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A Hybrid Baffle Approach for Reducing Pressure Drop without Compromising Heat Transfer in Shell-Side Flow of Heat Exchangers

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Abstract: The Shell and tube heat exchangers are widely used in thermal systems, and the configuration of internal baffles significantly influences their thermal and hydraulic performance. Traditional segmental baffles while enhancing heat transfer through turbulent flow, contribute to a substantial pressure drop. Conversely, inclined baffles offer smoother flow paths and reduced pressure losses but may underperform in turbulence generation.

This dissertation proposes and investigates a novel hybrid baffle configuration combining inclined and segmental baffles to achieve the best of both designs. The objective is to reduce excessive pressure drop associated with conventional segmental baffles while maintaining or improving the heat transfer coefficient. Computational Fluid Dynamics (CFD) simulations and theoretical models are utilized to compare the thermal performance, pressure drop, and flow characteristics across various baffle arrangements.

The results demonstrate that the hybrid baffle design achieves a balanced enhancement in heat exchanger performance, providing insights into effective heat exchanger design with practical relevance to industries.

***Keywords*:** Shell & tube heat exchanger, segmented & inclined baffles, overall heat transfer coefficient, and pressure drop.

I. Introduction

The heat exchanger is a device which is used to transfer the thermal energy between two or more fluids flowing at different temperatures and that too without mixing them. They are widely used components in variety of industries including electricity generation, air conditioning, chemical processing, refrigeration, oil refining etc.

The primary purpose of the heat exchanger is to either add heat to a cold fluid or remove heat from a hot fluid also achieving the situation in an efficient and controlled manner. The heat exchange depending on the application can occur between the three combination of fluid i.e. liquid-liquid, liquid-gas or gas-gas.

These devices operate on the basis of principle of thermal conduction and convection. Since the heat flows naturally from the fluid at higher temperature to a region of fluid at lower temperature. A solid interface or series of interfaces separate the two fluids so as to prevent mixing while permitting heat to pass through.

The Shell-and-tube heat exchangers are among the most commonly used types of heat exchangers in industrial applications due to their versatility, robustness, and efficiency in handling high-pressure and high-temperature fluids. A key challenge in optimizing their performance lies in balancing the pressure drop and heat transfer characteristics, especially on the shell side. Traditional baffle arrangements, such as segmental baffles, effectively enhance turbulence and heat transfer but often lead to significant pressure drops, resulting in higher pumping power requirements and operational costs. Conversely, designs that reduce pressure drop may sacrifice heat transfer performance, creating a trade-off that limits the overall efficiency of the system.

Recent advancements in fluid dynamics and thermal optimization have led to the exploration of alternative baffle configurations aimed at mitigating this trade-off. Among these, hybrid baffle designs—combinations of different baffle types or novel geometries—have shown promise in maintaining or even improving heat transfer rates while significantly reducing pressure losses.

This thesis introduces and investigates a Hybrid Baffle Approach designed to optimize the shell-side flow in shell-and-tube heat exchangers. The core motivation is to develop a baffle arrangement that strategically directs flow, minimizes recirculation zones, and reduces flow resistance, thereby lowering pressure drop without compromising thermal performance. The findings of this study are expected to contribute to the development of more energy-efficient and cost-effective heat exchanger systems across various industrial sectors, including power generation, petrochemicals, and process industries.

- Versatility in accommodating a broad range of operating conditions,
- Robustness under high pressure and temperature environments, and
- Efficiency in transferring heat between fluids with large flow rates.

However, one of the major engineering challenges in their design is achieving an optimal balance between shell side pressure drop and heat transfer performance.

Industrial uses:

- For Power Generation- feed water heaters, Steam condensers.
- For Oil & Gas- Gas coolers, Crude oil preheaters.
- At Chemical Processing units - Heat recovery, Reactant preheating.
- HVAC- Heating coils, Air conditioning.
- In Food & Beverage industry- Cooling systems, Pasteurization.

Modern engineering systems use heat exchangers for energy conservation, process efficiency, and thermal management. Heat transfer efficiency, pressure drop, maintenance, and cost must be balanced by their design depending on the application. Most widely used type of heat exchanger is the shell and tube type. Tube either in pattern or bundles are enclosed within a cylindrical shell. Indirect heat transfer between two fluids is facilitated: one fluid is made to flow through the tubes (tube side), while the other is directed to flow outside the tubes but within the shell (shell side). It is considered ideal for high-pressure, high-temperature, and large-scale heat exchange processes due to this design.

- The heat exchanger works on the principles which are as follows-
- The tube side is entered by a hot or cold fluid, while the shell side is traversed by another fluid.
- Heat is transferred across the tube walls from the hotter to the cooler fluid.
- The fluid is forced by baffles in the shell to move across the tubes multiple times, resulting in increased heat transfer efficiency.
- Counter-flow, parallel flow, or cross-flow configurations can be accommodated through customization of the design.

Key Performance Parameters

- Heat Transfer Rate (Q)
- Effectiveness (ε) – A measure of how close the exchanger gets to the ideal heat transfer.
- Pressure Drop (ΔP) – Represents resistance to fluid flow. Lower is generally preferred for energy efficiency.

Importance of Baffle Design in Heat Exchangers:

Baffles play a crucial role in enhancing the performance of shell and tube heat exchangers. Baffles are metal plates placed perpendicular to the shell-side fluid flow in a shell and tube heat exchanger. Their primary function is to direct and control the flow of the shell-side fluid, thereby increasing turbulence, improving heat transfer, and supporting the tube bundle structurally.
Main types of Baffles

Type	**Description**	**Key Features**
Segmental Baffles	Most common; semi-circular cutouts	Good heat transfer, higher pressure drop
Disc and Orifice Baffles	Alternating solid and ring-shaped plates	Low turbulence & heat transfer coefficient, low pressure drop
Helical Baffles	Spiral-shaped plates	Continuous spiral flow, low fouling, low ΔP, machining constraints
Rod Baffles	Use rods to guide flow	Low resistance, good for fouling fluids, low heat transfer coefficient

Main Functions of Baffles:

- Enhance Heat Transfer:

Promote Turbulence: Baffles induce the shell-side liquid to flow in a zig-zag or crossflow pattern across the tube sets or bundles, rather than moving directly. This creates turbulence, which enhances the heat transfer coefficient.

Increase Fluid Velocity: Baffles reduce the flow path, boosting the fluid velocity across the tubes and further improving the heat exchange rate.

➢ Support and Stabilize Tubes:

Prevent Tube Vibration: In the absence of baffles, fluid flow can cause vibrations and movement of the tubes, which may result in damage or failure. Baffles offer intermittent physical support, ensuring the tubes stay securely in position.

Reduce Mechanical Stress: Baffles support long tubes at intermediate points, helping to distribute mechanical loads and minimize stress concentrations.

➢ Control Pressure Drop

The spacing and design of baffles affect the pressure drop across the heat exchanger. Although closer baffle spacing enhances heat transfer, it also raises the pressure drop. Optimizing baffle design is key to balancing these two factors for efficient performance.

➢ Minimize Fouling:

➢ Avoid Stagnant Zones**:** Improperly designed baffles can create dead zones where fluid stagnates, leading to fouling and the buildup of deposits on the heat exchanger surfaces. A well-designed baffle arrangement ensures optimal flow distribution, helping to reduce the likelihood of fouling.

➢ Flow Direction Control

➢ Segmental Baffles: Typically, baffles are used to guide the fluid back and forth across the tube bundle, thereby increasing the effective flow length.

➢ Double Segmental and Disc-and-Doughnut Baffles: Used in specialized applications, baffles help to optimize flow and pressure drop characteristics.

➢ Helical Baffles: Encourage a continuous helical flow, which helps reduce pressure drop and fouling compared to conventional designs.

Issues with Conventional Baffle Designs:

Traditional baffle configurations, such as segmental baffles, are known to:

➢ Enhance fluid turbulence, thus improving heat transfer.

➢ Introduce higher pressure drops, increasing pumping power and operational costs.

➢ Conversely, baffle designs that minimize pressure drop often do so at the expense of heat transfer efficiency, leading to performance trade-offs that limit overall system effectiveness.

Here's how combining these two baffle types can be advantageous:

1. Improved Fluid Flow and Heat Transfer:

• Inclined Baffles: These baffles are inclined at an angle, typically between 15° and 30°, relative to the horizontal or vertical plane. The tilt creates a more controlled and smoother flow path for the shell-side fluid compared to traditional segmental baffles. This helps reduce flow mal-distribution, minimizes the formation of stagnant zones, and enhances overall heat transfer efficiency.

• Segmented Baffles: These are the most widely used baffles in shell and tube heat exchangers. They generate more turbulent flow by dividing the flow path into segments, which improves heat transfer but also increases pressure drop. Segmental baffles are usually positioned perpendicular to the shell's axis, guiding fluid flow in a cross-flow pattern.

• When combined, inclined baffles help direct the flow in a more controlled way, ensuring the fluid passes more evenly across the tubes. This minimizes dead zones and hot spots, leading to improved overall heat transfer efficiency.

2. Reduced Pressure Drop:

• Segmental baffles cause a notable pressure drop due to the turbulence and abrupt changes in flow direction. By incorporating inclined baffles, the fluid's velocity and pressure drop can be more effectively controlled, as the inclined design smooths the flow path and reduces sharp turns.

• A hybrid design that includes inclined baffles can reduce the high pressure drop typically associated with segmental baffles, while still maintaining strong turbulence and efficient heat transfer.

3. Enhanced Flow Distribution:

- Inclined baffles promote more uniform distribution of the shell-side fluid, especially in large diameter shells where traditional segmental baffles might cause uneven flow distribution. This is crucial in designs involving highly viscous fluids or significant differences in fluid properties.
- The combination of inclined and segmental baffles helps prevent stagnation zones, resulting in improved heat exchange performance throughout the heat exchanger.

4. Reduced Fouling Potential:

- Inclined baffles help reduce the risk of fouling by preventing the formation of stagnant zones where particles or debris might accumulate. By improving flow uniformity across the tube bundle, this hybrid design minimizes the chances of fouling and enhances the long-term efficiency of the heat exchanger.

5. Customization for Specific Applications:

- A combined approach of inclined and segmented baffles can be customized for specific applications. For instance, in a heat exchanger designed to handle high flow rates and maintain a low pressure drop, inclined baffles may be more advantageous in certain sections, while segmented baffles can be used in other areas to generate high turbulence where needed.
- The inclination angle and the design of the segmental baffles can be adjusted according to the application and performance requirements (e.g., achieving a balance between heat transfer and pressure drop).

➢ Research Objectives:

To investigate the results of proposed hybrid baffle approach on heat transfer and pressure drop, five different baffle configurations are analyzed, while all other parameters and boundary conditions remain constant. The fluid properties are assumed to be constant throughout the study. Each of the three geometric models is simulated under identical inlet mass flow rate and temperature conditions. The flow regime is considered turbulent.

Governing differential equation:

Momentum Equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0$$

$$\frac{\partial(\rho\, u_i' u_j')}{\partial t} = -\frac{\partial(\rho)}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i}$$

Where $\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_j}\right) - \left(\frac{2}{3}\right)\mu \frac{\partial u_k}{\partial x_k}\partial ij$

Energy equation

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial\left(u_i(\rho k + \rho \epsilon)\right)}{\partial x_i} = \frac{\partial\left(k\frac{\partial T}{\partial x_i}\right)}{\partial x_i}$$

Where, E is the total energy and k is the thermal conductivity.

Turbulent kinetic energy equation:

$$\frac{\partial \rho k}{\partial t} + \frac{\partial(\rho u_j\, k)}{\partial x} = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial k}{\partial x_j}\right) - \frac{\partial}{\partial x_j}\left(\frac{\rho}{2} u_j u_i u_i + p u_j\right) - \rho u_j u_i \frac{\partial}{\partial x} u_i - \mu \frac{\partial u_i}{\partial x_i}\frac{\partial u_j}{\partial x_j}$$

Rate of dissipation equation is:

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = C\varepsilon 1 P \frac{\varepsilon}{k} - \frac{\rho C\varepsilon 2}{k} + \frac{\partial}{\partial xj}\left[\frac{(\mu_t)\,\partial\varepsilon}{\sigma\varepsilon.\partial xj}\right]$$

II. DESIGN AND METHODOLGY

The cross-flow type heat exchanger has been used for the study. In a cross flow heat exchanger, one fluid moves through a series of tubes or plates, while the other fluid flows at a right angle across them. Heat is transferred from the hot fluid to the cold one through the separating walls, enabling efficient thermal exchange without mixing the two fluids.

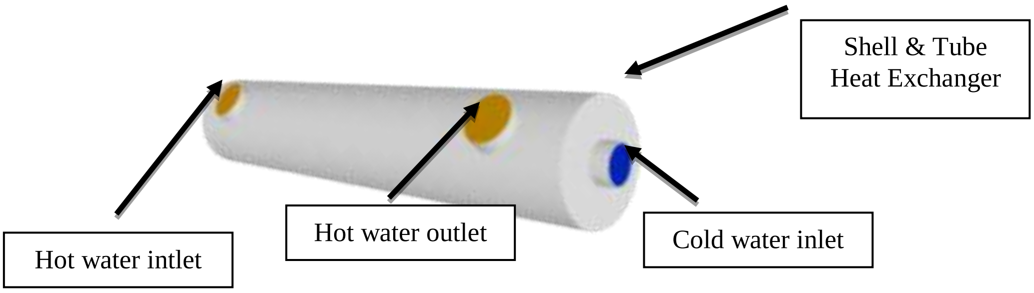

Figure 1: Schematic of the Shell and Tube Heat Exchanger showing fluid inlets and outlets.

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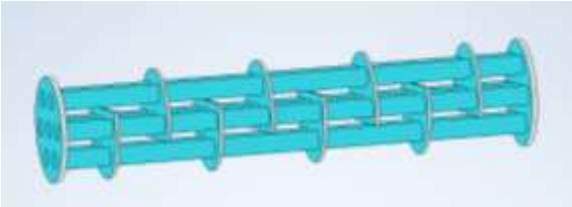
Heat Exchanger Design Parameters:

The dimensional configuration of heat exchanger with a diameter (D) of 94 mm is used as the model, featuring circular inlet and outlet sections, each with a diameter (ds) of 30 mm. The shell length is set to 500 mm. Inside of the shell, there are seven tubes arranged in a triangular bundle, each with an internal diameter (di) of 15 mm and a wall thickness of 1 mm. The shell is equipped with baffles 3mm thickness that are evenly spaced and are arranged as per the cases considered for 3D design and simulations.

Hybrid Baffle Geometry Development:

The baseline of study is the comparison of existing baffle configurations with the hybrid baffle configuration. To understand the above and simulate for results, certain cases have been developed based on the data of optimum angle of baffles and spacing. Baffle cut of 25% has been kept constant in all the baffles. Internal view of heat exchangers have been shown in the figure below.

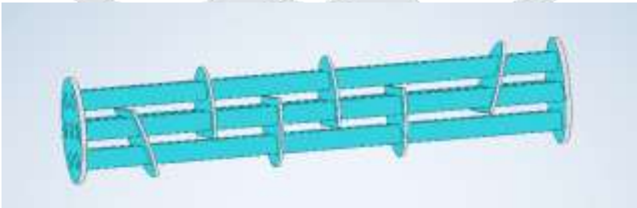
- CASE 1- Segmental baffle design with 8 baffle equidistant from each other.



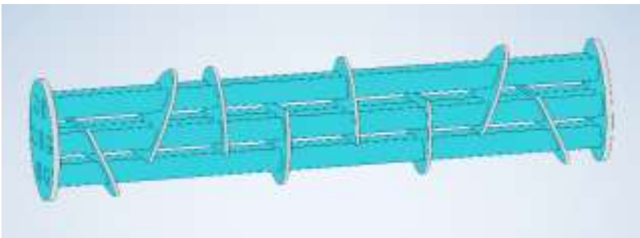
- CASE 2- Inclined baffle design with 8 baffles at 25° inclination angle.

For the hybrid baffle configuration of STHE, we have fixed the number of segmental baffles in between of inclined baffles by a qty of 4.

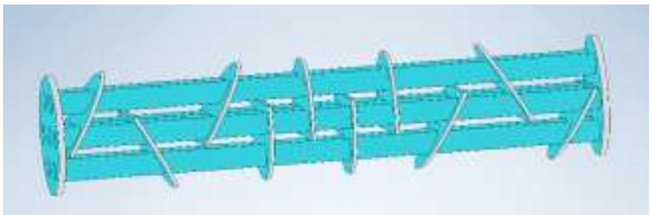
- CASE3a- Inclined baffles at entry and exit at 20° (2 nos.) & Segmental baffles in between (4nos.) total 6 baffles.



- CASE3b- Inclined baffles at entry and exit at 25° (4 nos.) & Segmental baffles in between (4nos.) total 8 baffles.



➢ CASE3c- Inclined baffles at entry and exit at 30° (6 nos.) & Segmental baffles in between (4nos.) total 10 baffles.



Computational Domain and Modeling Tools (CFD):

The advent of high-speed computers, combined with the development of accurate mathematical methods for solving physical problems, has revolutionized the way we study and analyze fluid flow and heat transfer. This approach, known as Computational Fluid Dynamics (CFD), has made it possible to examine complex flow geometries with ease—something that was once only feasible with simplified models and traditional techniques. CFD can thus be seen as a field that integrates fluid mechanics with numerical analysis.

Historically, the early development of CFD during the 1960s and 1970s was driven by the demands of the aerospace industry. However, modern CFD finds applications across a wide range of disciplines—including civil, mechanical, electrical, electronics, chemical, aerospace, marine, and biomedical engineering. CFD not only reduces the need for physical testing and experimentation but also significantly shortens the overall design and testing cycle.

The CFD procedure is classified mainly into 3 parts-

- Pre-procesor
- Main solver
- Post-processor

Pre-processing unit

It is the basic initial step towards CFD analysis where the designer plans the following activities-

- The displaying targets are characterized.
- Distinguishes the computational area
- Outlines and makes the framework.

The main solver unit

The primary functions of the main solver include the following:

- Selection of the appropriate physical model
- Specification of material properties
- Definition and application of boundary conditions
- Initialization of the computational solution
- Configuration of relaxation factors
- Establishment of convergence criteria
- Execution of the numerical calculation
- Storage and preservation of the computed results.

Post processing unit

The post-processor represents the final component of CFD software. It enables users to analyze the results and extract meaningful insights. The output may be visualized through vector plots of vector quantities such as velocity, contour plots of scalar variables such as pressure and temperature, streamlines, and animations in the case of unsteady simulations. Global parameters—such as the skin friction coefficient, lift coefficient, Nusselt number, and Colburn factor—can also be calculated using appropriate formulas. Furthermore, data from the CFD post-processor can be exported to advanced visualization software for enhanced presentation, or to specialized plotting tools for improved graphical representation.

CFD procedure

In Computational Fluid Dynamics (CFD), the problem-solving process is typically structured into five key stages:

1. Geometic Development of 3D model

2. Mesh Generation on components.
3. Specification of Flow Conditions.
4. Numerical Calculation and Solution
5. Results Analysis

In this study, a three-dimensional analysis of a shell-and-tube heat exchanger was performed using ANSYS FLUENT. All five stages of the CFD process were systematically executed using integrated CFD tools to model, simulate, and evaluate the thermal and fluid flow characteristics of the heat exchanger.

Mesh Generation & Refinement:

Mesh generation in ANSYS is a fundamental step that involves discretizing the computational domain into finite elements to enable numerical solution of the governing equations of fluid flow and heat transfer. This discretization allows the software to approximate the behavior of physical variables—such as velocity, pressure, and temperature—throughout the domain.
The accuracy and efficiency of a CFD simulation are highly dependent on the quality of the mesh. Finer meshes are applied in regions with steep gradients, such as boundary layers, while coarser meshes are used where variations are minimal. Mesh quality parameters, including skewness and aspect ratio, play a crucial role in ensuring numerical stability and solution convergence.
In this study, ANSYS Meshing was utilized to generate a high-quality mesh for the shell-and-tube heat exchanger model, ensuring reliable simulation of its thermal and flow characteristics.

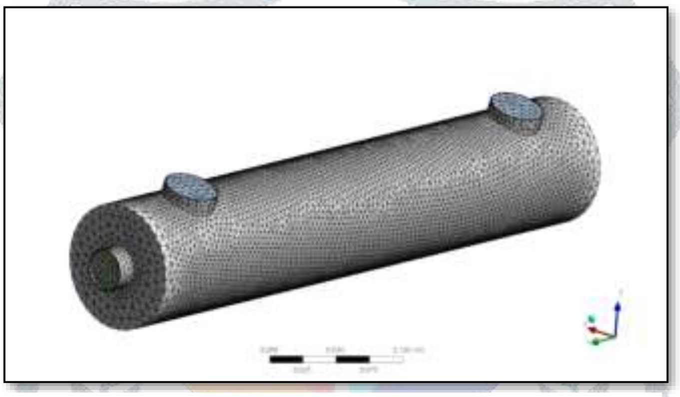


Figure II-1 Meshed computational domain for CFD analysis.

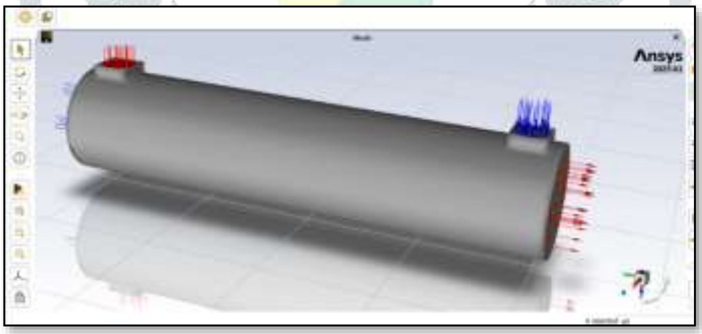


Figure II-2 Specification of boundary conditions in the ANSYS pre-processor for the shell-and-tube heat exchanger

Boundary Conditions and Solver Settings:

The following boundary conditions are applied to the CFD software of Ansys Fluent to solve the equations previously mentioned:

(i) All walls are set with non-slip boundary conditions.
(ii) The inlet velocities of both shell and tube sides are constant and in only one direction.
(iii) Flow is incompressible i.e. density of the fluid does not change.
(iv) Leakage from the gap between tube and baffle is neglected.
(v) Heat transfer to the baffles is neglected.
(vi) Water is taken as working fluid and its properties are considered to be constant.
(i) Header effect is neglected

Component	Fluid	Mass flow rate	Inlet temperature	Outlet
Shell Side	Hot Water	2kg/sec	373K	Pressure outlet
Tube Side	Cold Water	0.5 kg/s	293K	Pressure outlet

The solver setting for the cases planned to analyze are as follows-

- Solver- Pressure Based, steady state
- Model- Standard k-ε
- Material- Fluid-water, solid- copper
- Properties of water-
- Density 998.2 kg/m3
- Specific Heat 4182 J/kg-K
- Thermal conductivity 0.6 W/m-K
- Viscosity 0.001003 kg/m-s
- Properties of copper-
- Density 8978 kg/m3
- Specific Heat 381 J/kg-K
- Thermal conductivity 387.6 W/m-K

- Solution methods-
- Pressure-Velocity coupling-SIMPLE scheme
- Gradient-Green-Gauss Node Based
- Pressure-Second order
- Momentum-Second order upwind
- Turbulent kinetic energy-Second order upwind
- Turbulent dissipation rate- Second order upwind
- Energy- Second order upwind

III. NUMERICAL SIMULATIONS AND ANALYSIS

A. CASE 1 – STHE with Segmental Baffles:

Flow Visualization and Velocity Field Analysis

The below figure shows the streamlines of flowing fluid inside the heat exchanger chamber. The case consisted of 8 baffles spaced at a gap of 47mm from each other.

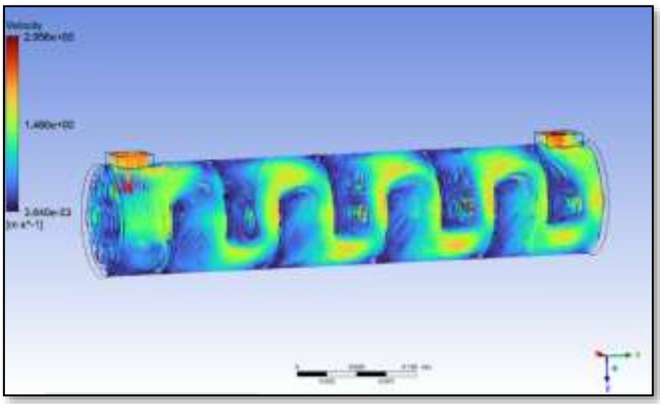


Figure III-1 Velocity streamlines

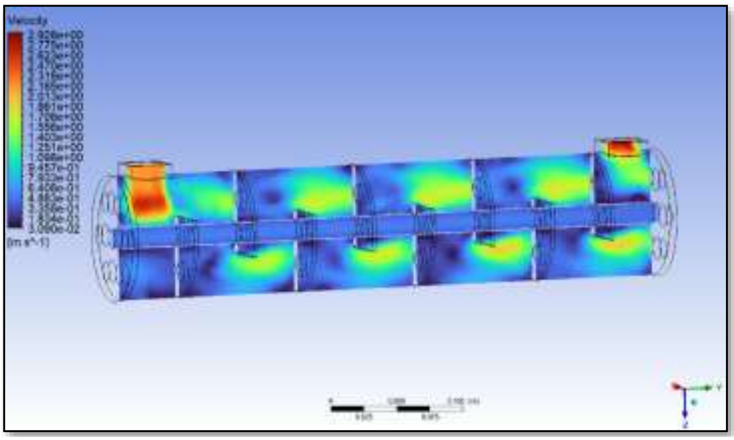


Figure III-2 Velocity contour plot

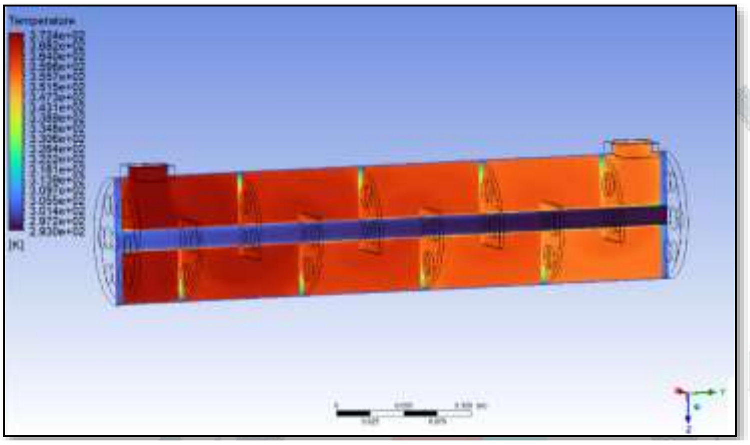


Figure III-3 Temperature contour plot

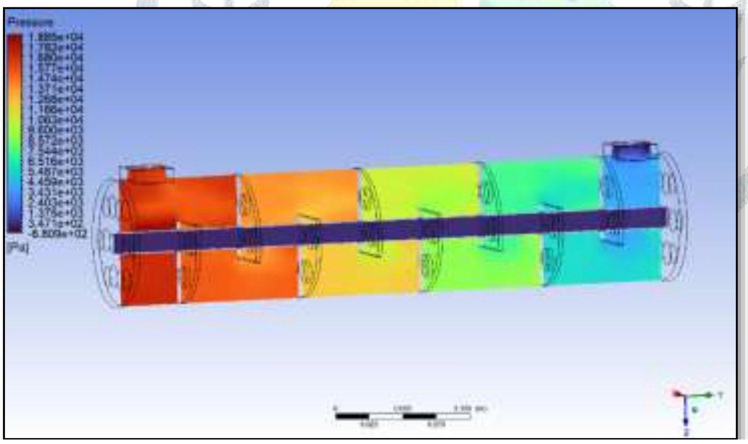


Figure III-4 Pressure contour plot

B. CASE 2 – STHE with Inclined Baffles

Flow Visualization and Velocity Field Analysis

The below figure shows the streamlines of flowing fluid inside the heat exchanger chamber.

The case consisted of inclined baffle design with 8 baffles at 25° inclination angle

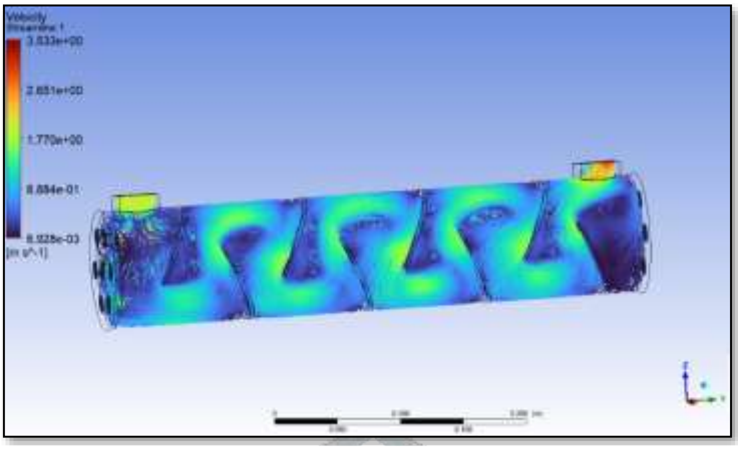


Figure III-5 Velocity streamlines for Case 2, showing helical flow.

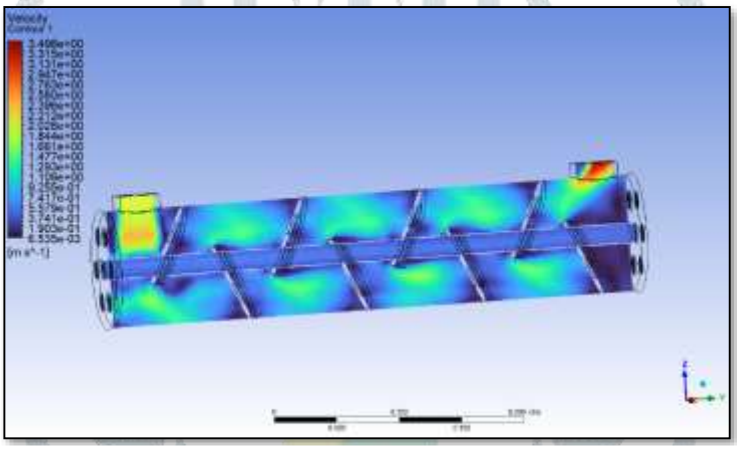


Figure III-6 Velocity contour plot

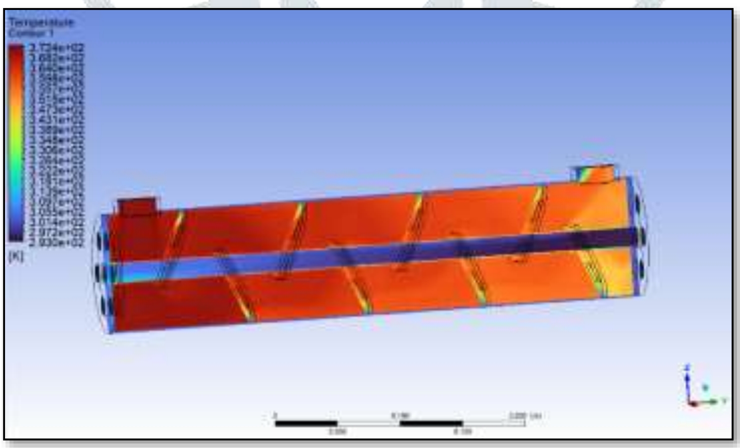


Figure III-7 Temperature contour plot

C. CASE 3a – STHE with Inclined baffles at entry and exit at 20° (2 nos.) & Segmental baffles in between (4nos.) total 6 baffles

Flow Visualization and Velocity Field Analysis

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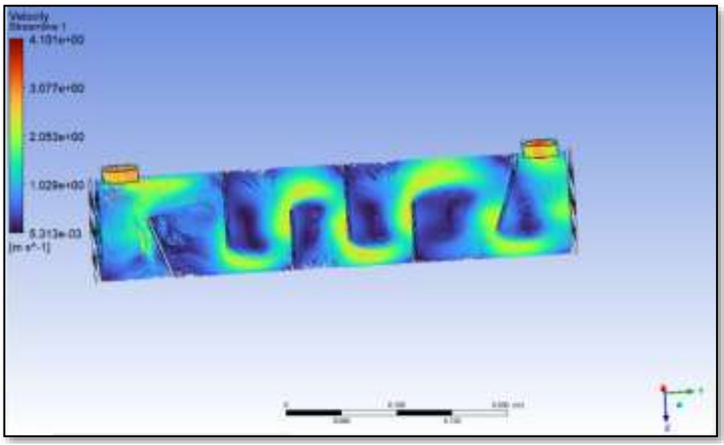

Figure III-8 Velocity streamlines

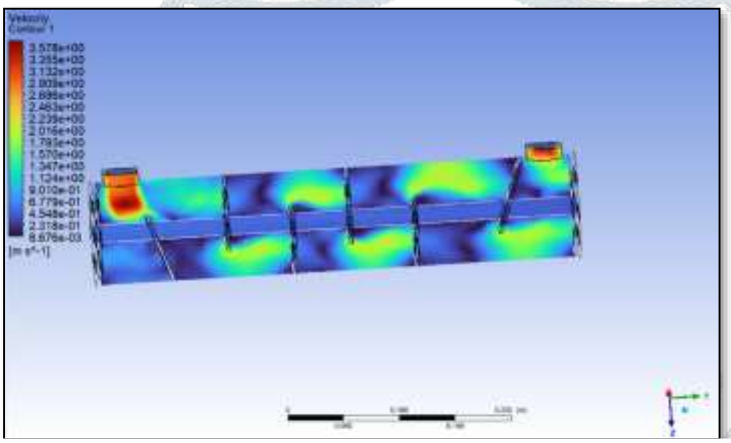

Figure III-9 Velocity contour

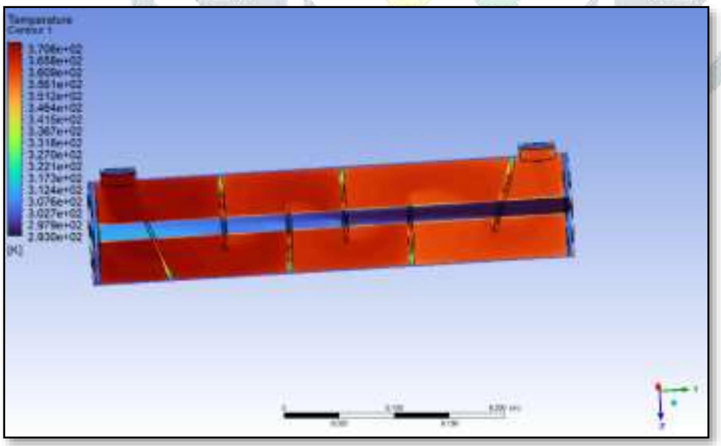

Figure III-10 Temperature contour

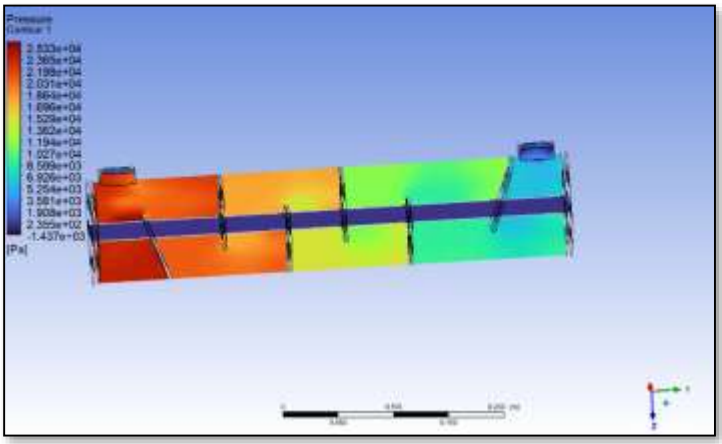

Figure III-11 Pressure contour plot

D. CASE 3b – STHE with Inclined baffles at entry and exit at 25° (4 nos.) & Segmental baffles in between (4nos.) total 8 baffles

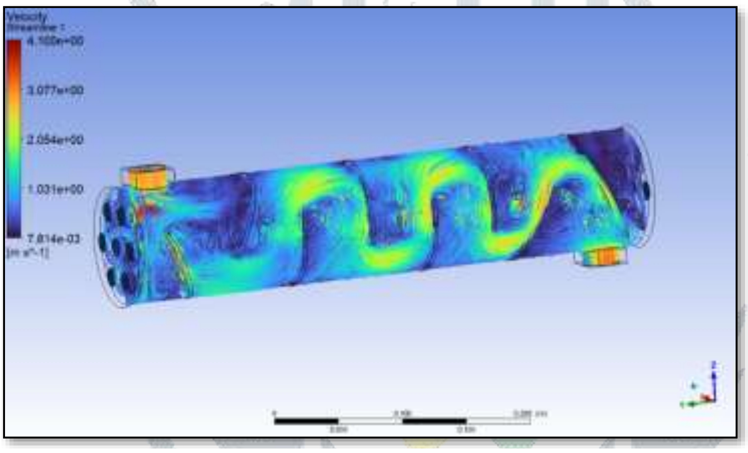

Figure III-12 Velocity streamlines

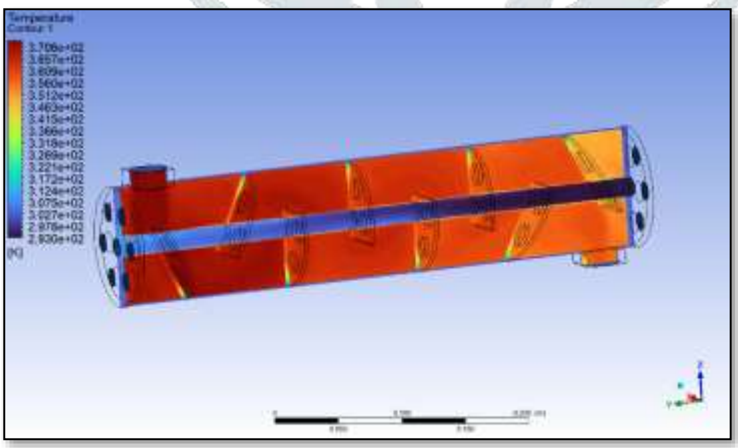

Figure III-13 Temperature contour

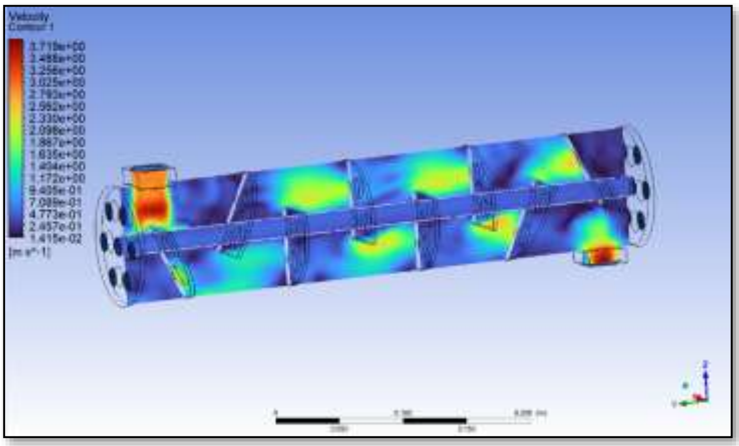

Figure III-14 Velocity contour

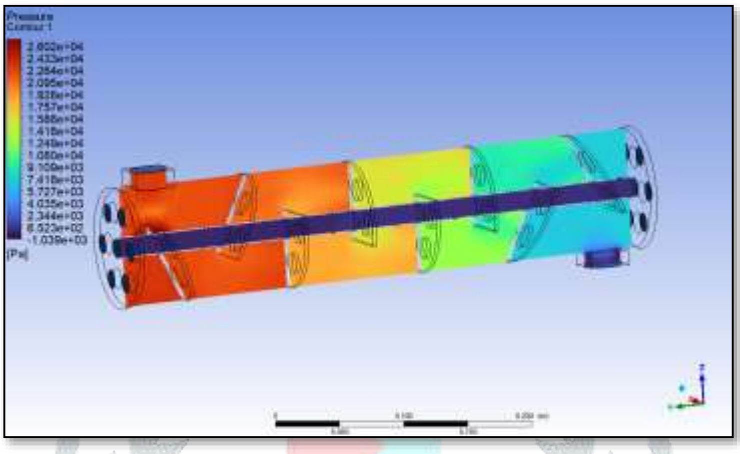

Figure III-15 Pressure contour

E. CASE 3c – STHE with Inclined baffles at entry and exit at 30° (6 nos.) & Segmental baffles in between (4nos.) total 10 baffles

Flow Visualization and Velocity Field Analysis

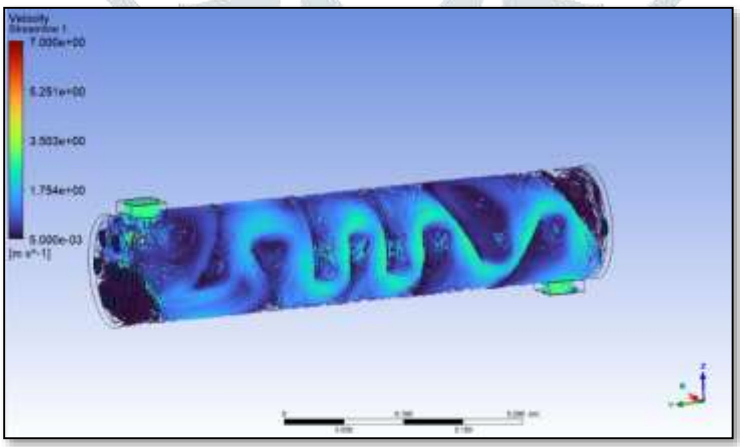

Figure III-16 Velocity streamlines

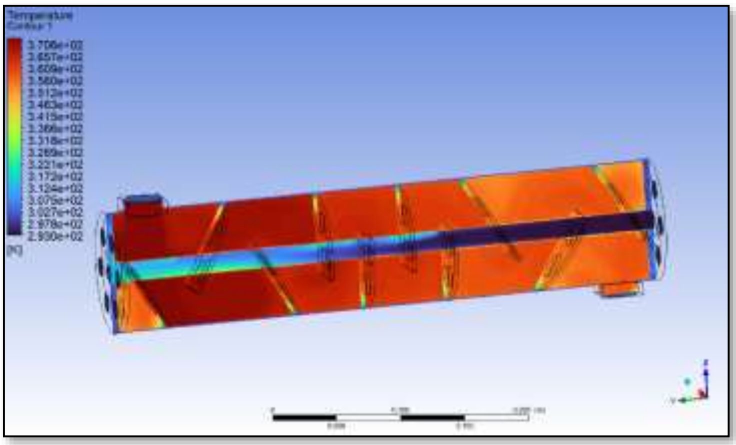

Figure III-17 Temperature contour

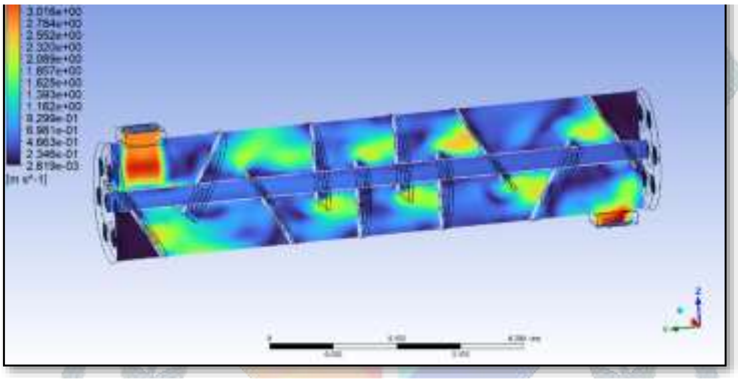

Figure III-18 Velocity contour

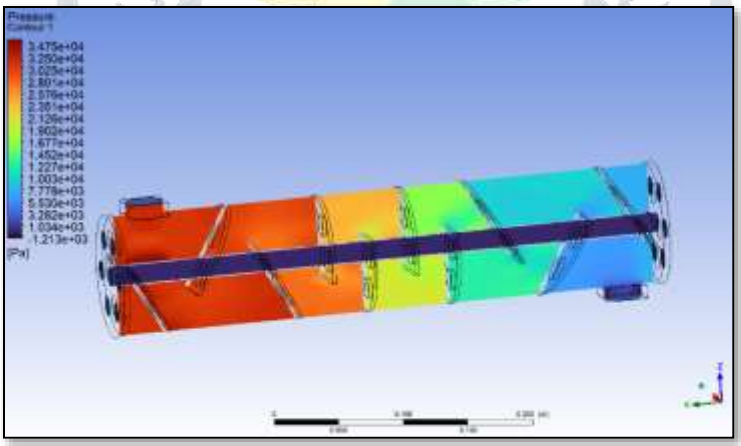

Figure III-19 Pressure contour

IV. RESULTS AND DISCUSSION

1. Comparative Pressure Drop Analysis

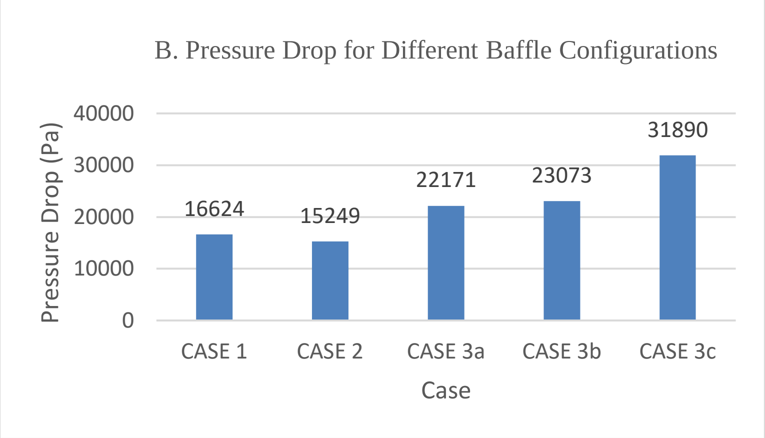

Figure-b: Comparison of shell-side Pressure Drop for all cases.

The hydraulic performance of the different heat exchanger configurations, quantified by their pressure drop, reveals significant variations directly linked to baffle geometry and flow path characteristics (Fig. b). Case 1 (Segmental Baffle STHE) serves as the baseline, exhibiting a Pressure Drop of 16624 Pa. This is attributed to the characteristic zig-zag flow induced by segmental baffles, leading to repeated and abrupt redirections of the fluid. The cumulative effect of localized pressure drops across each baffle pass, along with energy dissipation in recirculation zones, contributes to this substantial pressure loss. In contrast, Case 2 (Inclined Baffle STHE) demonstrates a significantly lower Pressure Drop of 15249 Pa (Fig. b). This reduction is a primary advantage of the inclined baffle design, as the fluid is guided along a predominantly continuous, helical or spiraling motion. This smoother, less tortuous path minimizes form drag and energy dissipation associated with abrupt flow redirections and large recirculation zones inherent to segmental designs. The hybrid configurations (Case 3a, 3b, 3c) present varying pressure penalties (Fig. b):

Case 3a, with a hybrid arrangement, shows a Pressure Drop of 22171 Pa. This is higher than both Case 1 and Case 2, indicating that while it enhances heat transfer, it comes at a cost of increased hydraulic resistance due to the complex and tortuous flow path induced by the combination of baffles.

Case 3b, another hybrid design, achieves a Pressure Drop of 23073 Pa. While higher than traditional inclined baffle designs (Case 2) and the segmental baffle (Case 1), this value represents a controlled increase, striking a balance between enhancing heat transfer and managing pumping power requirements.

Case 3c, characterized by a high number of baffles and steeper inclination for its inclined sections, records the highest Pressure Drop of 31890 Pa across all tested configurations. This significant hydraulic penalty is due to the exceptionally tortuous and turbulent flow path, with frequent and sharp changes in velocity contributing substantially to form drag and viscous losses. The pumping power requirements directly correlate with the pressure drop (Fig. e). Case 2 (30.55 W) demands the least pumping power, while Case 1 (33.3 W) is slightly higher. The hybrid designs require more: Case 3a (44.41 W), Case 3b (46.22 W), and Case 3c (63.88 W), with Case 3c requiring the most energy input due to its extreme flow resistance.

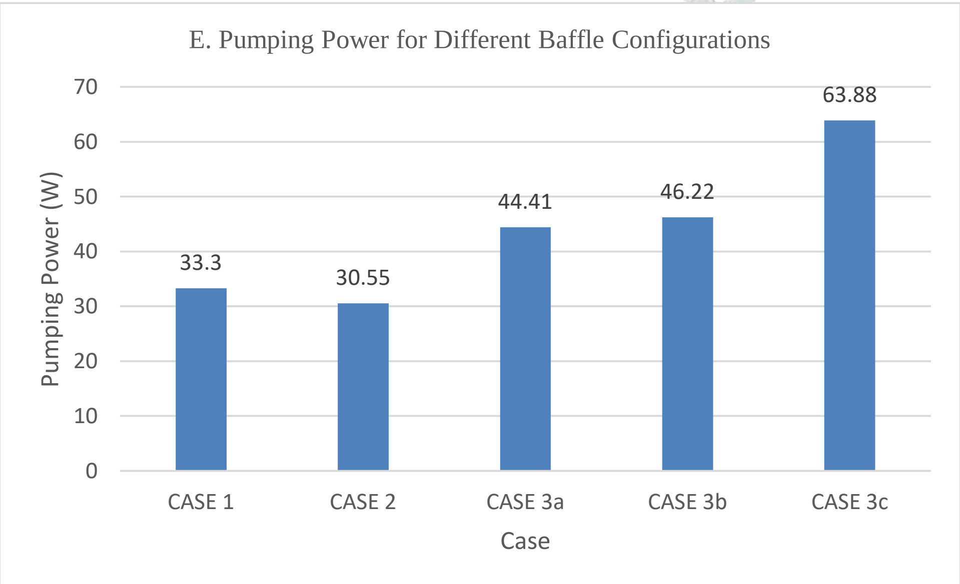

Figure- e: Comparison of required Pumping Power for all cases

2. Thermal Performance and Heat Transfer Trends

Thermal performance is primarily assessed through the Heat Transfer Coefficient (HTC), overall thermal effectiveness, and the hot and cold fluid outlet temperatures (Fig. a, d, and f respectively for comparative trends). Case 1 (Segmental Baffle STHE), with an effectiveness of 0.83, demonstrates an HTC of 5723.1 W/m²K. The hot fluid outlet temperature is 356.4 K, and the cold fluid outlet temperature is 359.4 K. The heat transfer rate for this baseline is 138842.4W.

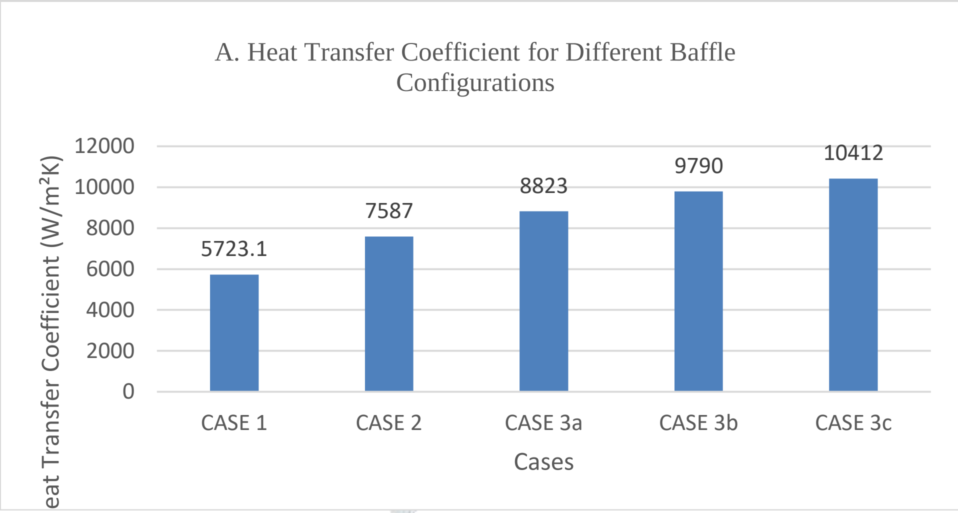

Figure- a: Comparison of Heat Transfer Coefficient (HTC) for all cases

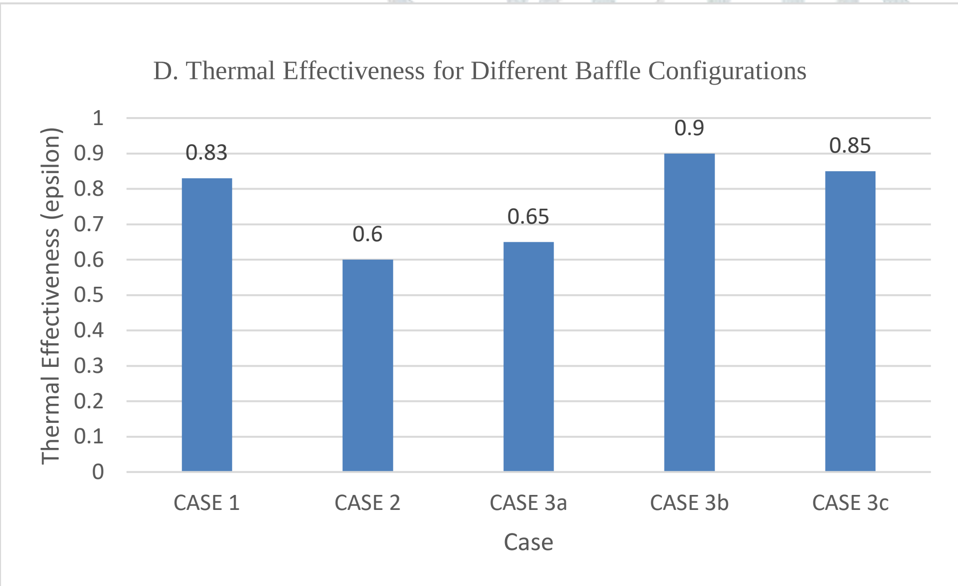

Figure- d: Comparison of Thermal Effectiveness for all cases

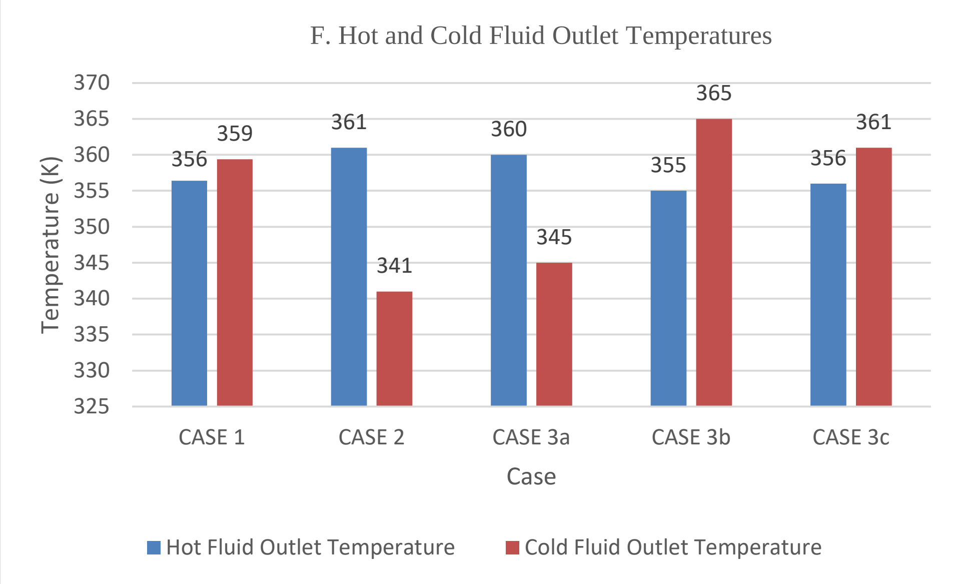

Figure- f: Comparison of Hot and Cold Fluid Outlet Temperatures for all cases

The effective disruption of the boundary layer and induced turbulence by segmental baffles promote energy transfer. Case 2 (Inclined Baffle STHE) exhibits an HTC of 7587 W/m²K, which is significantly higher than Case 1 (5723.1 W/m²K) (Fig. a). This suggests that despite a "smoother" helical flow, the continuous spiraling motion effectively promotes sustained contact over tube surfaces, enhancing local convective heat transfer. However, its thermal effectiveness is 0.6, lower than Case 1 (Fig. d). The hot fluid exits at 361 K, and the cold fluid at 341 K (Fig. f), indicating less complete overall thermal exchange across the heat exchanger length compared to Case 1. The hybrid baffle configurations (Case 3a, 3b, 3c) aim to combine the benefits of both segmental and inclined designs, often yielding superior heat transfer characteristics:

Case 3a achieves an HTC of 8823 W/m²K, notably higher than both Case 1 and Case 2 (Fig. a). Its effectiveness is 0.65 (Fig. d), with hot fluid exiting at 360 K and cold fluid at 345 K (Fig. f). This enhanced heat transfer is due to the complex and vigorous mixing induced by the hybrid arrangement.

Case 3b stands out with a very high HTC of 9790 W/m²K (Fig. a) and the highest thermal effectiveness of 0.9 among all cases (Fig. d). This configuration achieves a cold fluid outlet temperature of 365 K and a hot fluid outlet temperature of 355 K (Fig. f), demonstrating highly efficient heat exchange and significant heat recovery. The combined helical and cross-flow patterns ensure consistent fluid-to-surface contact and vigorous mixing.

Case 3c records the highest HTC (10412 W/m²K) (Fig. a). Its effectiveness is 0.85 (Fig. d), with hot fluid exiting at 356 K and cold fluid at 361 K (Fig. f). This exceptionally high HTC is attributed to the increased number of baffles and steeper inclination angles, promoting intense fluid mixing and maximizing contact area. Overall, all hybrid configurations (Case 3a, 3b, 3c) demonstrate higher HTCs than both Case 1 and Case 2 (Fig. a), affirming their ability to enhance heat transfer. Case 3b notably achieves the highest effectiveness, indicating the most complete heat exchange (Fig. d).

3. Effect of Baffle Geometry and Spacing

Baffle geometry and spacing play a pivotal role in dictating the fluid flow patterns, which in turn govern both heat transfer and pressure drop. Segmental baffles (Case 1) force the fluid into a characteristic zig-zag path. This repeated redirection effectively disrupts boundary layers and induces high levels of turbulence, enhancing convective heat transfer. High-velocity regions are formed as fluid is constricted through baffle windows, while swirling patterns and recirculation zones are evident downstream. Inclined baffles (Case 2) fundamentally alter the flow by promoting a predominantly continuous, helical or spiraling motion. This design minimizes abrupt changes in direction and reduces large-scale recirculation zones, leading to a smoother flow. The angled baffles guide the fluid efficiently across the tube bundle, promoting sustained sweep over tube surfaces. Hybrid baffle configurations (Case 3a, 3b, 3c) combine elements of both segmental and inclined designs, aiming to leverage their respective advantages:

Case 3a uses a hybrid arrangement, creating a complex and tortuous path with significant cross-flow and zig-zag patterns. High-velocity zones are observed at constrictions, leading to higher turbulence.

Case 3b features a combination that creates a helical path while ensuring extensive mixing across the tube bundle, demonstrating reduced stagnant zones compared to purely segmental baffles. The overall velocity distribution implies a well-distributed flow with minimal bypassing, essential for maximizing heat recovery.

Case 3c utilizes a high number of baffles and steeper inclination for its inclined sections, creating an exceptionally tortuous and turbulent flow with highly convoluted streamlines and vigorous swirling. This aggressive baffling effectively minimizes stagnant zones and ensures maximum interaction with tube surfaces. However, the continuous re-acceleration and redirection, while thinning thermal boundary layers, also contribute to very high form drag and viscous losses. The interplay between baffle cut, angle, and spacing dictates the balance between heat transfer enhancement and hydraulic resistance. Designs that create more aggressive mixing (like high-angle inclined or multiple segmental baffles) tend to increase HTC but at the cost of higher pressure drop.

4. Flow Uniformity, Recirculation Zones, and Dead Spots

The efficiency of heat transfer and the magnitude of pressure drop are significantly influenced by the uniformity of flow and the presence of recirculation zones or dead spots within the shell side. Case 1 (Segmental Baffles): Velocity streamlines vividly illustrate the zig-zag flow. While promoting turbulence, this design inherently leads to turbulent eddies and recirculation zones in the wake of the baffles. Velocity magnitude contours show areas of significantly lower velocity in corners and immediately downstream of the baffles, confirming regions of flow stagnation or recirculation. These areas represent energy dissipation and less effective fluid-to-surface interaction. Case 2 (Inclined Baffles): In stark contrast to Case 1, the fluid exhibits a predominantly continuous, helical or spiraling motion. There are fewer abrupt changes in direction and a noticeable reduction in large-scale recirculation zones. The velocity distribution appears more uniform, with active flow across a greater cross-sectional area and less pronounced regions of stagnation. This smoother flow minimizes energy dissipation related to form drag and avoids significant dead spots. Hybrid Baffle Configurations:

Case 3a: While aiming for enhanced mixing, this hybrid configuration still exhibits a complex and tortuous path with noticeable recirculation zones immediately downstream of the segmental baffles and in stagnant regions, as seen in velocity contours. These areas indicate less effective fluid interaction, despite overall higher average outlet velocity.

Case 3b: The combination of inclined and segmental baffles in Case 3b creates a helical path that ensures vigorous mixing across the tube bundle while demonstrating reduced stagnant zones compared to purely segmental baffles. The overall velocity distribution implies a well-distributed flow with minimal bypassing, essential for maximizing heat recovery.

Case 3c: This configuration creates an exceptionally tortuous and turbulent flow path with highly convoluted streamlines and vigorous swirling. This aggressive baffling effectively minimizes stagnant zones and ensures maximum interaction with the tube surfaces. However, the continuous re-acceleration and redirection, while thinning thermal boundary layers, also contribute to very high form drag and viscous losses.

5. Performance Optimization Parameters

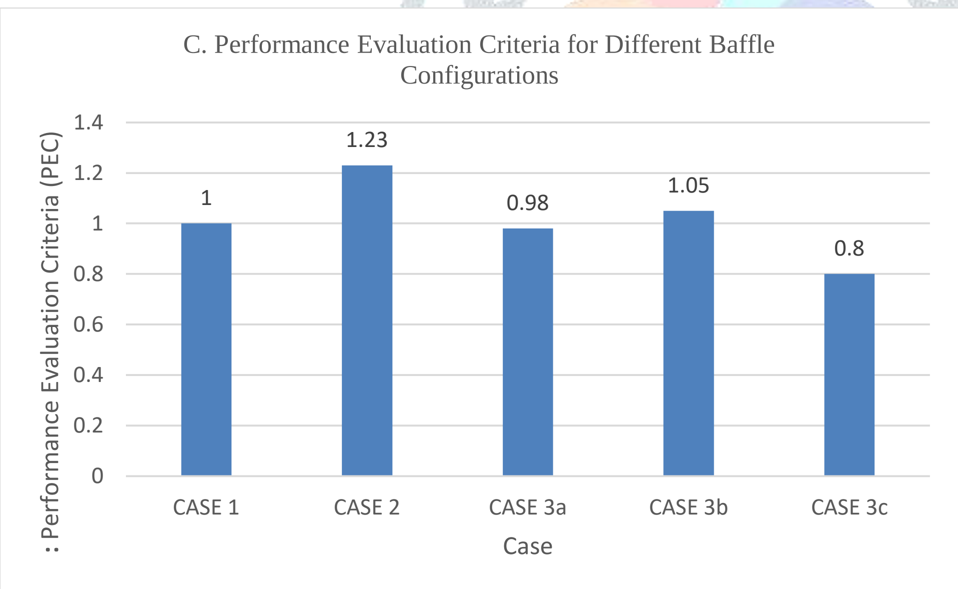

Figure- c: Comparison of Performance Evaluation Criteria (PEC) for all cases

The Performance Evaluation Criterion (PEC) serves as a crucial metric for identifying an optimized heat exchanger design by balancing heat transfer enhancement (HTC) against the hydraulic penalty (pressure drop/pumping power) (Fig. g and h). Within this study, Case 1 (Segmental) is defined as the direct reference, and its PEC is normalized to 1.0. A PEC value greater than 1.0 signifies an overall improvement in thermal-hydraulic performance compared to Case 1, while a value less than 1.0 indicates reduced efficiency. The PEC values for the investigated cases are (Fig. c):

Case 1 (Segmental): 1.0

Case 2 (Inclined): 1.23

Case 3a (Hybrid): 0.984

Case 3b (Hybrid): 1.05

Case 3c (Hybrid): 0.807 Based on the PEC:

Case 2 (PEC = 1.23) demonstrates the highest overall thermal-hydraulic performance among all tested configurations (Fig. c). This signifies that it achieves the best balance of heat transfer per unit of pumping power, despite its lower thermal effectiveness (0.6) compared to some other cases. Its significantly lower pressure drop and competitive HTC contribute to this leading PEC.

Case 3b (PEC = 1.05) emerges as a highly efficient hybrid baffle configuration (Fig. c). While its PEC is lower than Case 2, it achieves a remarkably high thermal effectiveness of 0.9 (the highest among all cases) (Fig. d), indicating superior heat recovery. Its PEC value, being greater than 1.0, signifies a substantial improvement in overall energetic efficiency compared to Case 1 for applications demanding high effectiveness. (Fig. h for PEC vs. Effectiveness trade-off).

Case 3a (PEC = 0.984) shows a slight reduction in overall performance compared to Case 1 (PEC < 1.0), meaning its higher pumping power outweighs its heat transfer benefits on a relative basis (Fig. c).

Case 3c (PEC = 0.807) is deemed less optimal compared to Case 1 despite having the highest HTC. Its very high pressure drop disproportionately offsets the thermal gains, leading to the lowest PEC, indicating an energetically less efficient design than the baseline (Fig. c). This analysis underscores that a high HTC alone does not guarantee an optimal design. The PEC effectively captures the crucial trade-off, guiding towards designs that are both thermally effective and energetically efficient (Fig. g and h).

6. Discussion of Trade-offs in Hybrid Designs

Heat exchanger design inherently involves trade-offs between maximizing heat transfer and minimizing the associated pressure drop (and thus pumping power) (Fig. g and h). Hybrid baffle designs are specifically conceived to navigate these trade-offs, aiming to surpass the limitations of conventional configurations. Traditional Segmental Baffles (Case 1) excel at inducing turbulence and achieving good heat transfer, as seen in their 0.83 effectiveness (Fig. d), but they impose a substantial hydraulic penalty (Fig. b) due to their zig-zag flow path and inherent recirculation zones. This translates to higher pumping power requirements (33.3 W) (Fig. e) and a PEC of 1.0 (serving as our reference baseline) (Fig. c). Pure Inclined Baffles (Case 2) significantly reduce pressure drop (15249 Pa) (Fig. b) and pumping power (30.55 W) (Fig. e) due to their smoother helical flow. They also achieve a high HTC (7587 W/m²K) (Fig. a). However, their limitation is often a lower overall thermal effectiveness (0.6) (Fig. d), as the helical flow, while beneficial for local heat transfer and pressure drop, may not provide the intensive cross-flow mixing needed for complete thermal exchange across the entire shell length. Hybrid Baffle Configurations (Case 3a, 3b, 3c) attempt to strike an improved balance.

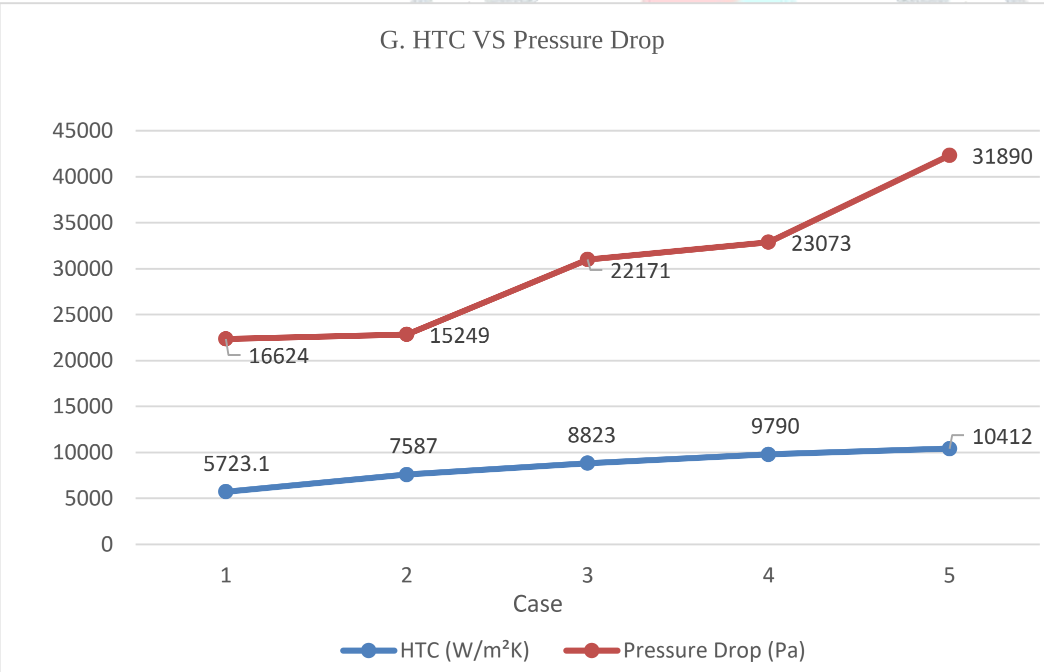

Figure-g: Line graph showing the trade-off between HTC and Pressure Drop.

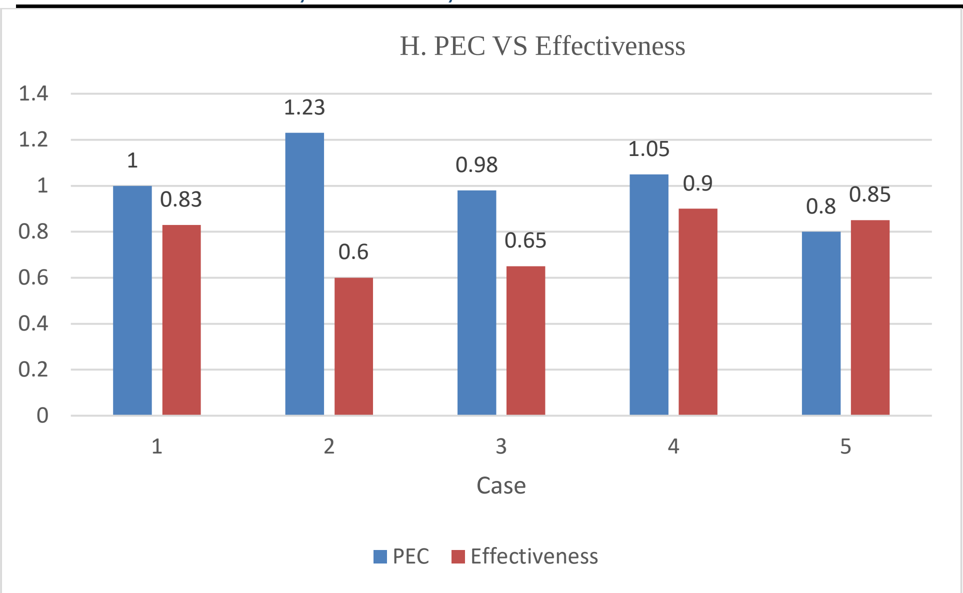

Figure-h: Bar chart showing the trade-off between PEC and Effectiveness

Case 3a demonstrates that combining inclined and segmental baffles can indeed increase HTC (8823 W/m²K) beyond Case 1 and Case 2 (**Fig. a**). Its PEC of 0.984 shows that while heat transfer is improved, the overall efficiency is slightly lower than Case 1 when considering the hydraulic penalty (**Fig. c**).

Case 3b stands out as a very efficient hybrid. It achieves the highest effectiveness (0.9) (**Fig. d**) and a very high HTC (9790 W/m²K) (**Fig. a**). While its pumping power (46.22 W) (**Fig. e**) is higher than Case 1 or Case 2, its PEC of 1.05 (**Fig. c**) confirms that the significant thermal gains more than compensate for the increased hydraulic cost compared to the baseline (**Fig. h**). This design successfully balances vigorous mixing for heat transfer with a systematically managed pressure loss, indicating that the benefits of increased turbulence are maximized without incurring excessive hydraulic penalties.

Case 3c represents the extreme end of the trade-off. It achieves the absolute highest HTC (10412 W/m²K) (**Fig. a**), but at the disproportionately high cost of the highest pressure drop (31890 Pa) (**Fig. b**) and pumping power (63.88 W) (**Fig. e**). This results in a PEC of 0.807 (**Fig. c**), which is less than 1.0, indicating that the hydraulic penalty overwhelms the thermal benefits compared to Case 1, making it an energetically less efficient design for most applications (**Fig. g and h**). This highlights the diminishing returns when hydraulic losses become excessive in the pursuit of higher heat transfer. This discussion of trade-offs emphasizes the vital importance of utilizing multi-objective performance metrics like PEC (**Fig. g and h**). They allow designers to identify truly optimized heat exchanger designs that achieve specific thermal performance targets (like high effectiveness) without incurring economically or energetically prohibitive pumping power requirements.

7. Summary :

Cases	HTC (W/m²K)	Pressure Drop (Pa)	V inlet (m/s)	V outlet (m/s)	Hot Fluid Outlet Temperature (K)	PEC	Cold Fluid Outlet Temperature (K)	Effectiveness	Heat Transfer Rate (W)	Pumping Power (W)
CASE 1	5723.1	16624	2.88	2.11	356	1	359	0.83	138842	33.3
CASE 2	7587	15249	2.88	2.16	361	1.23	341	0.6	100368	30.55
CASE 3a	8823	22171	2.88	2.75	360	0.98	345	0.65	108732	44.41
CASE 3b	9790	23073	2.88	2.79	355	1.05	365	0.9	150552	46.22
CASE 3c	10412	31890	2.88	2.74	356	0.8	361	0.85	142188	63.88

This study conducted a comprehensive CFD analysis of various shell and tube heat exchanger baffle configurations, including traditional segmental baffles (Case 1), inclined baffles (Case 2), and several hybrid designs (Case 3a, 3b, 3c). The objective was to evaluate their thermal and hydraulic performance, identifying optimal designs that balance heat transfer enhancement with pressure drop minimization. The key findings are:

Case 1 (Segmental Baffles), serving as the baseline for this study, has an effectiveness of 0.83 (Fig. d), demonstrates moderate heat transfer capabilities (HTC 5723.1 W/m²K) (Fig. a), incurs a notable pressure penalty (16624 Pa) (Fig. b), and has a PEC normalized to 1.0 (Fig. c).

Case 2 (Inclined Baffles) provides excellent hydraulic performance with the lowest pressure drop (15249 Pa) (Fig. b) and lowest pumping power (30.55 W) (Fig. e), contributing to the highest overall PEC of 1.23 (Fig. c). It also shows a higher HTC (7587 W/m²K) than Case 1 (Fig. a), but its thermal effectiveness (0.6) is lower than configurations designed for higher heat recovery (Fig. d).

Hybrid designs successfully enhance heat transfer. All hybrid cases (3a, 3b, 3c) achieved higher HTCs than both Case 1 and Case 2 (Fig. a).

Case 3b emerged as a highly efficient hybrid configuration, demonstrating a superior balance between thermal and hydraulic performance. It achieved the highest thermal effectiveness (0.9) (Fig. d) and a very high HTC (9790 W/m²K) (Fig. a) while maintaining a strong PEC of 1.05 (Fig. c). This indicates that its significant heat transfer gains effectively compensate for its increased pressure drop (23073 Pa) (Fig. b) and pumping power (46.22 W) (Fig. e) compared to the baseline (Fig. h).

Case 3a offered improved HTC (8823 W/m²K) over Case 1 (Fig. a), with a PEC of 0.984 (Fig. c), indicating slightly lower relative performance than the baseline.

Case 3c achieved the absolute highest HTC (10412 W/m²K) (Fig. a) but at the severe cost of the highest pressure drop (31890 Pa) (Fig. b) and pumping power (63.88 W) (Fig. e), resulting in a PEC of 0.807 (Fig. c). This illustrates that maximizing heat transfer without considering the disproportionate hydraulic penalty leads to an energetically less efficient design than the baseline (Fig. g and h). In conclusion, while Case 2 exhibits the highest PEC (Fig. c), making it highly efficient from an energy consumption perspective for its heat transfer, Case 3b stands out as the best choice for applications requiring very high heat recovery (high effectiveness) (Fig. d), as it achieves the highest effectiveness while still maintaining a robust PEC significantly above the baseline (Fig. h). The study underscores the critical importance of utilizing multi-objective criteria like PEC for heat exchanger optimization, as it guides designers towards configurations that are not only thermally efficient but also operationally viable by balancing performance with energy expenditure. This research demonstrates that thoughtfully designed hybrid baffle arrangements offer innovative solutions to overcome the inherent trade-offs in conventional STHE designs

V. CONCLUSIONS

In culmination, this dissertation definitively concludes that the proposed novel hybrid baffle configurations offer a superior and energetically more efficient alternative to conventional baffle designs in shell and tube heat exchangers. Specifically**,** Case 3b, integrating four 25° inclined baffles at entry/exit with four segmental baffles in between, stands out as the optimal design. It successfully mitigates the excessive pressure drop of traditional segmental baffles while significantly enhancing heat transfer and achieving high overall thermal effectiveness. This work provides critical insights into the complex interplay of baffle geometry, fluid dynamics, and heat transfer, paving the way for the development of more efficient, compact, and sustainable heat exchange technologies for diverse industrial applications.

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