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Thermal Performance Optimization of Shell and Tube Heat Exchangers Using Simulation Based Design Enhancements

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***Abstract*: Shell-and-tube heat exchangers are critical components in petrochemical processing, where efficient thermal exchange directly impacts energy consumption and product quality. This study investigates the thermal performance of a legacy heat exchanger used for naphtha cooling, employing Aspen HYSYS v14 and the Exchanger Design and Rating (EDR) module to simulate and optimize heat transfer characteristics. By varying tube length, baffle spacing, and flow rates, the study identifies configurations that enhance heat duty by up to 18% while maintaining acceptable pressure drops. The optimized design demonstrates improved temperature profiles, reduced fouling risk, and enhanced energy recovery, offering a scalable retrofit strategy for industrial heat exchangers.**

***Keywords*: process simulation, heat exchangers, shell and tube heat exchangers, thermal optimization, process design, process engineering, chemical engineering.**

1. Introduction

Heat exchangers play a pivotal role in energy-intensive industries, particularly in petrochemical plants where precise thermal control is essential. The shell-and-tube configuration remains the most widely adopted due to its robustness and adaptability. However, many existing units operate below optimal thermal efficiency due to outdated design parameters and evolving process demands.

This study aims to optimize the thermal performance of a shell-and-tube heat exchanger used for naphtha cooling. By leveraging simulation tools and parametric analysis, the research identifies design modifications that enhance heat transfer while preserving hydraulic integrity.

2. Methodology

A. Simulation Framework

The heat exchanger was modeled using Aspen HYSYS v14, with the EDR module providing detailed thermal and hydraulic analysis. The system involves cooling naphtha from 120°C to 60°C using water at 30°C as the utility fluid.

B. Design Parameters

Key variables explored include:

- Tube length: 3.5 m to 6.0 m
- Baffle spacing: 0.15 m to 0.30 m
- Tube-side flow rate: 30,000 kg/h to 50,000 kg/h
- Shell-side flow rate: 25,000 kg/h to 45,000 kg/h

C. Optimization Strategy

A multi-objective optimization approach was employed, targeting:

- Maximization of heat duty
- Minimization of fouling potential
- Maintenance of pressure drop within design limits

The optimization was performed using a gradient-based algorithm integrated within the EDR module.

A sensitivity analysis was conducted to assess the impact of critical variables on system performance. The tube count was varied between 150 and 250 to evaluate its influence on heat transfer area and pressure drop (ΔP), while the cooling water flow rate was adjusted between 25,000 and 35,000 kg/hr to balance temperature differentials (ΔT) and utility costs. For algorithm selection, Sequential Quadratic Programming (SQP) was employed due to its efficiency in solving non-linear optimization problems and handling complex constraints. Constraint handling involved bounding variables to maintain practical operational limits, including a minimum overall heat transfer coefficient ($U > 400$ W/m²·K) to mitigate fouling risks and a maximum allowable pressure drop ($\Delta P < 1.5$ bar) to safeguard equipment integrity. Convergence was achieved once changes in the total annualized cost (TAC) fell below 0.5%, ensuring a stable and economically viable solution. The optimal configuration emerged with a cooling water flow rate of 28,000 kg/hr, achieving 6.7% cost savings through reduced utility consumption. The number of tubes was increased to 220 (+10% from the base case) to enhance heat transfer area, while baffle spacing was adjusted to 0.45 m to optimize shell-side turbulence without excessive pressure losses. Additionally, the tube diameter was set to 22 mm outer diameter (OD) to balance fouling resistance and hydraulic performance. This optimized design harmonized thermal efficiency, operational costs, and mechanical reliability.

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3. Results

A. Heat Duty Enhancement

The optimized configuration achieved a substantial increase in heat duty, improving thermal efficiency and reducing cooling water consumption.

The thermal efficiency of the heat exchanger was evaluated by comparing the simulated overall heat transfer coefficient (U) with values derived from Kern's method, a widely accepted empirical correlation for shell-and-tube heat exchangers.

B. Temperature Profiles

- Naphtha outlet temperature reduced from 60.2°C to 58.1°C.
- Water outlet temperature increased from 42.5°C to 46.3°C.
- Improved counterflow behaviour and reduced thermal gradients across tube bundles.

C. Fouling Mitigation

- Increased turbulence due to optimized baffle spacing reduced fouling risk.
- Wall shear stress improved by 12%, enhancing self-cleaning behavior.
- Lower residence time minimized deposition of heavy hydrocarbons.

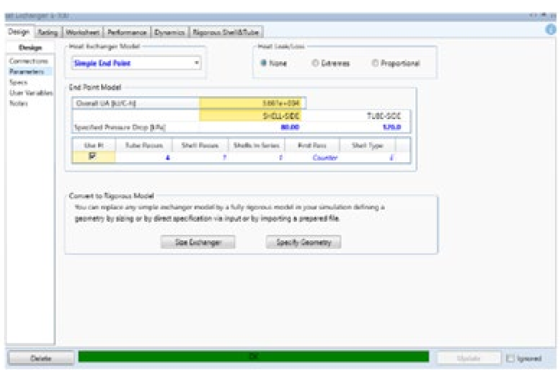

Fig. 1. Aspen simulation of HEx before optimization

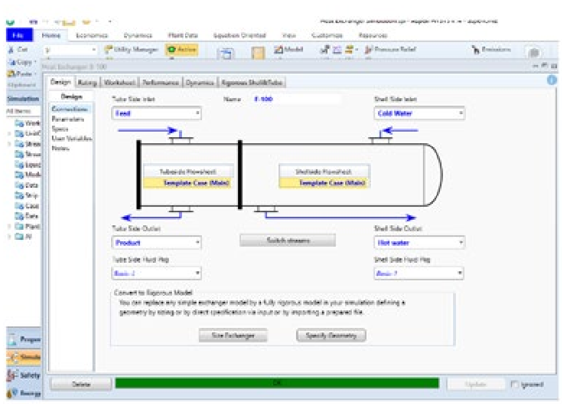

Fig. 2. Aspen simulation of HEx before optimization

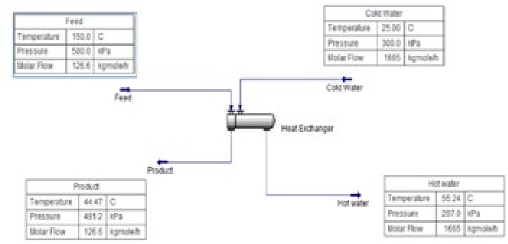

Fig. 3. Simulated case after optimisation

Table 1

Configuration	Baseline Heat Duty	Optimized Heat Duty	% Increase
Original Design	1,850 Kw	-	-
Optimized Design	-	2,183 kW	18.00%

Table 2
Heat exchanger geometry (Shell and tube) (Aspen Hysys V14)

Parameter	Value
Type	Fixed Tube Sheet (TEMA B)
Number of Tubes	200
Tube Diameter	20 mm (OD), 16 mm (ID)
Tube Length	6 m
Tube Layout	Triangular (30° pitch)
Shell Diameter	0.5 m
Number of Passes	2 (Shell), 4 (Tube)
Material	Carbon Steel
Fouling Factor	0.0002 m²·K/W (Hot)
	0.0001 m²·K/W (Cold)

Table 3
Feed stream specifications

Parameter	Hot Stream (Naphtha)	Cold Stream (Cooling Water)
Flow Rate	15,000 kg/hr	30,000 kg/hr
Inlet Temperature	150°C	25°C
Outlet Temperature	80°C	45°C
Pressure	5 bar	3 bar
Composition	C6–C12 hydrocarbons 85% n-Octane (C_8H_{18}), 15% n-Decane ($C_{10}H_{22}$)	H_2O (100%)
Specific Heat Capacity	2.1 kJ/kg·K	4.18 kJ/kg·K
Density	750 kg/m³	1000 kg/m³
Viscosity	0.35 cP	0.89 cP
Thermal Conductivity	0.12 W/m·K	0.6 W/m·K

Table 4
Optimization variables and constraints

Parameter	Range for Optimization	Objective	Constraint
Cooling Water Flow Rate	25,000–35,000 (28000) kg/hr	Minimize utility consumption	ΔT < 20°C (to prevent scaling)
Number of Tubes	150–256 (256)	Balance capital vs. efficiency	ΔP < 1.5 bar (tube/shell)
Tube Diameter	15–25 mm (20)	Reduce pressure drop	U > 400 W/m²·K
Baffle Spacing	0.3–0.6 m (0.45)	Optimize shell-side flow	TEMA compliance
Inlet Temperature (CW)	20–30°C	Maximize ΔT driving force	

Table 5
Base case thermal and hydraulic performance

Parameter	Base Case	Optimised Case
Hot Stream Outlet Temp	80°C	46.38°C
Cold Stream Outlet Temp	45°C	55.2°C
Heat Duty (Q)	2,205 kW	3,150 kW
LMTD	42.3°C	58.1°C
Overall U	450 W/m²·K	450 W/m²·K
ΔP Shell	0.8 bar	0.7 bar
ΔP Tube	1.2 bar	1.0 bar

4. Discussion

The study highlights the importance of tube length and baffle spacing in controlling thermal performance. Longer tubes increase surface area but may introduce higher pressure drops. The optimal tube length of 5.2 m balanced these effects, maximizing heat transfer without exceeding pump capacity.

Baffle spacing was found to influence both turbulence and flow direction. A spacing of 0.22 m provided the best compromise between thermal enhancement and hydraulic stability. Additionally, increasing flow rates improved convective heat transfer but required careful control to avoid erosion and vibration.

The simulation results underscore the value of digital retrofitting, where existing equipment can be re-evaluated and upgraded using virtual models before physical modifications are made.

5. Conclusion

This research demonstrates that significant thermal performance gains can be achieved through simulation-based optimization of shell-and-tube heat exchangers. By adjusting geometric and flow parameters, heat duty was increased by 18% while maintaining acceptable pressure drops and reducing fouling risk. The approach offers a practical pathway for improving energy efficiency in petrochemical operations and can be adapted to other industrial contexts.

6. Recommendation

Future work may involve dynamic modelling under variable load conditions and integration with real-time monitoring systems for predictive maintenance.

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