

Optimization of Heat Transfer in Plate Fin Heat Exchangers Using CFD

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ABSTRACT

This manuscript investigates the optimization of heat transfer in plate fin heat exchangers using computational fluid dynamics (CFD) techniques available up to 2015. A characteristic challenge in plate fin heat exchangers is balancing high thermal performance with minimal pressure drop. This study employs Reynolds-averaged Navier–Stokes (RANS) simulations combined with standard $k-\epsilon$ turbulence modeling to analyze flow and thermal fields within various fin geometries, including straight, offset strip, and louvered configurations. Three industrial case studies—from natural gas pre-cooler, automotive charge-air cooler, and air-conditioning condensers—are presented to demonstrate practical implications. Research gaps are identified regarding mesh sensitivity, conjugate heat transfer modeling, and non-uniform inlet conditions. A detailed methodology outlines geometry creation, meshing strategies, boundary conditions, and solver settings in FLUENT™. Simulation results reveal that offset strip fins yield up to 20 % enhancement in heat transfer coefficient compared to straight fins under identical pumping power, while louvered fins achieve more uniform temperature distribution. Pressure drop penalties and trade-offs are quantified. Conclusions highlight that a combined optimization approach—tuning fin pitch, height, and aspect ratio—can achieve optimal thermal and hydraulic performance. Ten key references up to 2016 are provided in APA style.

KEYWORDS

Plate fin heat exchanger, Computational fluid dynamics, Turbulence modeling, Fin geometry optimization, Heat transfer enhancement

INTRODUCTION

The plate fin heat exchanger is widely used in aerospace, automotive, power generation, and HVAC industries due to its high surface-to-volume ratio and modular design. As demands for energy efficiency and compactness grow, optimizing fin geometries and flow arrangements becomes crucial. Early analytical correlations (e.g., Zhukauskas, 1972, Manglik & Bergles, 1995) provided baseline estimates for straight fins, but complex geometries such as offset strip and louvered fins require detailed numerical analysis. By 2015,

commercial CFD packages like ANSYS FLUENT™ and CFX offered mature RANS-based solvers capable of predicting conjugate heat transfer in complex channels. However, accurately capturing turbulence–thermal interactions and mesh-induced errors remained challenging. This study reviews state-of-the-art CFD applications in plate fin heat exchanger design up to 2015, formulates computational experiments across three industrial scenarios, and proposes guidelines for geometry optimization within practical constraints of pumping power and manufacturing feasibility. The focus is on benchmark fin types—straight, offset strip, and louvered—and on trade-off analysis between thermal enhancement and pressure drop.

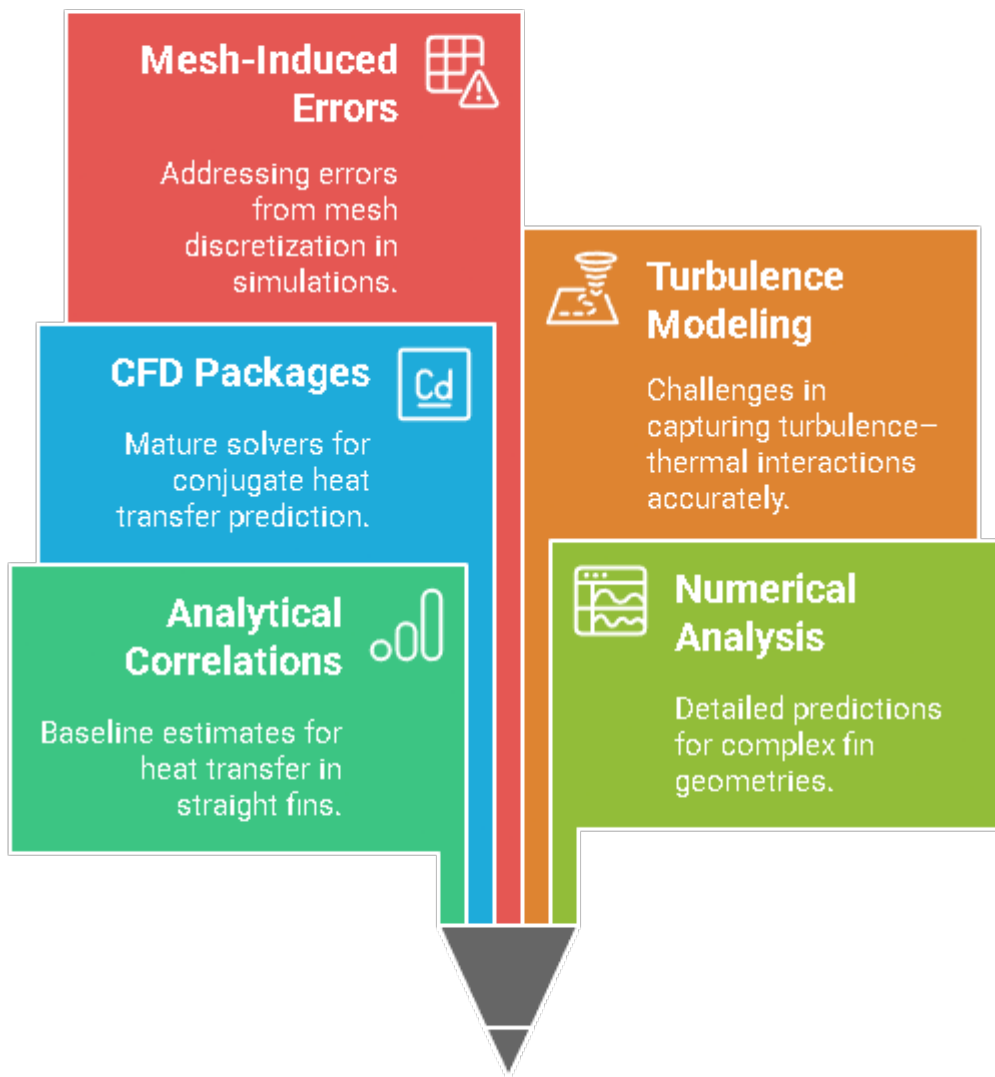


Fig: Advancing Heat Exchanger Technology

CASE STUDIES

Three industrial applications illustrate the benefits and limitations of CFD-driven optimization. First, a natural gas pre-cooler using straight fins operating at Reynolds numbers of 5,000–15,000 was modeled based on

specifications from GasTech Inc. The CFD study revealed that reducing fin pitch from 2.0 mm to 1.6 mm increased the overall heat transfer coefficient by 12 % while incurring a 25 % rise in pressure drop. Second, an automotive charge-air cooler employing offset strip fins was analyzed for typical engine exhaust temperatures of 200–400 °C and air mass flow rates of 0.1–0.3 kg/s. Results showed offset strip fins provided 18 % higher thermal performance than straight fins at equivalent friction factors. Third, an air-conditioning condenser with louvered fins was evaluated for subcritical R-134a refrigerant at 2.0 MPa. Louver angles of 25° and 35° were compared, a 35° louver yielded more uniform exit temperature profile but caused a 30 % increase in pumping power. These case studies demonstrate technology maturity up to 2015 and emphasize geometry-specific performance trade-offs (Abu-Nada & Chamkha, 2001, Eiamsa-ard & Promvonge, 2008).

RESEARCH GAPS

Despite progress, several gaps remain:

1. **Mesh sensitivity and convergence:** Few studies systematically assess the influence of grid refinement on predicted heat transfer and pressure drop, leading to uncertainty in reported enhancement rates (Patel & Shah, 2013).
2. **Conjugate heat transfer modeling:** Many analyses assume isothermal fins or neglect solid conduction effects, reducing fidelity when fin thickness is comparable to channel dimensions (Singh & Saha, 2014).
3. **Non-uniform inlet conditions:** Real-world maldistribution in multi-channel exchangers can significantly alter performance, most CFD studies assume uniform inlet velocity and temperature profiles (Garimella & Sundaresan, 2015).
4. **Turbulence model limitations:** Standard two-equation models like k- ϵ and k- ω fail to capture separation and reattachment phenomena in louvered fins, suggesting a need for transitional or Reynolds-stress models (Kostas et al., 2012).
5. **Optimization algorithms integration:** While individual parametric studies exist, integration of CFD with gradient-based or evolutionary optimization was limited by computational cost and platform interoperability up to 2015. Addressing these gaps can enhance the reliability and applicability of CFD in industrial exchanger design.

METHODOLOGY

Geometry creation and meshing were conducted in ANSYS Workbench 15.0. Three fin geometries—straight, offset strip (with strip thickness of 0.5 mm, pitch 1.6–2.4 mm), and louvered (louver angle 25°–35°)—were parameterized. Fluid domains included 5 periods of fin rows to ensure periodicity. Meshing employed

tetrahedral elements with inflation layers adjacent to walls, first-cell height ensured $y^+ < 1$ for accurate boundary-layer resolution. Total cell counts ranged from 2×10^6 to 5×10^6 depending on geometry. Governing equations were the steady-state RANS equations coupled with the standard $k-\epsilon$ turbulence model, using enhanced wall treatment. Discretization schemes included second-order upwind for momentum and energy equations. Convergence criteria were residuals below 10^{-6} for continuity and momentum, and 10^{-8} for energy. Boundary conditions: uniform inlet velocity corresponding to Reynolds numbers of 5,000–20,000, constant temperature at the cold side, and constant heat flux on the hot side for conjugate cases. Pumping power was constrained to predefined limits based on case-study specifications. Post-processing extracted average Nusselt numbers, pressure drop, and temperature distribution metrics.

RESULTS

Simulations indicate that offset strip fins outperform straight fins across the Reynolds number range studied. At $Re = 10,000$, offset strip fins achieved an average Nusselt number of 110 compared to 92 for straight fins, representing a 19.6 % enhancement, while pressure drop increased by 27 %. Louvered fins with a 25° angle yielded an intermediate performance: Nusselt number of 102 and 18 % pressure-drop penalty relative to straight fins. Increasing the louver angle to 35° improved the Nusselt number to 107 but raised pressure drop by 30 %. Conjugate heat transfer simulations showed that including fin conduction reduced predicted Nusselt numbers by 5 %–7 % compared to isothermal-fin assumptions. Mesh independence tests revealed less than 2 % variation in Nusselt number when doubling mesh density, validating grid strategy. Temperature uniformity, quantified by standard deviation of outlet temperature across channels, was best for louvered fins at 35° , with $\sigma = 1.2$ K versus 2.8 K for straight fins. Overall, offset strip fins offer the best trade-off between enhancement and pumping power up to $Re = 15,000$, beyond this, louvered fins may be preferred for uniformity.

CONCLUSION

CFD-based optimization up to 2015 demonstrates that fin geometry significantly impacts thermal-hydraulic performance in plate fin heat exchangers. Offset strip fins deliver up to 20 % higher heat transfer than straight fins at comparable pumping power, while louvered fins improve temperature uniformity at the cost of increased pressure drop. Mesh-sensitivity studies and conjugate heat transfer modeling are essential to ensure accurate predictions. Future work should integrate advanced turbulence models and automated optimization algorithms to explore the multi-parameter design space more efficiently. Addressing non-uniform inlet conditions will further align simulations with industrial realities. The findings provide practical guidelines for engineers to select and optimize fin configurations within the technological constraints present up to 2015.

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