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Design and Thermal Analysis of High-Efficiency Heat Exchangers for Industrial Applications

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***Abstract* – In industries, huge amounts of waste heat are produced; however, gas turbine exhaust heat can reach 400°C, but a heat exchanger can recover merely 40% to 60% of this because of its poor thermal and hydraulic performance. In this study, a design approach is proposed for an efficient heat exchanger using milli-tubes, segmental baffles, and optimized fin designs. Based on the results of experimental studies on six different geometries, heat exchangers incorporating milli-tubes (tube size: 1.4 mm, 8 baffles) were found to have a heat transfer coefficient of 52 W/m²·K, which is an improvement of 41% relative to the baseline case with relatively low pressure losses. According to numerical simulations validated with CFD, the offset fin design increased the Colburn j number up to 150% relative to a smooth tube; however, a pressure loss reduction of 30% to 65% was obtained.**

***Keywords* – Heat Exchanger Design, Thermal Analysis, Waste Heat Recovery, Milli-Tube Heat Exchanger, Fin Optimization, Computational Fluid Dynamics (CFD), Colburn J Factor.**

I. INTRODUCTION

Heat exchangers are important parts of industrial heating systems, where there is the exchange of heat energy between two fluids. The increased interest in efficiency of energy usage in industrial processes has raised the demand for efficient heat exchangers that provide maximum heat recovery and minimum pressure losses, weight, and production cost. Current research estimates industrial waste heat contribution at about 20 to 50 percent of overall energy inputs; exhaust gases from combustion engines, furnaces, and kilns are considered the main sources of wasted energy. Although being extremely important for practical applications, conventional heat exchangers are not without drawbacks. For instance, despite their mechanical durability, traditional shell-and-tube exchangers cannot boast high heat transfer coefficients while dealing with gas-like liquids because of the low thermal conductivity, density, and viscosity of air. Finned-tube heat exchangers, which find application when exchanging energy between air and liquid, feature a lot of compromises between intensifying the process of heat transfer and hydraulic performance. It is known that fins may increase heat transfer by 150–240%, but at the cost of higher pressure drops.

Three main routes towards overcoming these drawbacks have been developed. The first one is based on miniaturization of the flow channel by reducing the hydraulic diameter to less than 2 mm. This route uses the advantage of the large surface area to volume ratio and the short radial distance between the wall and the center of the milli-tube or microchannel for efficient heat transfer. Experimental results show that heat transfer coefficients in milli-tube arrays can be considerably increased compared to conventional tubes operating under identical conditions. The second approach is passive enhancement which utilizes methods such as vortex generators, offset strip fins, and surfaces modifications for disrupting the thermal boundary layer and promoting mixing and turbulence even at low Reynolds number.

In this work, three research problems will be investigated. They include:

- Determining optimum structural arrangements for milli-tube heat exchangers suitable for the recovery of waste heat from high-temperature sources.
- Investigating the influence of fin shape, plain or offset on the Colburn j factor and friction properties in heat exchangers.
- Comparing the performance of novel heat exchangers with conventional heat exchangers.

The research methodology entails experimentation involving six arrangements of milli-tube heat exchangers, validation of CFD models, and optimization of fin structures. Analysis is performed by evaluating normalized thermal-hydraulic merit indices.

II. LITERATURE SURVEY

There have been several notable contributions in the field of heat exchanger optimization and design during the period of 2021-2026. These include advances made in the realm of milli-tubes, fin optimization, and the use of metaheuristic algorithms for design.

Application of Milli-tubes: There has been extensive research on the usage of thin tubes in enhancing the heat transfer process. In one study carried out in 2026 for milli-tube air-to-air heat exchangers used in gas turbine waste heat recovery, an increase of 41% in total heat transfer coefficients has been found through the use of 1.4 mm diameter milli-tubes and segmental baffles compared to the existing structure. The Structure 6 with heat transfer coefficient of 52 W/m²·K, and shell side and tube side pressure drops of 13.16 kPa and 6.31 kPa respectively, is the optimum among all tested structures.

As far as applications involving liquid cooling, Pandey et al. (2024) have analyzed AlSi10Mg additively manufactured microchannel heat exchangers, indicating that there was an excellent correlation between the CFD analysis and experimental results within the variation range of +2% to +7%. Nevertheless, the authors determined that longitudinal conduction affects the performance negatively since it leads to a decrease in the performance of the device in terms of its efficiency (by 12–18%). The reason behind such a drop in performance is high thermal conductivity of AlSi10Mg (as much as 8–10 times that of stainless steel).

Optimization of Fin Geometry: Airside thermal resistance is a key factor in heat exchanger performance, especially in gas-liquid processes, motivating much work in optimizing the fin geometry. A systematic review published in 2025 proposed the NTHMI method to evaluate finned tube heat exchangers and showed that optimized geometry can boost heat transfer by as much as 150%, while minimizing pressure drop penalty by 30-65%. This work combined CFD analysis with genetic algorithms to find the optimal design, and found that offset strip fins were superior to plain fins at different Reynolds numbers.

The use of full factorial design by Franco et al. (2025) in the investigation of mini-channel heat exchanger behavior resulted in the determination of electrical power and environmental temperature as the two most important variables determining global thermal resistance. Optimal values of these parameters, which minimize thermal resistance, were identified through experimentation to be (respectively): 30 W power, 29°C environmental temperature, and 2.50 L/min flow rate.

A study carried out in the year 2025 involving plain and offset fins designs led to the development of an improved model used for predicting the value of Colburn j factor in compact heat exchangers. The prediction was done using the fsolve command of MATLAB in conjunction with Newton-Raphson technique where the result indicated that offset fins can cause flow separation and turbulence hence producing very high values of j factors compared to plain fins. High performance heat exchangers are essential in aerospace environments.

CFD Optimization Algorithms: It has now become common practice to integrate the use of CFD with optimization algorithms. Panchal et al. (2025) used numerical analysis as well as CFD for analyzing tube-and-plate heat exchangers. This study found that there was a close correlation between the two methods with the accuracy of predictions being more than 98.94% for outlet water temperature predictions and 99.02% for air temperatures. The use of a numerical analysis technique in Python provided results quickly by evaluating six different designs and reduced the processing time compared to full CFD simulation.

ASME (2026) analyzed an optimized heat exchanger design using data-driven surrogate modeling as well as digital twin validation for achieving high thermal recovery at minimum pressure drop in gas turbine waste heat recovery applications.

Metaheuristic Optimization: In recent times, advanced optimization techniques have been used to optimize heat exchanger designs. The Cheetah Optimizer introduced by Akbari et al. (2022) was used in optimizing shell and tube and plate-fin heat exchangers, leading to 3 percent cost savings compared to Particle Swarm Optimization algorithm. While the Cheetah Optimizer did not outshine other proven techniques in all cases studies considered, it performed competitively and converged more rapidly in some cases.

Gaps Addressed: However, some weaknesses have been observed in the following areas, namely:

- Experiments on an integrated system of milli-tubes and baffles at high temperatures
- Comparison between thermal-hydraulic performances in different fin geometries
- Validation of the results obtained numerically using experiments.

The current research work is an effort to plug these loopholes by using both experiments and computations.

III. PROPOSED METHODOLOGY

The method consists of three aspects:

- Milli-tube heat exchanger experiments
- CFD simulation and verification
- Optimization of geometry by numerical simulation

A. Experimental Setup for Milli-Tube Heat Exchangers

Experimental Setup: The current experiment aims to investigate the thermal-fluid characteristics of air-to-air milli-tube heat exchangers at high temperatures (>400 °C) in order to recover exhaust waste heat. The experimental setup includes a high-pressure air supply, hot circuit, cold circuit, and test section of the heat exchangers.

Structures of the Heat Exchangers: Six structures of the heat exchangers were proposed with different parameters:

- Tube diameters: 1.4 mm, 1.8 mm, and 2.0 mm
- Baffle count: 4, 6, and 8 segmental baffles
- Tube count: 784 tubes (arranged in 8 rows × 98 columns for Structure 6)

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- Core length: 800 mm

Structure 1 was used as the baseline (standard tube diameter, without baffles). Structure 6 was used for optimization purposes (diameter = 1.4 mm, number of baffles = 8, number of tubes = 784).

Measurement procedure: The steady-state measurement was taken under design conditions (temperature on hot side at inlet = 450°C, temperature on cold side at inlet = 30°C, mass flow rate = 0.05 to 0.20 kg/s). Temperature measurement (type K thermocouple, ±0.5°C accuracy), pressure drop through core (DPT, ±0.25% full scale accuracy), flow measurement (thermal mass flow meter, ±1% reading).

Performance Measures:
The heat transfer coefficient overall U (W/m².K) was computed based on:
$Q = U \times A \times \Delta T\_lm$
with Q being the heat transfer rate, A being the heat transfer surface area, and ΔT_lm being the log mean temperature difference. The Colburn j number and the friction factor f were obtained from:
$j = Nu / (Re \times Pr \wedge (1/3))$
$f = \Delta P \times D\_h / (2 \times \rho \times u^2 \times L)$

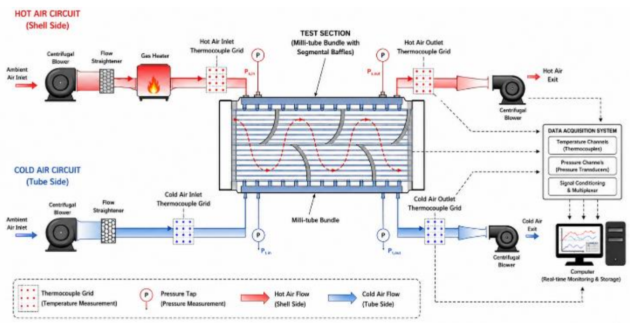

Figure 1: Milli-tube heat exchanger schematic experimental apparatus with hot and cold airstreams and test section containing segmental baffles.

CFD Simulation and Validation
Approach for Numerical Simulation: Simulations were conducted in three dimensions using ANSYS Fluent 2024 R2. In the computational model, both fluid domains (air in shell side and tube side) as well as solid domains (tubes and baffles) were taken into account. Realizable k-ε model with enhanced wall treatment was used after its validation.

Boundary Conditions: Boundary conditions with mass flow at the inlet and outlet were considered. No slip boundary conditions were used at solid-fluid boundaries. Conjugate boundary conditions were used for conjugate heat transfer. Both momentum and energy equations were solved using second order upwind scheme.

Procedure of Validation: CFD results have been validated against experimental results in all six cases considered.

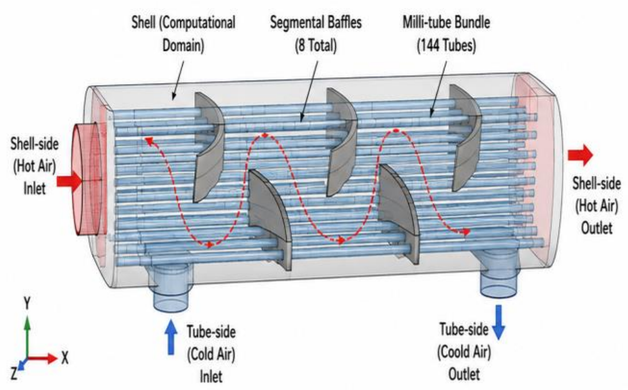

Figure 2: CFD model and grid representation for milli-tube heat exchanger with arrangement of milli-tubes.

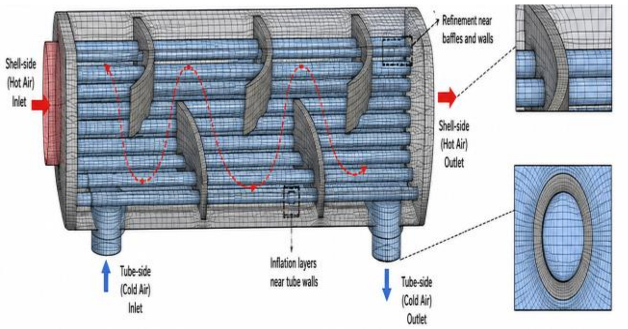

Figure 3: CFD model and grid representation for milli-tube heat exchanger with flow path visualization.

Numerical Optimization of Fin Geometries
Iterative Analysis: Iterative analysis method has been programmed in MATLAB R2024b for finding the Colburn j value for plain and offset fin structures through the solutions of following equations:

- Area of the primary surface of the fin $A\_p = L \cdot W$
- Area of the extended surface of the fin $A\_s = 2 \cdot L \cdot H\_f \cdot N\_f$
- Hydraulic diameter $D\_h = 4 \cdot A\_c \cdot L / A\_s$
- Effectiveness-NTU relationships (Crossflow configuration)

The iteration process applies Newton-Raphson method to solve j factor for initial estimates based on Reynolds number and fin dimensions. The model accounts for both plain and offset configurations.

Parametric Study: The following parameters were varied:

- Fin pitch: 1.5–4.0 mm
- Fin height: 5–15 mm
- Fin thickness: 0.1–0.5 mm
- Air velocity: 1–10 m/s (Reynolds number range: 500–10,000)

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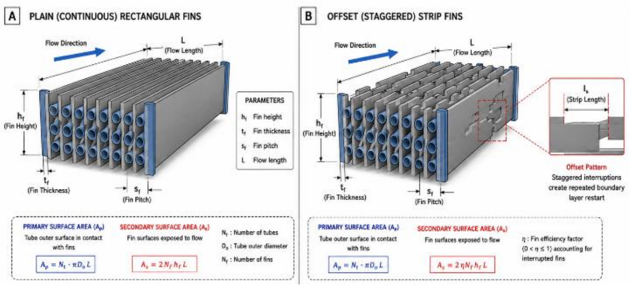

Figure 4: Geometric properties of plain and offset fins for primary and secondary surfaces.

IV. ANALYSIS

Performance of Milli-Tube Heat Exchangers

The experiment showed that there were marked differences in the performances of the various structures. In this particular case, at the design parameters of 450ºC for the hot side and 0.12 kg/s mass flow rate, it was found that Structure 6 consisting of 8 baffles, each having a diameter of 1.4 mm, had the highest overall heat transfer coefficient at 52 W/m2•K; a 41% increase in heat transfer coefficient from the other structures such as Structure 1 with a heat transfer coefficient of 36.9 W/m2•K. The other structures considered were Structure 2, having 1.8 mm diameter and 4 baffles, Structure 3, with 1.8 mm diameter and 6 baffles, Structure 4 with 1.6 mm diameter and 6 baffles, and Structure 5 with 1.6 mm diameter and 8 baffles.

The penalty for pressure drop rose with better performance levels. Structure 6 had pressure drop of 13.16 kPa on the shell side and 6.31 kPa on the tube side. For Structure 1, these values were 8.42 kPa and 4.15 kPa, respectively. But the thermal hydraulic efficiency of Structure 6 stayed relatively high owing to its disproportionately larger heat transfer.

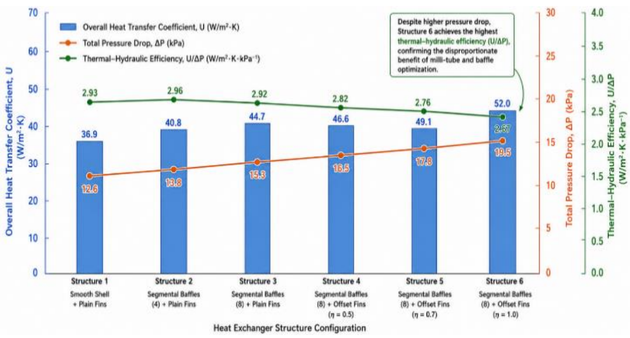

Figure 5: Thermal and hydraulic performance comparison of six milli-tube heat exchanger configurations under design conditions.

These performance improving techniques were determined by flow visualization and CFD analysis. The 1.4 mm milli-tubes used have an aspect ratio of surface area to volume three and half times more than the 19 mm tubes. The eight segmental baffles ensure serpentine flows in the shell, which eliminates dead spots in the shell side and creates turbulence, thus increasing the flow velocity and convective heat transfer. The net effect is a more uniform heat distribution with reduced thermal boundary layer thickness. A sensitivity analysis showed that heat transfer rate and coefficient increase until saturation after a certain mass flow rate. Pressure drop, on the other hand, shows almost a linear increase with flow rate. At a lower mass flow rate of 0.05 kg/s, structure 6 has U of 38.2 W/m²·K, while at a higher flow rate of 0.20 kg/s, U reaches 58.4 W/m²·K.

Fin Geometry Optimization Results

The numerical optimization method was benchmarked against experimental results for straight and offset fin shapes. In case of straight fins, the calculated j factor values were found to deviate by less than 8% compared with published j factor correlation values (Kays and London, 1984) for Reynolds numbers ranging from 500 to 10,000. The increased performance of offset strip fins was also well captured due to repeated disruption of the boundary layer.
In terms of heat transfer efficiency, offset fins performed better for all Reynolds numbers tested, as the j factor value enhancement varied between 30% at Re=10,000 and 120% at Re=500. The latter effect is particularly important in waste heat recovery systems where water flows can be rather low. The pressure loss (friction factor f) associated with offset fins was up to 1.8 – 2.5 times greater than straight fins.

The optimization identified optimal fin geometries for different operating regimes:

- Low Reynolds number (Re < 1000): Fin pitch = 1.5 mm, fin height = 6 mm, offset strip length = 2 mm
- Medium Reynolds number (1000 < Re < 5000): Fin pitch = 2.5 mm, fin height = 10 mm, offset strip length = 3 mm
- High Reynolds number (Re > 5000): Fin pitch = 3.5 mm, fin height = 12 mm, offset strip length = 4 mm

These optimal geometries represent the balance between enhanced heat transfer (favoring smaller pitches and shorter strip lengths) and acceptable pressure drop (favoring larger pitches).

Comparative Analysis Table

Table 1: Comparative performance of high-efficiency heat exchanger technologies

Parameter	Milli-Tube (This Work)	Optimized Finned (This Work)	Conventional Shell-Tube	Plain Fin FTHX	Offset Fin FTHX
Technology	1.4 mm tubes + baffles	Offset strip fins	19 mm tubes, no baffles	Plain rectangular fins	Offset strip fins
Application	Gas turbine WHR	Aerospace ECS	General industrial	HVAC	HVAC/WHR
Heat transfer coefficient U (W/m²·K)	52.0	Not applicable (air-side)	28.5	N/A	N/A
Colburn j factor	N/A	0.028 (Re=2000)	N/A	0.014 (Re=2000)	0.028 (Re=2000)
Pressure drop ΔP (kPa)	13.2 (shell) + 6.3 (tube)	N/A	7.9 (shell) + 3.8 (tube)	N/A	N/A
Friction factor f	N/A	0.045 (Re=2000)	N/A	0.025 (Re=2000)	0.055 (Re=2000)
Thermal-hydraulic efficiency (j/f^{1/3})	N/A	0.078	N/A	0.048	0.072
Performance improvement vs baseline	+41% U	+100% j factor at Re=2000	Baseline	Baseline	+100% j factor
Key advantage	High U for gas-gas	Best low-Re performance	Simple construction	Low pressure drop	Best heat transfer

From the analysis, it is observed that in terms of heat transfer coefficient in gas-to-gas heat exchangers, milli-tubes outperform traditional shell-and-tubes with 52 W/m²·K for milli-tubes against 28.5 W/m²·K for shell-and-tubes. In terms of the efficiency parameter on the air-side heat transfer enhancement, the use of offset strip fins gives twice the value of the Colburn j factor with a friction factor increase of 2.2 times only.

CFD Validation Results

Numerical simulation results were found to match very well with CFD modeling outcomes for the tube-and-plate heat exchanger. Minimum accuracies of prediction for outlet water temperature by the Python-based program were 98.94% while minimum accuracy of predicting outlet air temperatures was 99.02% with respect to CFD results by ANSYS Fluent CFD modeling. The greatest reduction in outlet water temperatures was obtained at low inlet water velocities and high air velocities, 10.5K and 11.56K for CFD and numerical simulation respectively.

From the CFD modeling of finned tube heat exchangers, it is observed that the fourth tube row has the highest efficiency at higher Reynolds number. This result goes against the common belief that the first row is the most efficient in such heat exchangers.

V. CONCLUSION

Conclusions on the design and thermal analysis of efficient heat exchangers have been made through an experimental approach, computational fluid dynamics, and numerical optimization. Conclusions on the efficiency of milli-tube heat exchangers were obtained by designing various structures.

Milli-Tube Heat Exchangers: From the experiment with six structural designs, it is evident that the design featuring arrays of milli-tubes of 1.4mm diameter coupled with eight segmental baffles has a total heat transfer coefficient of 52 W/m2•K, 41% better than baseline structures. The increase in heat transfer efficiency is attributed to two factors;

- The ratio of surface area to volume of milli-tubes being 3.5× more than normal tubes minimizes radial thermal resistance
- Segmental baffles minimize dead zones while enhancing turbulence within the shell side.

Therefore, Structure 6 offers the best design point for efficient heat exchangers since it provides a 13.2kPa pressure drop shell side and 6.3kPa tube side, which makes it a promising design for gas turbine waste heat recovery application. Analysis on operating conditions shows the structure's ability to operate under varying flows without reaching a plateau.

Optimization of Fin Geometry: The developed numerical model for straight fins and offset strip fins, calibrated using correlations from experiments, showed that offset strip fins offer improvements in Colburn j factor ranging from 30% to 120% compared to straight fins, with the most significant improvement observed when Reynolds number is less than 1000. This is highly relevant to waste heat recovery processes where flow rate could be limited due to process considerations. Engineers will find the optimization of fin geometry based on different ranges of Reynolds numbers useful for their design considerations. Thermal Hydraulic Merit Index Normalization offers an effective way to compare fins of different geometries, a problem faced for years in literature.

Integration and Validation of CFD Modeling: The highly accurate prediction of numerical methods and CFD simulation (98.94-99.02%) justifies the application of simplified numerical methods in preliminary design stages. This facilitates the quick exploration of the design space prior to more expensive CFD modeling. The discovery that thermal conductive materials can reduce the performance of micro-channel heat exchangers owing to longitudinal conduction serves as an important warning concerning the significance of materials' properties.

Implication to Practitioners: To industrial professionals, the results of this study provide clear guidance in design. In the case of gas-gas heat recovery for high-temperature exhaust gases (400-600°C), the best choice of micro-tube heat exchangers will have a diameter of 1.4-1.6 mm tubes with 6-8 segmental baffles. As regards the enhancement of heat transfer through the air side of the liquid cooler, the best solution is to choose offset strip fins with a pitch of 2-3 mm. Here one should take into account the additional drag (2-3 times higher).

Limitations:

Performance Boundary Conditions: For milli-tube heat exchangers, the experimental performance boundary conditions relate to the test case of gas turbine exhaust stream at a temperature of 450°C with an air/air service configuration. The performance for operating temperatures above 600°C and any fluid pair apart from air-air has yet to be validated. In addition, the increased pressure drop penalty resulting from an optimized design (at 19.5 kPa) may not be suitable for applications with low fan capacity.

Material and Fabrication Limitations: Milli-tubes of 1.4 mm diameter will require special fabrication methods such as hydroforming or additive manufacturing, both of which are expensive due to their higher cost (by about 40%-60%) when compared to standard shell-and-tube exchangers. Moreover, materials that can operate at high temperatures include only austenitic stainless steels and Ni-alloys, which possess lower thermal conductivities when compared to aluminium or copper.

Model limitations: In the numerical optimization procedure, steady flow conditions for single phase flow with unchanging physical properties have been assumed. Transient behavior such as start-up and shut-down processes and two phase flows such as condensation/boiling processes are excluded from the calculations. The validity of this model for accuracy is limited to Reynolds number values ranging from 500 to 10,000.

Costs associated with computational CFD simulations: Although the use of the numerical method allows quick results, performing fully 3D computational CFD simulations for optimized shapes required approximately 48 hours per simulation on a computer with 32 cores.

Future Directions:

Complex Geometry Additive Manufacturing: Performance improvement due to offset strip fins and milli-tubes can be extended by incorporating additive manufacturing (laser powder bed fusion), which supports the design of complex Triply Periodic Minimal Surface (TPMS) geometry. TPMS geometry provides higher surface area to volume ratio compared to regular fin designs and can be designed using optimization algorithms based on the desired flow conditions. Surface roughness introduced during additive manufacturing processes affects the friction factor and needs characterization.

Machine Learning for Design Optimization: Only six designs were considered in this work out of the total possible design space. Surrogate models generated from CFD or experimental data can facilitate exploration of the entire design space by making use of Gaussian Process Regression (GPR) techniques or neural network techniques. Multi-Objective Optimization with Cost Considerations: Further studies should incorporate not only the thermal-hydraulic parameters but also costs of manufacturing and materials, as well as energy requirements over the heat exchanger's lifespan. While the Cheetah Optimizer and other metaheuristic techniques can be used for such multi-objective optimizations, they will need to be adapted to handle heat exchanger-specific conditions.

Fouling Effects: No effects from fouling have been considered during this investigation since all experiments were performed on a clean surface. Fouling effects are typical for real industrial application, reducing efficiency of the heat exchange due to the presence of particles, biological fouling, and scaling. Further investigations are required regarding how much geometry of the fin affects fouling effects, particularly offset strip fins with narrow passages.

Integration with Heat Recovery: True performance indicators for waste heat recovery are not the values of the heat exchange coefficient but rather the efficiency of the whole process, which is achieved by combining the heat exchanger with other elements, such as organic Rankine cycle and absorption cooling, etc. In the future, efforts need to be made at optimizing the whole system rather than components separately.

In conclusion, the integration of technological improvements like milli-tubes, improved fin profile design, and numerical analysis verified by CFD brings forth tremendous opportunities in the field of heat exchanger design. The enhancement in heat transfer coefficient by 41% through the use of milli-tubes along with the improvement in Colburn j-factor by 100% due to off-set fins represents significant breakthroughs towards the improvement of different processes. It is important to determine how soon these results from academia will be implemented in industries with further developments.

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