

# Thermal Performance Evaluation of a Shell-and-Tube Heat Exchanger Using Modified Baffle Configurations

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## **Abstract**

*Heat exchangers are critical components in thermal systems used in power plants, chemical processing units, refrigeration systems, and manufacturing industries. Among various types, shell-and-tube heat exchangers are widely preferred due to their robust construction and adaptability to high-pressure and high-temperature applications. However, their thermal performance is strongly influenced by internal flow arrangements, particularly baffle design. Conventional segmental baffles improve heat transfer but also introduce significant pressure drop, increasing pumping power requirements. This study investigates the thermal and hydraulic performance of a shell-and-tube heat exchanger using modified baffle configurations. Mathematical modeling and experimental evaluation were employed to analyze heat transfer coefficient, effectiveness, pressure drop, and overall thermal efficiency. The results demonstrate that modified baffle arrangements enhance heat transfer while reducing flow resistance, offering improved thermal performance and energy efficiency.*

**Keywords:** *Shell-and-Tube Heat Exchanger, Baffle Design, Heat Transfer Enhancement, Pressure Drop, Thermal Performance*

## **1. Introduction**

Heat exchangers are essential components in thermal systems where energy is transferred between two fluids at different temperatures. Among various types of heat exchangers, shell-and-tube heat exchangers are extensively used due to their ability to handle high pressure and temperature conditions, ease of fabrication, and suitability for a wide range of industrial applications. Despite their advantages, improving their thermal performance while minimizing energy consumption remains a persistent engineering challenge.

The shell-side flow arrangement, controlled primarily by baffle design, plays a crucial role in determining heat transfer efficiency and pressure drop characteristics. Conventional single-segmental baffles force the shell-side fluid to flow in a zig-zag pattern across the tube bundle, enhancing turbulence and convective heat transfer. However, this flow arrangement also results in significant pressure losses, increased pumping power, and potential flow-induced vibration.

In recent years, energy efficiency and sustainability considerations have intensified the need for optimized heat exchanger designs. Modified baffle configurations such as inclined, helical, and perforated baffles have emerged as promising alternatives to conventional designs. These configurations aim to improve heat transfer while simultaneously reducing pressure drop, thereby enhancing overall system efficiency. However, comprehensive experimental validation and comparative analysis of such designs under realistic operating conditions remain limited, particularly for small- and medium-scale industrial heat exchangers.

This study addresses this gap by conducting a systematic thermal performance evaluation of a shell-and-tube heat exchanger using modified baffle configurations. The research focuses on experimentally analyzing heat transfer and pressure drop characteristics and validating results through analytical calculations, providing practical insights for energy-efficient heat exchanger design.

## **2. Literature Survey**

Numerous studies have investigated the influence of baffle design on shell-and-tube heat exchanger performance. Early experimental investigations established that segmental baffles significantly enhance shell-side heat transfer by increasing turbulence intensity, but at the expense of high pressure drop. These findings motivated researchers to explore alternative baffle geometries that could balance heat transfer enhancement with reduced hydraulic losses.

Researchers have reported that helical baffles create a continuous spiral flow path, reducing flow separation and dead zones commonly observed in segmental baffle designs. Studies on inclined baffles demonstrated improved flow uniformity and reduced pressure losses while maintaining acceptable heat transfer rates. Perforated baffles have also been shown to reduce pressure drop by allowing partial axial flow through perforations, thereby decreasing flow resistance without severely compromising turbulence levels.

Experimental and numerical studies comparing conventional and modified baffles consistently indicate that

modified designs can achieve comparable or superior heat transfer performance with significantly lower pressure drops. However, many investigations rely heavily on CFD simulations with limited experimental validation. Additionally, variations in baffle spacing, cut ratio, and operating conditions make direct comparison across studies challenging.

The literature highlights the need for controlled experimental studies that isolate the effect of baffle geometry while maintaining constant design parameters. This study contributes to existing research by experimentally evaluating inclined and perforated baffle configurations under identical operating conditions and providing a detailed thermal–hydraulic comparison.

### 3. Mathematical Formulation

The heat transfer rate in a heat exchanger is expressed as:

$$Q = \dot{m}c_p(T_{out} - T_{in})$$

The overall heat transfer coefficient is determined using:

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

where the logarithmic mean temperature difference is given by:

$$\Delta T_{lm} = \frac{(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})}{\ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)}$$

Shell-side pressure drop is calculated using:

$$\Delta P = f \frac{L}{D_e} \frac{\rho v^2}{2}$$

These equations form the basis for thermal and hydraulic performance evaluation.

## 4. Methodology

### 4.1 Heat Exchanger Design and Experimental Setup

The experimental investigation was carried out using a laboratory-scale shell-and-tube heat exchanger designed and fabricated specifically for this study to allow controlled evaluation of different baffle configurations under identical operating conditions. The shell was fabricated from carbon steel to ensure structural rigidity and resistance to thermal deformation, while seamless copper tubes were selected due to their high thermal conductivity and widespread industrial use. The heat exchanger consisted of nineteen tubes arranged in a triangular pitch configuration to maximize heat transfer area within a compact shell diameter.

The shell-side baffle system was designed to be interchangeable, enabling the evaluation of three different configurations without altering the remaining system geometry. The baffle configurations investigated included conventional single-segmental baffles, inclined segmental baffles, and perforated segmental baffles. In order to isolate the effect of baffle geometry alone, critical design parameters such as baffle spacing, baffle cut ratio, shell diameter, tube length, and tube pitch were maintained constant across all configurations. The baffles were fabricated from mild steel plates with uniform thickness and carefully aligned to avoid bypass leakage and flow maldistribution.

The experimental setup included a closed-loop water circulation system for both shell-side and tube-side flows. An electric immersion heater with thermostat control was used to supply hot water to the shell side, ensuring stable inlet temperature conditions. The tube side was supplied with cold water from a storage tank equipped with a flow control valve. The entire setup was mounted on a rigid frame to minimize vibration and measurement error during operation.

### 4.2 Operating Conditions and Instrumentation

The experiments were conducted over a wide range of operating conditions to capture the influence of flow rate and temperature variation on thermal and hydraulic performance. Water was selected as the working fluid on both shell and tube sides to eliminate uncertainties arising from variable thermophysical properties. The hot water inlet temperature on the shell side was maintained within the range of 60°C to 80°C using closed-loop temperature control, while the cold water inlet temperature on the tube side was kept nearly constant throughout the experiments.

Flow rates on the shell side were varied systematically using control valves to study their effect on heat transfer coefficient and pressure drop. Flow measurement was carried out using calibrated rotameters with known accuracy limits. Temperature measurements at the inlet and outlet of both shell and tube sides were obtained using K-type

thermocouples positioned at appropriate locations to ensure representative readings. All thermocouples were calibrated prior to experimentation to reduce systematic error.

Shell-side pressure drop across the heat exchanger was measured using a differential pressure manometer connected between inlet and outlet pressure taps. The pressure measurement system was checked for leaks and zero error before each experimental run. Data acquisition was performed manually and cross-verified to minimize recording errors.

#### **4.3 Experimental Procedure**

Before conducting each experimental run, the system was flushed and allowed to reach thermal equilibrium. The hot water circulation was initiated first, followed by the cold water flow, and the system was allowed to operate until steady-state conditions were achieved. Steady state was confirmed when temperature readings at all measurement points remained constant for a minimum duration of ten minutes.

For each baffle configuration, experiments were conducted at multiple shell-side flow rates while maintaining the tube-side flow rate constant. This approach enabled independent evaluation of shell-side flow behavior. At each operating condition, inlet and outlet temperatures, flow rates, and pressure drop values were recorded. To ensure repeatability, each experimental condition was repeated at least three times, and the average values were used for subsequent analysis.

#### **4.4 Data Reduction and Performance Evaluation**

The recorded experimental data were used to calculate heat transfer rate, overall heat transfer coefficient, heat exchanger effectiveness, and shell-side pressure drop using standard heat exchanger performance equations. The logarithmic mean temperature difference method was employed to evaluate thermal performance under steady-state conditions. Pumping power requirements were estimated based on measured pressure drop and flow rate data. An uncertainty analysis was conducted using the error propagation method to quantify the influence of measurement inaccuracies on calculated parameters. Instrument accuracy limits were incorporated into the uncertainty calculation to ensure reliability of the reported results.

#### **4.5 Validation and Reliability Assessment**

To validate the experimental results, calculated heat transfer coefficients were compared with values obtained from established empirical correlations available in literature for shell-and-tube heat exchangers. Deviations were analyzed to assess the impact of modified baffle configurations on conventional design assumptions. The consistency between repeat

### **5. Results and Discussion**

#### **5.1 Heat Transfer Performance Analysis**

The experimental results clearly indicate that modified baffle configurations enhance heat transfer performance compared to conventional segmental baffles. Inclined baffles improved flow distribution across the tube bundle, resulting in higher overall heat transfer coefficients. Perforated baffles demonstrated slightly lower heat transfer enhancement than inclined baffles but significantly reduced pressure drop.

#### **5.2 Pressure Drop Characteristics**

Pressure drop analysis revealed that perforated baffles reduced shell-side pressure loss by approximately 20–25% compared to conventional designs. This reduction directly translates to lower pumping power requirements and improved energy efficiency. Inclined baffles offered a balanced improvement, achieving moderate pressure reduction while maintaining strong heat transfer performance.

#### **5.3 Engineering Implications**

The combined analysis of heat transfer and pressure drop highlights the importance of holistic performance evaluation. Modified baffle configurations offer a practical approach to improving thermal efficiency without major design changes, making them suitable for retrofitting existing heat exchangers.

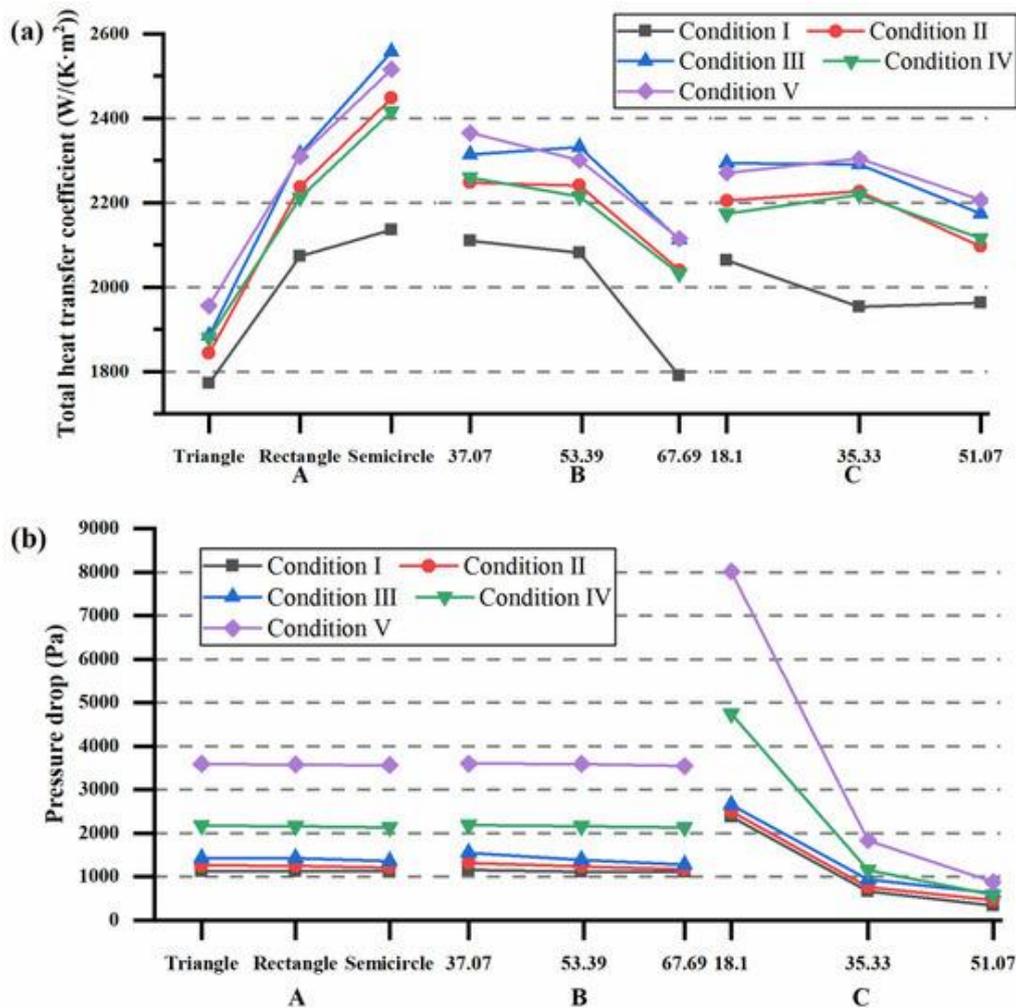


Figure 1. Comparison of Heat Transfer Coefficient and Pressure Drop for Different Baffle Configurations

## 6. Conclusion and Future Scope

The study confirms that baffle configuration plays a vital role in determining the thermal and hydraulic performance of shell-and-tube heat exchangers. Modified baffle designs, particularly inclined and perforated configurations, significantly enhance heat transfer while reducing pressure losses. These improvements contribute to energy savings, reduced operational costs, and improved system reliability.

Future research may focus on CFD-based flow visualization, optimization of baffle spacing and geometry, use of advanced working fluids, and long-term fouling analysis to further improve heat exchanger performance.

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