Performance Limitations of Shell-and-Tube Heat Exchangers at High Effectiveness (E > 0.85): Industrial Challenges, and Mitigation Strategies

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Abstract : Shell-and-tube heat exchangers (STHEs) are the most commonly utilized heat transfer equipment in the refining, petrochemical, and power generation industries. Heat exchanger effectiveness (ε) is a widely adopted metric for evaluating thermal performance. While high effectiveness is generally advantageous in terms of energy recovery, practical experience and established design guidelines indicate that STHEs designed for effectiveness values above approximately 0.85 may encounter diminishing performance benefits and operational difficulties. These challenges may include elevated pressure drops, heightened fouling susceptibility, flow maldistribution, and reduced design robustness. This paper presents a comprehensive technical review of the performance characteristics of high-effectiveness STHEs, supported by a thorough examination of existing literature and industry design practices. It also proposes practical strategies to mitigate potential issues and enhance the reliability of industrial operations.

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I. INTRODUCTION

Shell-and-tube heat exchangers (STHEs) continue to be the preferred solution for high-pressure and high-temperature industrial applications, owing to their robust mechanical integrity and adaptable design capabilities. The thermal performance of these exchangers is typically assessed using either the log mean temperature difference (LMTD) method or the effectiveness–number of transfer units (ε–NTU) approach.

In applications emphasizing energy integration and heat recovery, designers often aim for high effectiveness to optimize energy utilization. However, as the effectiveness approaches unity, the system becomes increasingly susceptible to non-ideal factors such as fouling, flow maldistribution, and manufacturing tolerances. Industry guidelines supported by findings in the published literature, consistently warn that targeting effectiveness values above approximately 0.80–0.85 may result in designs that are impractical or lack sufficient operational flexibility. This paper examines the underlying causes of these performance limitations and offers practical recommendations to mitigate them, supporting more robust and reliable heat exchanger design.

II. EFFECTIVENESS–NTU FUNDAMENTALS

Effectiveness (ε) is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate between two fluids:

$$\varepsilon = Q\_actual / Q\_max$$

Where $Q\_max = C\_min (T\_h,in - T\_c,in)$, and C_min is the smaller heat capacity rate of the two fluids. The ε–NTU relationship demonstrates that effectiveness increases asymptotically with NTU. While counterflow exchangers theoretically approach $\varepsilon = 1$ at very high NTU, achieving such conditions in practical STHEs requires large surface area or high heat transfer coefficients, both of which introduce cost and hydraulic penalties.

III. PERFORMANCE ISSUES AT HIGH EFFECTIVENESS (ε > 0.85)

Designing shell-and-tube heat exchangers (STHEs) for effectiveness values exceeding approximately 0.85 generally necessitates a high number of transfer units (NTU). This is typically achieved through an increase in heat transfer area, elevated fluid velocities, or enhanced turbulence, often realized through tighter baffle spacing or the use of tube inserts. However, these design strategies tend to result in higher pressure drops on either the shell side, tube side, or both.

Elevated pressure drop translates to increased pumping power requirements and may violate process constraints that impose upper limits on allowable pressure loss. Furthermore, high-effectiveness exchangers operate with minimal terminal temperature differences, rendering them highly susceptible to fouling and performance degradation under off-design operating conditions. This sensitivity can compromise both thermal efficiency and operational reliability.

IV. FOULING AND FLOW MALDISTRIBUTION SENSITIVITY

Fouling represents one of the most significant challenges in the design and operation of high-effectiveness shell-and-tube heat exchangers (STHEs). As the desired effectiveness increases, the available temperature driving force diminishes, making the exchanger increasingly vulnerable to even minor fouling resistances. A relatively small fouling layer can result in a substantial reduction in heat transfer duty. Designs that incorporate insufficient fouling margin often experience performance shortfalls early in their operational life, failing to meet guaranteed thermal performance.

In addition to fouling, flow maldistribution further compromises exchanger effectiveness. Phenomena such as shell-side bypassing, leakage streams, and uneven tube-side flow distribution reduce the overall heat transfer coefficient and lead to underutilization of the available heat transfer surface. Consequently, the actual effectiveness of the exchanger frequently falls significantly below the predicted design value.

V. DESIGN PERSPECTIVE

Thermal software design methodologies for heat exchangers prioritize a balanced approach to thermal and hydraulic performance, rather than focusing solely on maximizing effectiveness. As highlighted in the published technical guidelines, shell-and-tube heat exchangers (STHEs) designed for effectiveness values exceeding approximately 0.80–0.85 often exhibit heightened sensitivity to factors such as fabrication tolerances, fouling assumptions, and operational variability.

Resistance analysis conducted using thermal software frequently reveals that, at higher effectiveness levels, one side of the exchanger, typically either the shell or tube side, becomes the dominant contributor to the overall thermal resistance. Achieving further improvements in effectiveness under these conditions requires disproportionately large increases in surface area or fluid velocities, which in turn lead to excessive pressure drops. This results in unfavourable lifecycle economics, as the marginal gains in thermal performance are outweighed by increased energy consumption and reduced operational flexibility.

VI. MITIGATION STRATEGIES

Several mitigation strategies can be employed to address high-effectiveness limitations. A primary strategy is to adopt realistic effectiveness targets, typically between 0.75 and 0.85, and improve overall energy efficiency through process integration rather than single-exchanger optimization.

Design improvements include optimized baffle configurations, enhanced shell-side sealing, and improved flow distribution. Tube-side inserts or surface enhancements may be selectively applied, provided their impact on pressure drop and fouling is carefully assessed. Conservative fouling allowances and operational flexibility remain essential for reliable long-term performance.

VII. CONCLUSION

High-effectiveness shell-and-tube heat exchangers provide attractive energy recovery potential; however, effectiveness values exceeding approximately 0.85 often result in diminishing returns and increased operational risk. Pressure drop, fouling sensitivity, flow maldistribution, and fabrication tolerances become dominant limiting factors. Literature review and industry design practice consistently support the adoption of balanced effectiveness targets combined with robust hydraulic and mechanical design. Such an approach ensures reliable long-term performance and favourable lifecycle economics.

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