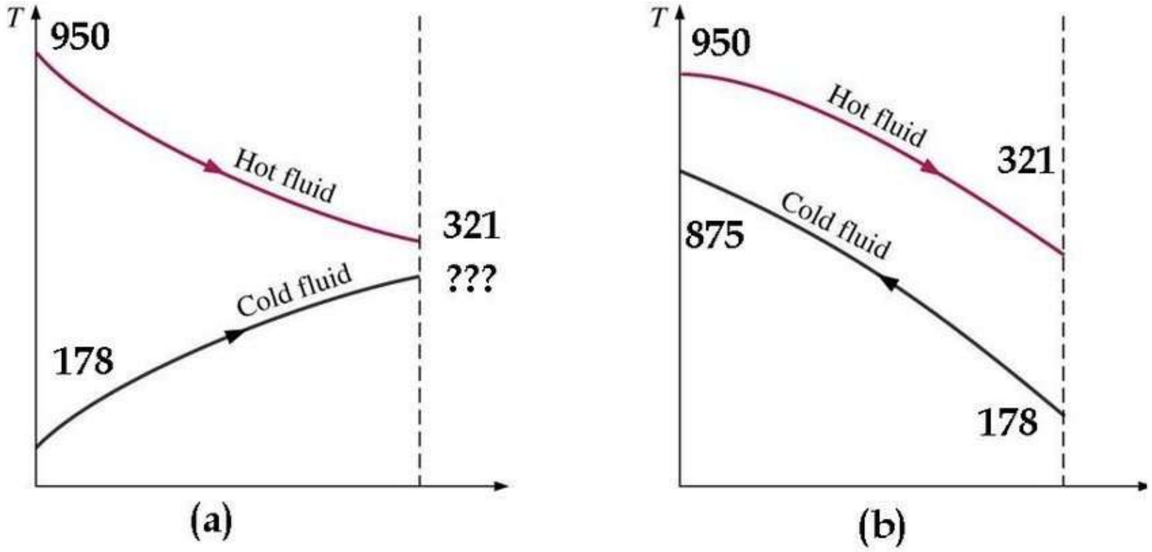
Convection involves energy transfer between solid surfaces and moving fluids and is governed by Newton's Law of Cooling:

$$q = hA(Ts - T\infty) \qquad eq\ (2)$$

Where h represents the convection heat transfer coefficient (W/m²·K).

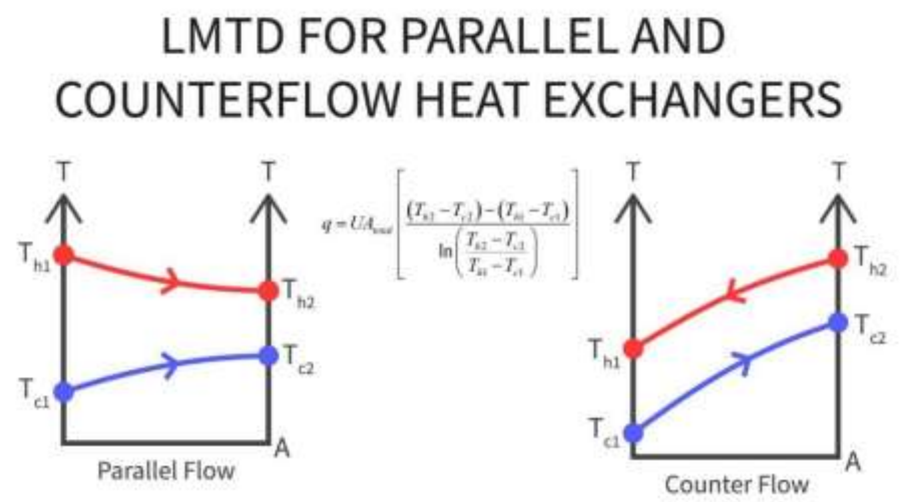
Parallel Flow Heat Exchangers

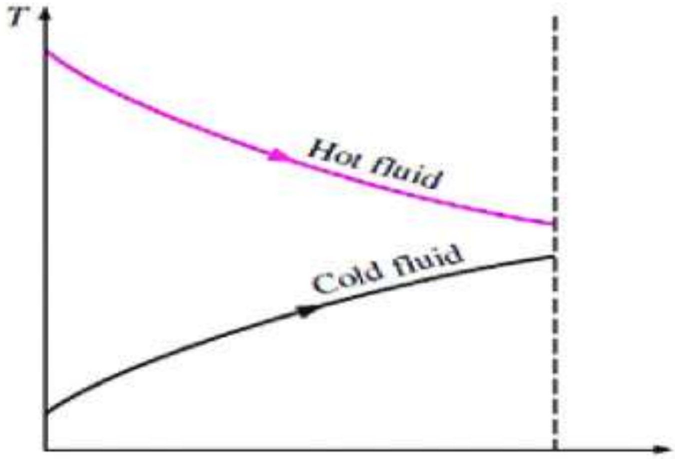
In a parallel flow heat exchanger, the hot and cold fluids enter the exchanger at the same end and flow in the same direction along the tube length. Because both fluids travel side-by-side from the inlet to the outlet, the temperature difference between them is highest at the inlet but becomes small toward the outlet. This leads to a rapid reduction in the rate of heat transfer as the fluids move downstream (Cengel & Ghajar, 2022).

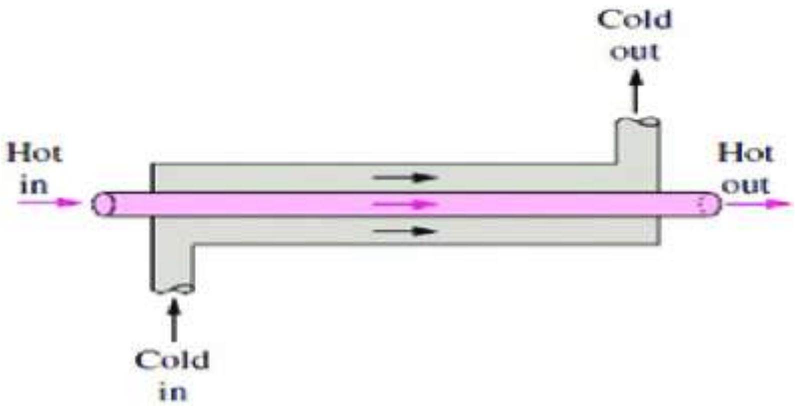


Performance Characteristics

Parallel flow exchangers have less thermal effectiveness than other configurations because the temperature of the cold fluid can never rise above the outlet temperature of the hot fluid. The outlet temperatures of both fluids tend to approach each other, leading to limited thermal driving force. For this reason, the Log Mean Temperature Difference (LMTD) for parallel flow systems is usually lower and reduces heat transfer capability (Kakaç et al., 2020).





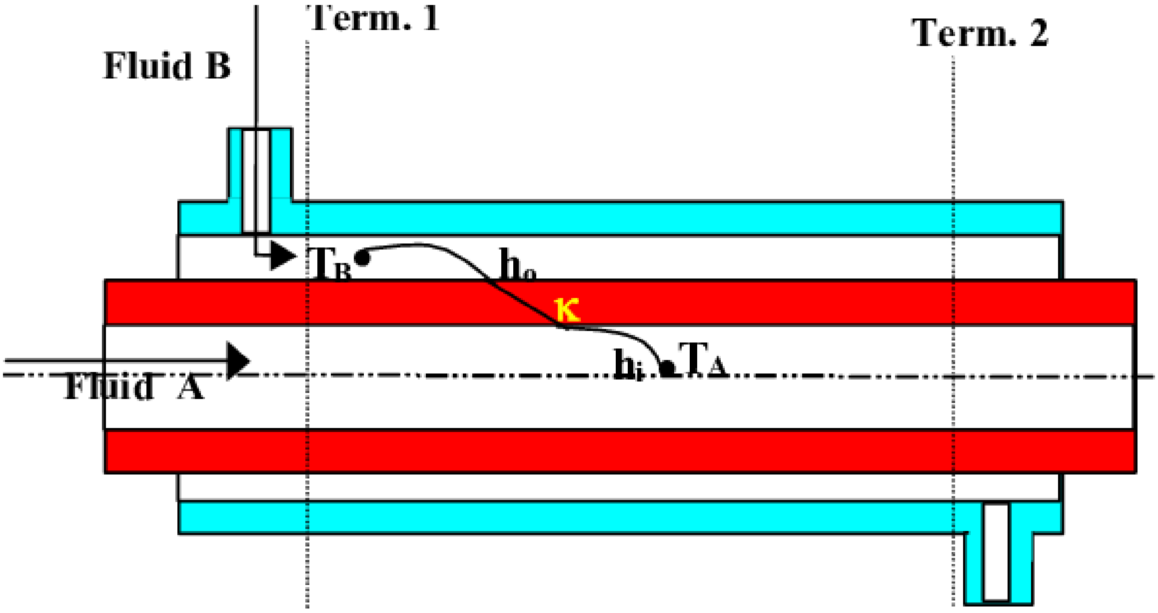


Applications

Parallel flow systems are used where:

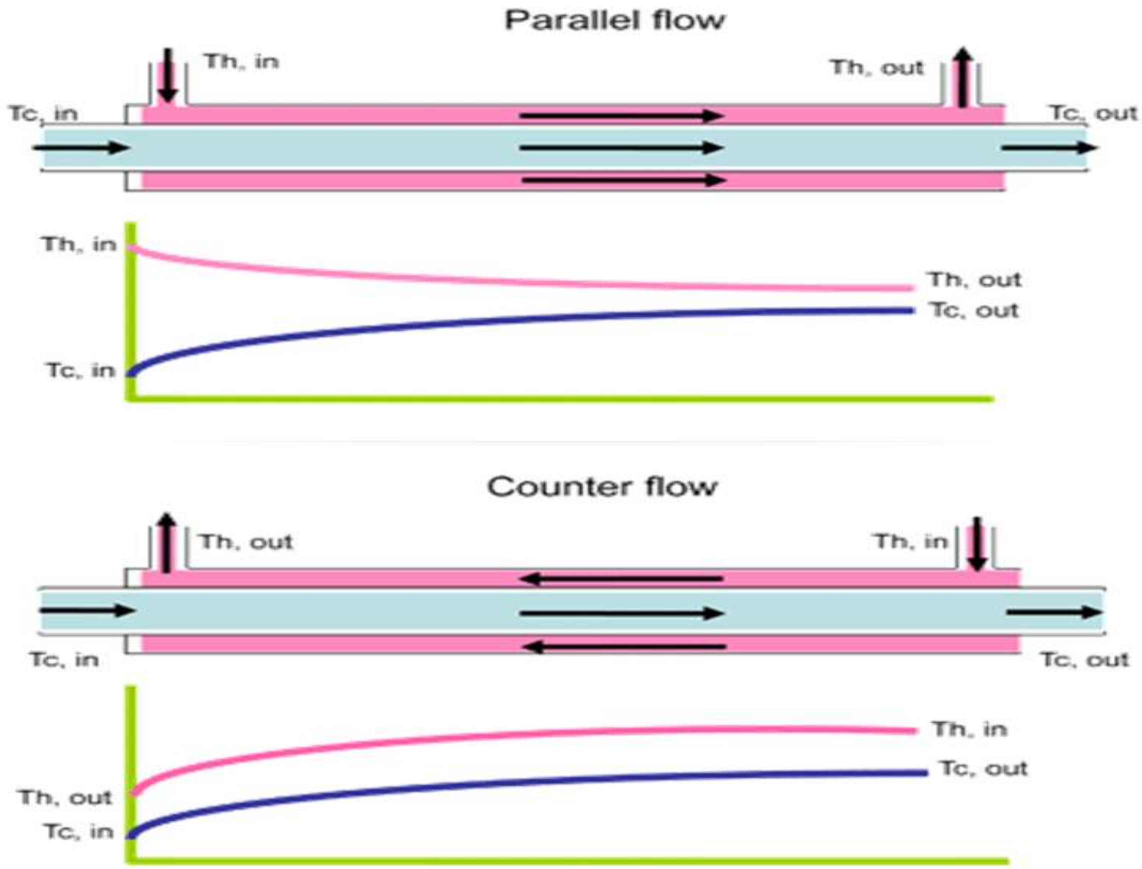
- Temperature changes required are small
- Fluid outlet temperatures must be close to each other
- Thermal stress on the material must be minimized

Examples include medical sterilizers and some small heating coils.



Counter Flow Heat Exchangers

In a counter flow configuration, the fluids flow in opposite directions, allowing the cold fluid to meet the hottest section of the hot fluid and vice versa. This maintains a higher temperature difference over the entire length of the exchanger (Incropera et al., 2017).



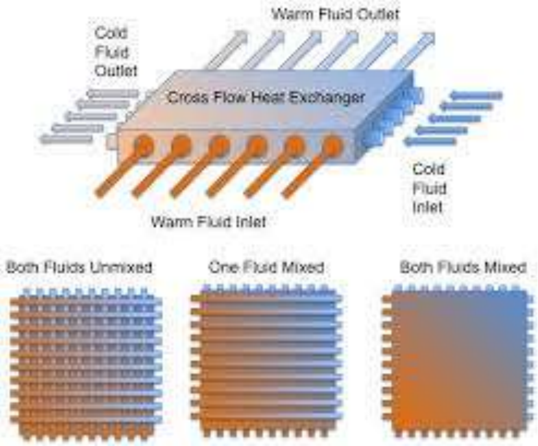
Applications

Counter flow heat exchangers are used widely in:

- Refrigeration and HVAC evaporators and condensers
- Power plant economizers
- Chemical processing plants

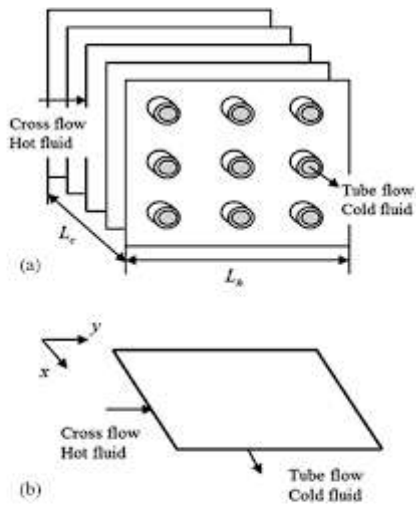
- Double tube experimental systems (like in this research work)

Cross Flow Heat Exchangers



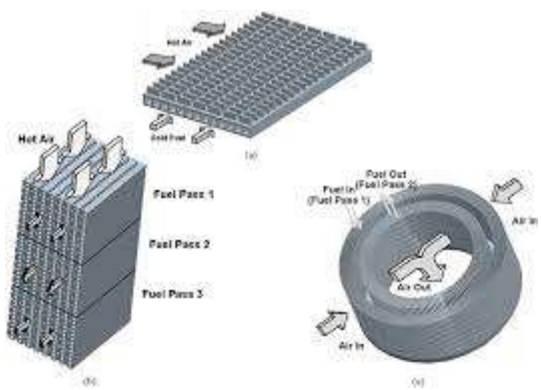
In cross flow systems, the hot and cold fluids flow perpendicular to each other**.** These exchangers are common when one of the fluids must pass through a large area in multiple channels or fins (Cengel & Ghajar, 2022).

For example, in car radiators, the coolant flows inside small tubes while air flows across the tubes at right angles using fan-driven convection.

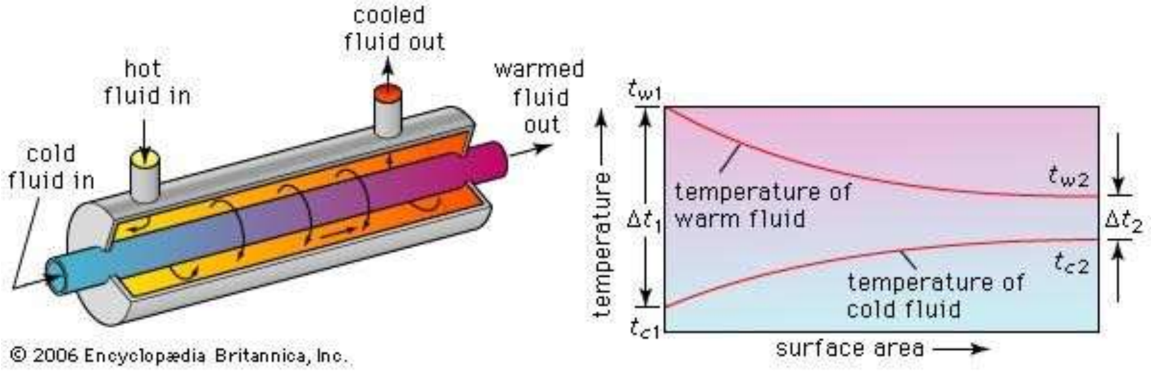


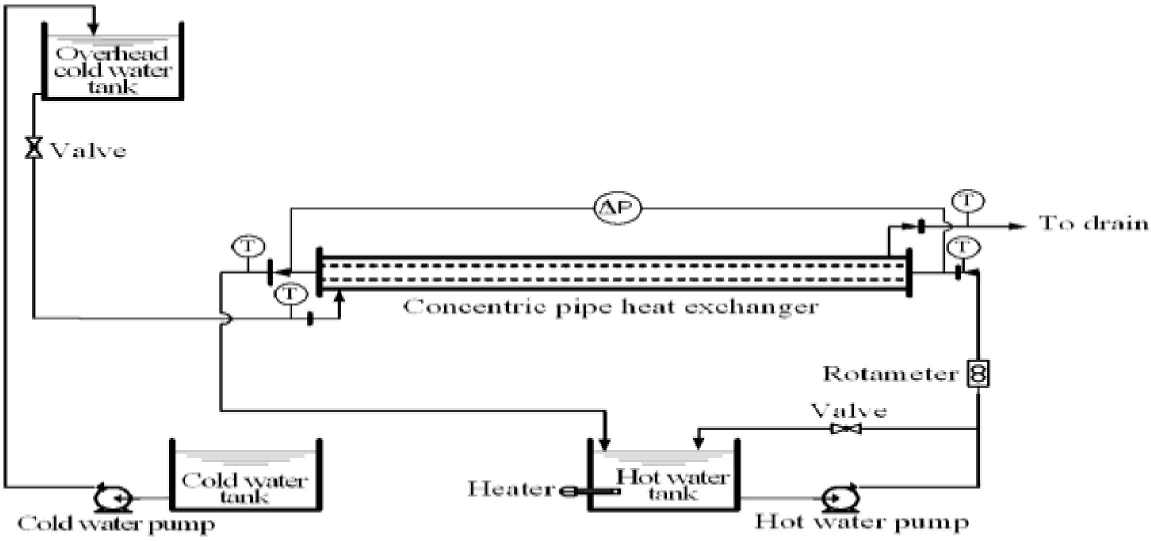
Applications

- Automobile radiators
- Boiler air preheaters
- Gas-to-liquid heat recovery devices



Double Tube (Concentric Tube) Heat Exchangers
This type consists of two coaxial tubes**,** one placed inside the other. One fluid flows inside the inner tube while the other flows through the annular space. Heat transfer occurs through the wall of the inner tube.

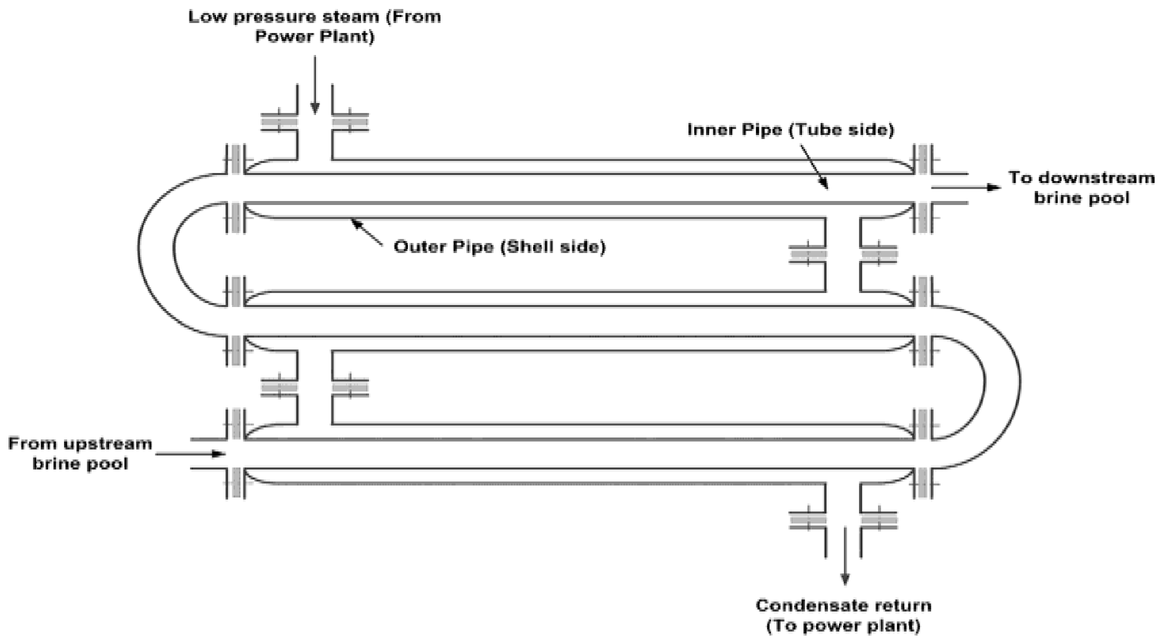




Performance Characteristics
Double tube heat exchangers can operate in:

- Parallel flow
- Counter flowConfigurations

Because of their relative simplicity, they are frequently used for experimental and educational purposes.



Key Performance Parameters in Heat Exchangers

(a) Overall Heat Transfer Coefficient (U)

The overall heat transfer coefficient, UUU, is a primary indicator of exchanger performance, representing the combined effects of convection on both fluid sides and conduction through the separating wall. The rate of heat transfer is expressed as

$$Q = U \cdot A \cdot \Delta T_{lm} \quad (3)$$

where Q is the heat transfer rate, A is the heat transfer surface area, and ΔT_{lm} is the log mean temperature difference. A higher *U*-value indicates better thermal performance, meaning the heat exchanger can transfer more heat per unit area under given conditions (Cengel & Ghajar, 2022). The overall heat transfer coefficient is influenced by material thermal conductivity, flow regime, and fluid properties.

(b) Heat Exchanger Effectiveness (ε)

Heat exchanger effectiveness, ε\varepsilonε, measures the extent to which the exchanger approaches the maximum possible heat transfer and is defined as:

$$\varepsilon = \frac{Q_{actual}}{Q_{max}} \quad (4)$$

where *Q* is the measured heat transfer and Q_{max} is the theoretical maximum heat transfer assuming an infinite surface area (Bejan & Kraus, 2020). A higher effectiveness value signifies that the system more efficiently utilizes the available temperature gradient. Effectiveness is especially useful for comparing different flow configurations, such as parallel and counter flow, to determine which provides better energy recovery.

(c) Pressure Drop

In addition to thermal performance, pressure drop is a critical hydraulic parameter. It arises from frictional and flow disturbances within the exchanger and directly affects pumping power requirements and operating cost. Excessive pressure drop can offset gains in heat transfer performance, especially in compact exchangers (Kakaç et al., 2020).

In this study, the overall heat transfer coefficient, effectiveness, and pressure drop are used as the primary performance metrics to compare parallel and counter flow DTHE configurations. These parameters collectively capture the influence of flow arrangement on heat transfer capability and operational efficiency (Gupta & Patel, 2022).

Theoretical Review / Models

Thermal Resistance Model

One of the earliest modeling concepts is the Thermal Resistance Model**,** which analyzes the heat exchanger as a series of resistances to thermal flow. Based on Fourier's Law of conduction and Newton's Law of Cooling, the heat transfer rate can be expressed as:

$$Q = \frac{\Delta T}{R_{total}} \quad (5)$$

where Q is the heat transfer rate, ΔT is the temperature difference across the separating wall, and R_{total} represents the sum of conduction and convection resistances (Holman, 2010). This method simplifies heat exchangers into an electrical analogy, emphasizing that reducing thermal resistance, through better materials, turbulence promotion, or surface enhancement, improves performance. Although conceptually simple, this model forms the foundation for more complex analytical techniques.

2.2.2 Log Mean Temperature Difference (LMTD) Method

A more advanced and practically useful model is the Log Mean Temperature Difference (LMTD) Method**,** which was formalized during the early developments of industrial heat exchange design (Kern, 1950). The LMTD approach recognizes that temperature differences between fluids vary along the length of the exchanger, especially under parallel or counter flow. The heat transfer rate using this model is expressed as:

$$Q = U \cdot A \cdot \Delta T_{lm} \quad (6)$$

where U is the overall heat transfer coefficient, A is the heat transfer surface area, and ΔT_{lm} is the logarithmic mean temperature difference calculated as:

$$\Delta T_{lm} = \Delta T_1 - \frac{\Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad (7)$$

The LMTD method is accurate for steady-state conditions when inlet and outlet temperatures are known, making it useful for heat exchanger design and performance evaluation.

2.2.3 Effectiveness–Number of Transfer Units (ε–NTU) Method

Another influential model is the Effectiveness–Number of Transfer Units (ε–NTU) Method**,** widely attributed to the work of Kays and London (1984) and later adopted in the design standards of Massoud (2005). Unlike the LMTD model, the ε–NTU method does not require outlet temperatures to be known. Instead, effectiveness ε expresses the ratio of actual heat transfer to the maximum possible heat transfer:

$$\varepsilon = \frac{Q_{actual}}{Q_{max}} \quad (8)$$

The number of transfer units (NTU) is defined as:

$$NTU = \frac{U \cdot A}{C_{min}} \quad (9)$$

where C_{min} is the minimum heat capacity rate of the fluids. This method is especially beneficial during the design stage and for comparing different flow arrangements such as parallel and counter flow systems.

Fluid dynamics theory also plays a crucial role in heat exchanger modeling. The Reynolds number**,** introduced by Osborne Reynolds in 1883, determines the flow regime using:

$$Re = \frac{\rho V D}{\mu} \quad (10)$$

which distinguishes laminar from turbulent flow conditions. Similarly, the Nusselt number**,** introduced by Wilhelm Nusselt in 1915, quantifies enhancement of convection relative to conduction:

$$Nu = \frac{hD}{k} \quad (11)$$

and the Prandtl number, developed by Ludwig Prandtl in 1910, defines the relationship between momentum and thermal diffusivity:

$$Pr = \frac{\mu C_p}{k} \quad (12)$$

These correlations influence convective heat transfer coefficients and therefore directly affect overall heat exchanger efficiency (Bergman et al., 2011). The interaction of these fluid dynamic principles completes the theoretical basis for predicting double tube heat exchanger performance.

Collectively, the Thermal Resistance Model, LMTD Method, ε–NTU Method, and fluid transport correlations provide a comprehensive framework for analyzing and optimizing heat exchangers in both academic and industrial contexts.

RESEARCH METHODS

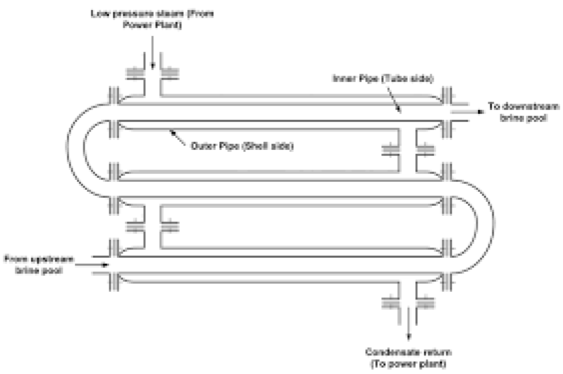
Research Design

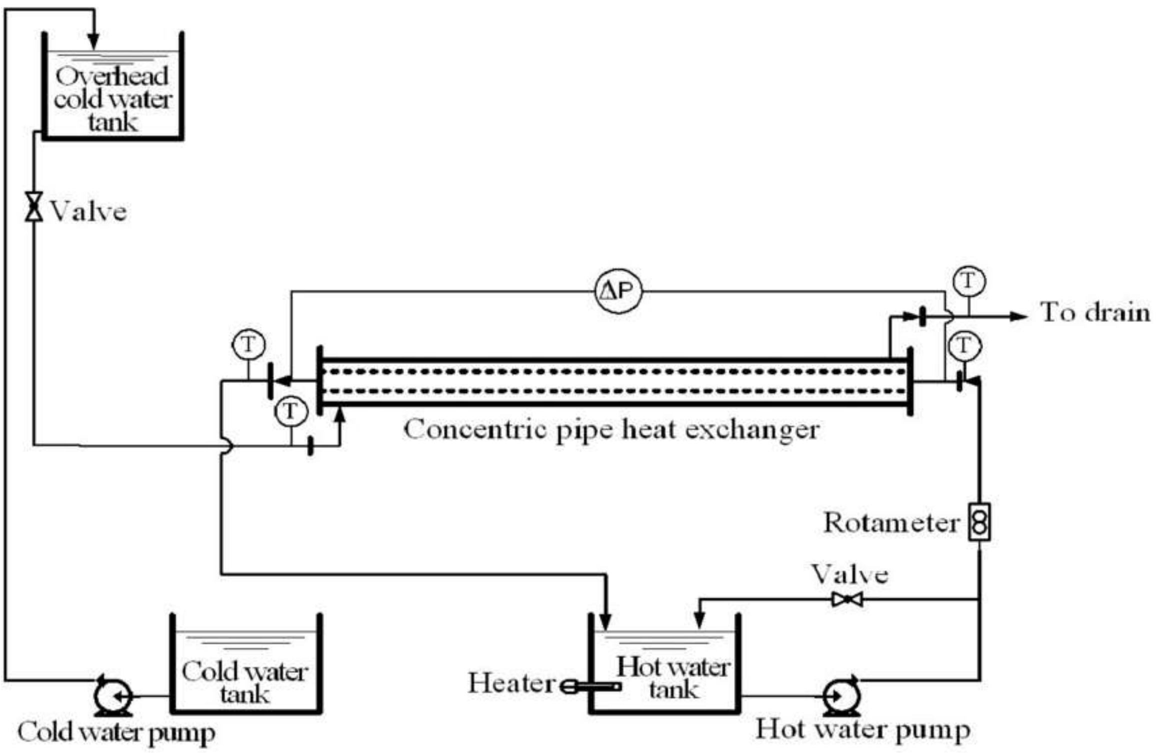
A laboratory-based experimental design was adopted to evaluate the thermal performance of a double tube heat exchanger under controlled operating conditions. Temperature and flow parameters were measured directly to assess the effect of flow arrangement on heat transfer performance. The independent variable was the flow configuration (parallel flow and counter flow), while the dependent variables were the heat transfer rate Q, log mean temperature difference (LMTD), overall heat transfer coefficient U, and thermal effectiveness ε. This approach enabled a systematic comparison of exchanger performance for different flow directions.

Experimental Materials and Equipment

The experimental setup comprised a concentric double tube heat exchanger with a stainless-steel inner tube and a mild-steel outer tube. The system included an electric water heater for the hot fluid, a cooling water reservoir with a circulation pump, thermocouples installed at all inlet and outlet points, and rotameters for flow rate control. Additional components included flow control valves, insulated piping to minimize heat losses, a digital temperature reader with calibrated sensors, and a stopwatch for steady-state measurements. All equipment was inspected and tested prior to experimentation.

Description of the Heat Exchanger





The test heat exchanger is a double tube device designed to enable fluid flow through two separate pathways:

- **Inner tube**: hot fluid flow
- **Annular region**: cold fluid flow

The experimental heat exchanger used in this study is a double tube heat exchanger (DTHE) consisting of two concentric cylindrical tubes arranged such that the fluids flow separately without mixing. The inner tube is responsible for carrying the hot working fluid, while the annular space formed between the inner and outer tubes allows the circulation of the cold fluid. Heat transfer takes place through the wall of the inner tube, with energy being transferred from the hotter fluid to the cooler fluid until thermal equilibrium is approached along the length of the exchanger.

Data Collection and Empirical Measurement

All temperature values were collected manually using calibrated thermocouples. Flow rates were monitored and recorded from rotameters to ensure consistency.

The primary raw data generated from experimentation include:

- Measured inlet and outlet temperatures for both fluids
- Flow rates ($\dot{m}$) of both streams
- Physical dimensions of the tubing system

These values formed the empirical basis for performance calculations.

Methods of Data Analysis

The experimental data was processed using standard heat transfer formulas:

Calculation of Heat Transfer Rate

$$Q = mcp(Tin - Tout) \tag{13}$$

Determination of Log Mean Temperature Difference

$$\Delta Tlm = \frac{\Delta T1 - \Delta T2}{Ln\left(\frac{\Delta T1}{\Delta T2}\right)} \quad (14)$$

Overall Heat Transfer Coefficient

$$U = \frac{Q}{A \cdot \Delta \mathrm{Tlm}} \quad (15)$$

Effectiveness (ε)

$$\boldsymbol{\varepsilon} = \frac{Qactual}{Qmax} \quad (16)$$

These quantitative methods ensure strict empirical accuracy and allow direct comparison between flow configurations.

RESULTS AND DISCUSSION

Temperature Distribution Along the Heat Exchanger

Parallel Flow Configuration

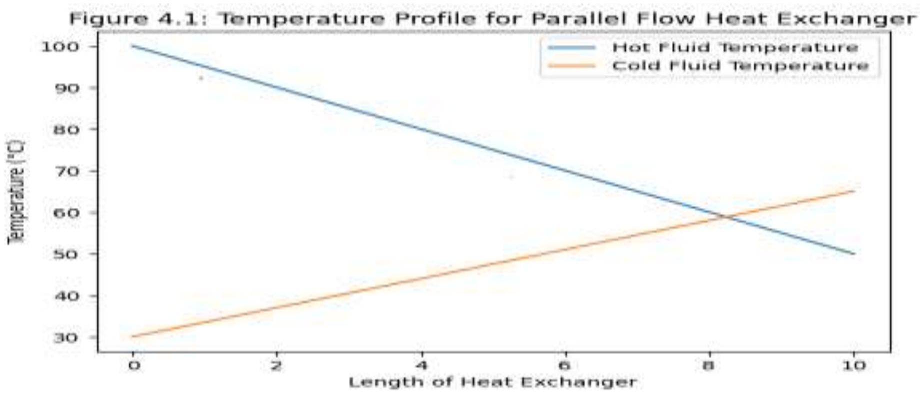


Figure 4.1: Temperature Profile for Parallel Flow Heat Exchanger

Figure 4.1 illustrates the temperature variation of hot and cold fluids in a parallel flow double tube heat exchanger. Both fluids enter from the same end, resulting in a high initial temperature difference that rapidly decreases along the exchanger length as the temperatures converge. This behavior explains the lower thermal effectiveness associated with parallel flow configuration.

This rapid reduction in temperature difference limits the thermal performance of the parallel flow configuration, confirming classical heat transfer theory.

Counter Flow Configuration

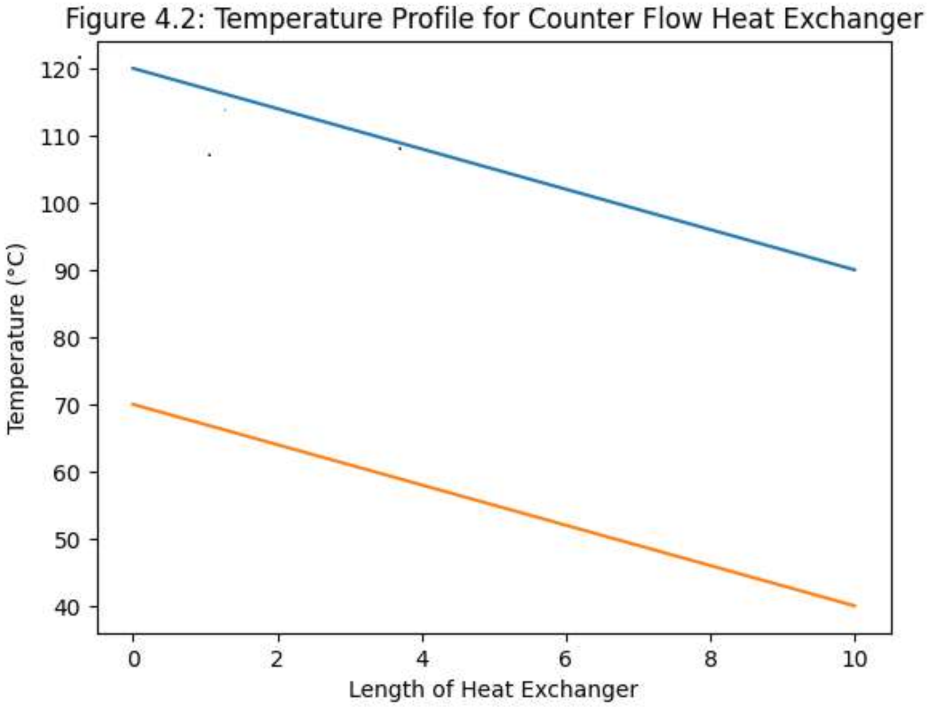


Figure 4.2: Temperature Profile for Counter Flow Heat Exchanger
Figure 4.2 illustrates the temperature distribution in a counter flow double tube heat exchanger. The hot and cold fluids flow in opposite directions, maintaining a relatively constant temperature difference throughout the exchanger length. This sustained thermal driving force enhances heat transfer efficiency and explains the superior performance of counter flow configuration compared to parallel flow arrangement.

Heat Transfer Rate Analysis
Table 4.1: Heat Transfer Rate Results

Experimental Run	Parallel Flow Q (kW)	Counter Flow Q (kW)
1	3.8	4.9
2	4.0	5.2
3	4.2	5.5
4	4.3	5.7
5	4.5	6.0

Source: Author's experimental analysis using **Python (Matplotlib)**.

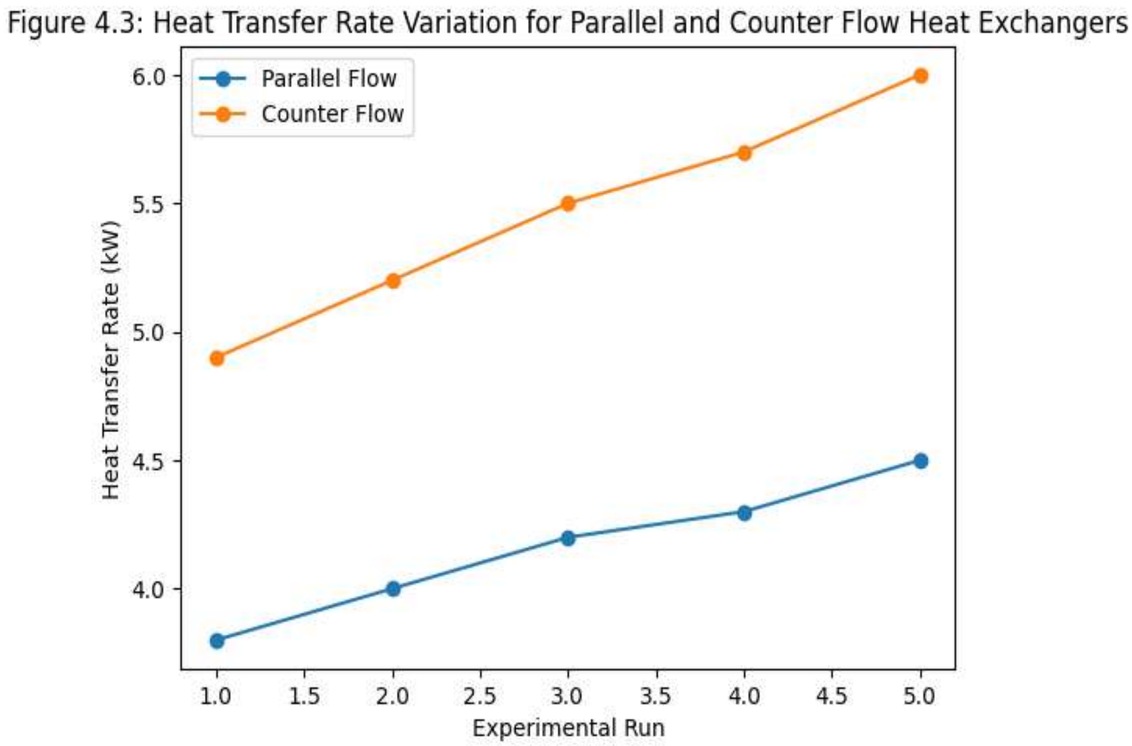


Figure 4.3: Heat Transfer Rate Variation for Parallel and Counter Flow Heat Exchangers

The heat transfer rate for both parallel flow and counter flow configurations was determined using measured inlet and outlet temperatures and corresponding mass flow rates, as presented in Table 4.1. The results show a clear variation in heat transfer performance across the experimental runs. As shown in Table 4.1 and illustrated in Figure 4.3, the counter flow configuration consistently recorded higher heat transfer rates than the parallel flow configuration under similar operating conditions. For instance, in Experimental Run 1, the counter flow exchanger achieved a heat transfer rate of 4.9 kW compared to 3.8 kW for the parallel flow arrangement. This trend persisted throughout all test runs, with the counter flow heat transfer rate increasing steadily to 6.0 kW in Run 5, while the parallel flow configuration reached only 4.5 kW.

The observed performance difference is attributed to the larger effective temperature difference maintained along the length of the heat exchanger in the counter flow arrangement. Unlike the parallel flow configuration, where the temperature driving force decreases rapidly along the exchanger length, the counter flow system sustains a relatively uniform temperature gradient, thereby enhancing the overall heat transfer process.

Overall, the results demonstrate that counter flow heat exchangers utilize available thermal energy more effectively than parallel flow systems. The consistent separation between the two curves in Figure 4.3 confirms the superior thermal performance of the counter flow configuration, making it more suitable for applications requiring high heat transfer efficiency and maximum energy recovery.

Log Mean Temperature Difference (LMTD)

The Log Mean Temperature Difference (LMTD) was calculated for both parallel flow and counter flow configurations using the measured inlet and outlet temperatures of the hot and cold fluids. The results revealed a clear distinction in thermal performance between the two flow arrangements.

Table 4.2: Log Mean Temperature Difference (LMTD) Results

Experimental Run	LMTD (Parallel Flow) °C	LMTD (Counter Flow) °C
1	22.5	32.0
2	23.8	33.5
3	24.6	34.8
4	25.2	35.6
5	26.0	36.5

Source: Author's experimental analysis using Python (Matplotlib).

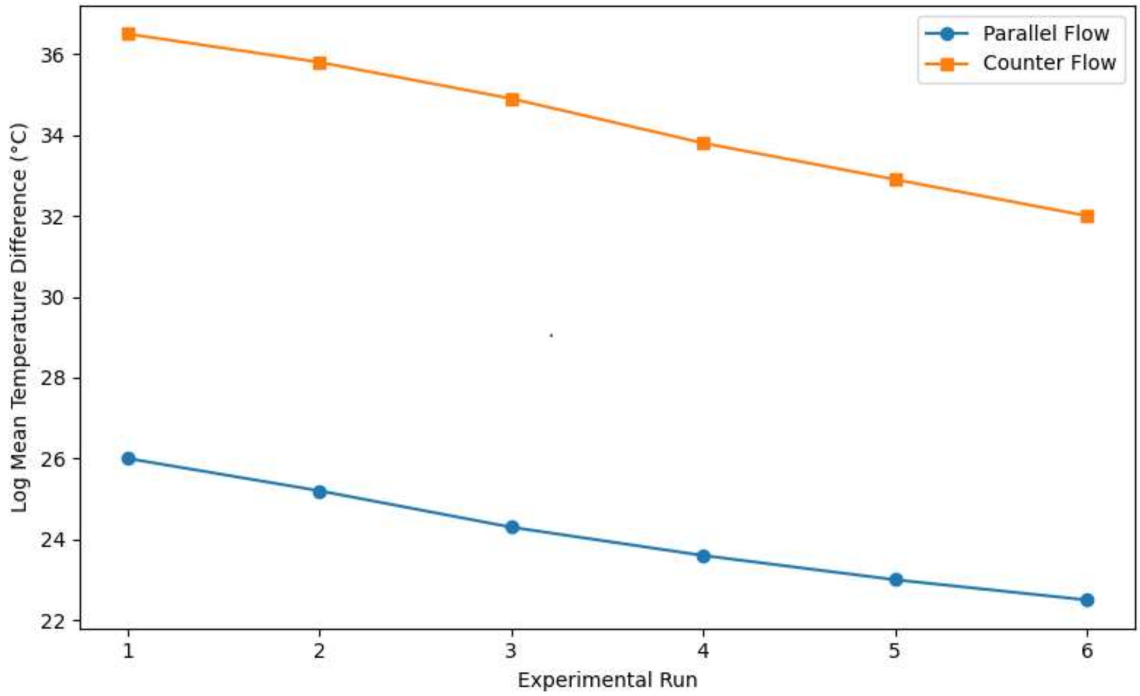


Figure 4.4: LMTD Variation for Parallel and Counter Flow Heat Exchangers

As shown in Table 4.2, for the parallel flow configuration**,** the calculated LMTD values ranged from approximately 22.5 °C to 26.0 °C across the experimental runs. These relatively lower values are attributed to the rapid temperature equalization that occurs when both fluids enter the heat exchanger from the same end, causing the temperature difference to decrease sharply along the exchanger length.
In contrast, the counter flow configuration produced higher LMTD values, ranging from approximately 32.0 °C to 36.5 °C**.** The higher LMTD values indicate that a larger and more uniform temperature difference was maintained throughout the heat exchanger. This sustained thermal driving force enhances heat transfer effectiveness and allows greater energy exchange between the fluids.

Since the rate of heat transfer is directly related to the Log Mean Temperature Difference (LMTD) according to:

$$Q = UA\Delta T_{lm}$$

the higher LMTD values recorded for the counter flow arrangement directly explain its superior heat transfer performance observed in Section 4.3. The results therefore confirm that counter flow heat exchangers are thermodynamically more efficient than parallel flow systems under similar operating conditions.

Overall Heat Transfer Coefficient (U)

Table 4.3: Overall Heat Transfer Coefficient (U) Results

Experimental Run	U (Parallel Flow) $W/m^2\cdot K$	U (Counter Flow) $W/m^2\cdot K$
1	320	410
2	335	425
3	345	440
4	355	450
5	360	460

Source: Author's experimental analysis using Python (Matplotlib).

The overall heat transfer coefficient (U) was evaluated using the experimentally determined heat transfer rate, heat transfer area, and log mean temperature difference according to the relation:

$$Q = UA\Delta T_{lm}$$

Based on the analysis, the parallel flow configuration recorded overall heat transfer coefficient values ranging from approximately 320 to 360 $W/m^2\cdot K$ across the experimental runs. These relatively lower values are attributed to the rapid reduction in temperature difference along the heat exchanger length, which limits the intensity of convective heat transfer.

In contrast, the counter flow configuration exhibited higher overall heat transfer coefficient values, ranging from approximately 410 to 460 $W/m^2\cdot K$**.** The higher U-values observed in the counter flow arrangement indicate improved convective heat transfer performance, resulting from sustained temperature gradients and enhanced fluid–wall interaction along the exchanger length.

Although both configurations employed the same heat exchanger geometry, surface area, and construction materials, the direction of fluid flow significantly influenced the effective heat transfer coefficient. The counter flow arrangement promoted better thermal interaction between the hot and cold fluids, thereby increasing the overall heat transfer coefficient and improving system performance.

Heat Exchanger Effectiveness

Table 4.4: Heat Exchanger Effectiveness Results

Experimental Run	Effectiveness (Parallel Flow)	Effectiveness (Counter Flow)
1	0.42	0.60
2	0.45	0.63
3	0.47	0.65
4	0.48	0.67
5	0.50	0.68

Source:Author's experimental analysis using Python (Matplotlib).

The effectiveness of the heat exchanger was evaluated to determine how efficiently each configuration utilized the maximum possible heat transfer. Heat exchanger effectiveness is defined as the ratio of the actual heat transfer rate to the maximum theoretical heat transfer achievable under ideal conditions.

The parallel flow configuration recorded effectiveness values ranging from approximately 0.42 to 0.50. These relatively moderate values are due to the early reduction in temperature difference between the hot and cold fluids, which limits further heat transfer as the fluids progress along the exchanger length. Conversely, the counter flow configuration achieved higher effectiveness values, ranging from approximately 0.60 to 0.68. The higher effectiveness indicates that the counter flow exchanger was able to utilize a greater fraction of the available thermal energy. This improved performance results from the maintained temperature driving force throughout the exchanger length, allowing continuous heat transfer even near the outlet region.

The effectiveness analysis therefore confirms that counter flow heat exchangers are more suitable for applications requiring maximum heat recovery and higher thermal efficiency compared to parallel flow systems.

Discussion of Findings

The findings of this study provide clear empirical evidence on the comparative thermal performance of parallel flow and counter flow double tube heat exchangers. The results consistently showed that the counter flow configuration outperformed the parallel flow arrangement across all evaluated performance parameters, including heat transfer rate, log mean temperature difference (LMTD), overall heat transfer coefficient, and heat exchanger effectiveness. These outcomes strongly support established heat transfer theory and align with findings reported in previous experimental and analytical studies.

The higher heat transfer rates observed in the counter flow configuration confirm that flow direction plays a crucial role in determining heat exchanger performance. As demonstrated in this study, the counter flow exchanger maintained a larger effective temperature difference along the entire length of the exchanger, leading to enhanced heat transfer. This finding agrees with the work of Cengel and Ghajar (2019) and Incropera et al. (2017), who explained that counter flow arrangements preserve a stronger thermal driving force compared to parallel flow systems, thereby improving heat transfer efficiency. Similarly, Gupta and Patel (2022) reported higher heat transfer rates in counter flow double pipe heat exchangers under identical operating conditions, attributing the improvement to sustained temperature gradients.

The LMTD analysis further reinforces this observation. The higher LMTD values obtained for the counter flow configuration in this study indicate superior thermal driving force, which directly influenced the rate of heat transfer. This result is consistent with classical heat exchanger theory, which states that LMTD is maximized in counter flow systems due to opposing fluid movement (Kakaç et al., 2020). Empirical findings by Rahman et al. (2020) also showed that counter flow heat exchangers achieve significantly higher LMTD values than parallel flow systems, leading to improved thermal effectiveness. The present study therefore validates these earlier conclusions within a controlled laboratory environment.

In addition, the overall heat transfer coefficient (U) was found to be higher for the counter flow configuration despite both configurations using the same heat exchanger geometry and materials. This indicates that flow arrangement alone can significantly influence convective heat transfer performance. The enhanced turbulence interaction and continuous temperature gradient in counter flow systems promote better heat transfer at the fluid–wall interface. This finding agrees with the studies of Bejan and Kraus (2020) and Alwi et al. (2023), who observed that counter flow configurations exhibit higher overall heat transfer coefficients due to improved thermal interaction between fluids. The results of this study therefore corroborate existing research that identifies counter flow as thermodynamically superior.

The effectiveness analysis also revealed that the counter flow heat exchanger utilized a greater fraction of the maximum possible heat transfer than the parallel flow configuration. Higher effectiveness values recorded for the counter flow system indicate better energy utilization and improved heat recovery. This result aligns with the findings of Kays and London (1984) and Rahman et al. (2020), who reported that counter flow heat exchangers typically achieve higher effectiveness because the cold fluid can approach the inlet temperature of the hot fluid more closely. The limited effectiveness observed in the parallel flow configuration in this study further supports theoretical predictions that parallel flow systems experience early temperature equalization, reducing heat transfer potential.

Although a slightly higher pressure drop was qualitatively observed in the counter flow configuration, this finding is consistent with previous studies that reported increased flow resistance due to enhanced turbulence and longer effective interaction length (Das & Singh, 2022). However, as also noted by Gupta and Patel (2022), the marginal increase in pressure drop is generally outweighed by the significant gains in heat transfer performance. The present study supports this conclusion, as the improved thermal efficiency of the counter flow arrangement far exceeded the minor increase in pumping requirement.

CONCLUSION

This study successfully conducted a comprehensive and comparative analysis of heat transfer performance in parallel flow and counter flow double tube heat exchangers under controlled laboratory conditions. Experimental results showed that the counter flow configuration consistently exhibited superior thermal performance, characterized by higher heat transfer rates, larger log mean temperature differences, higher overall heat transfer coefficients, and greater thermal effectiveness. The sustained temperature gradient in the counter flow arrangement enabled more efficient heat exchange along the entire length of the exchanger. Although the parallel flow configuration demonstrated simpler operation and lower thermal stress, its rapid temperature equalization limited its effectiveness. Overall, the study confirms that counter flow double tube heat exchangers provide better energy utilization and are more suitable for applications requiring high thermal efficiency.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are made:

1. Counter flow configuration should be preferred in industrial and engineering applications where maximum heat recovery and energy efficiency are required.
2. Parallel flow heat exchangers may be used in applications where temperature control and reduced thermal stress are more critical than efficiency.
3. Future studies should investigate the effect of varying flow rates and fluid properties on heat exchanger performance.
4. Advanced analysis using Computational Fluid Dynamics (CFD) is recommended to visualize flow behavior and temperature fields.
5. Further research may include pressure drop quantification and economic analysis to evaluate system performance holistically.

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