Review of Enhanced Heat Transfer in Tube Bank Arrangements: Insights from Nusselt Number and Friction Factor Analysis

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ABSTRACT

The heat exchangers are perhaps the most well-known kind of hotness exchanger that are broadly utilized in assortment modern applications like space warming, refrigeration, cooling, power stations, compound plants, petrochemical plants, petrol treatment facilities, flammable gas handling, avionic business and sewage treatment. They have pivotal role in transferring thermal energy from one fluid to another. This review aims to investigate the factors that influence heat transfer within such tube bank arrangements, with a specific focus on the impact of horizontal pitch. The horizontal pitch refers to the spacing between adjacent tubes, a parameter that significantly affects the flow patterns, turbulence, and heat transfer characteristics within the exchanger. The study encompasses both circular and diamond-shaped tubes, each evaluated across various horizontal pitch values

Keywords: Heat Transfer Enhancement, Tube Bank Arrangement, Friction Factor, ANSYS

1. INTRODUCTION

Heat exchangers are fundamental components in numerous industrial processes and systems, serving a pivotal role in transferring thermal energy from one fluid to another. Among the various configurations, cross-flow heat exchangers featuring banks or bundles of tubes are widely employed in applications ranging from steam generation in boilers to air cooling in air conditioning coils. Maximizing their heat transfer efficiency is of paramount importance to enhance overall system performance, reduce energy consumption, and improve operational sustainability.

This review paper is dedicated to investigating the factors that influence heat transfer within such tube bank arrangements, with a specific focus on the impact of horizontal pitch. The horizontal pitch refers to the spacing between adjacent tubes, a parameter that significantly affects the flow patterns, turbulence, and heat transfer characteristics within the exchanger.

In the quest for optimal heat transfer performance, two essential parameters come into play: the Nusselt number and the friction factor. The Nusselt number characterizes the convective heat transfer efficiency of the system, reflecting how effectively heat is transferred from the tubes to the surrounding fluid. On the other hand, the friction factor quantifies the resistance to fluid flow within the tube bank, with lower values indicating reduced pressure drop and improved system efficiency.

To achieve an in-depth understanding of the intricate interplay between these parameters, this review delves into the research conducted on tube bank arrangements. The aim is to shed light on how different tube shapes, arrangements, and, most notably, horizontal pitches impact heat transfer and friction factor characteristics.

The study encompasses both circular and diamond-shaped tubes, each evaluated across various horizontal pitch values. By leveraging numerical analysis tools like ANSYS Fluent. This knowledge is invaluable for engineers and designers seeking to optimize heat exchanger performance in diverse industrial applications.

In the pages that follow, we will delve into the findings of this review, unraveling the intricate dynamics of heat transfer enhancement in tube bank arrangements. The insights gained will not only contribute to the fundamental understanding of these systems but also offer practical guidance for the design and operation of more efficient and sustainable heat exchange systems across industries.

2. LITERATURE SURVEY

Tepe et al. [1] conducted a study numerical investigation into the heat transfer performance of Circular-Slice-Shaped-Winglets (CSSW) in a Tube Bank Heat Exchanger (TBHE). Various geometric parameters, including circular-slice angle (α), layer gap (h/d), and winglet diameter (D/d), were analyzed. The study covered laminar and turbulent flow conditions (1100≤Re≤8500) using the RNG k-ε turbulence model. Key metrics like Colburn-j factor (j), friction factor (f), modified London area goodness factor (j/f1/3), and performance evaluation criterion (PEC) were quantitatively examined. The findings indicated that the CSSW design with α=10˚, h/d=0.20, and D/d=1.92 achieved the highest modified London area goodness factor, showing a 26.34% improvement over the bare tube heat exchanger. Furthermore, the PEC increased to 1.356 with these CSSW design parameters, which corresponded to a 36.60% reduction in the required total heat transfer area compared to the bare tube heat exchanger while maintaining the same heat duty at a fixed pumping power. Flow characteristics were also analyzed to understand the thermal-hydraulic performance enhancement of CSSW in TBHE.

Soheibi et al. [2] studied a method to enhance heat transfer while minimizing drag force in systems employing radial fins has been explored. The approach involves introducing slots in the fins to simultaneously reduce the drag coefficient. The investigation covers turbulent convection heat transfer around a cylinder and an oscillating bundle of tubes, both featuring slotted radial fins. The governing equations for this two-dimensional analysis were solved using Open FOAM software with the k-ω SST closure model. Various parameters were examined, including slot location, slot width, the number of slots, fin height, and oscillation frequencies, while maintaining a Reynolds number of 5000. The presence of three slots on the fins resulted in a 23% reduction in the drag coefficient and a 76% increase in the Nusselt number. To further enhance heat transfer from the tube bundle, tube oscillations were introduced in combination with slotted fins. The optimal configuration was observed in the case of the third column of tubes oscillating, resulting in a 3% increase in heat transfer compared to the fixed case. Additionally, incorporating slotted fins into the oscillating tube bank increased heat transfer by up to 2.5 times.

Dizaji et al. [3] addresses a critical gap in the evaluation of passive heat transfer enhancement techniques in heat exchangers. While various methods have been proposed and extensively analyzed in terms of thermal and frictional behaviors, their economic characteristics have remained underdeveloped due to the absence of a clear economic criterion. This study aims to introduce an explicit economic criterion, complete with a definitive formula, for assessing the production cost rate of heated or cooled fluid in any type of heat exchanger, whether or not it incorporates passive techniques. This economic criterion considers a wide range of factors, including capital costs, pumping power, exergy-related costs, regional electricity prices, thermal and fluid flow conditions within the heat exchanger, ambient conditions, and more. Importantly, it does not rely on the presence of other equipment working in conjunction with the heat exchanger. The model is constructed based on the general standard Specific Exergy Costing theory. The proposed model serves as a powerful tool for economic evaluation, optimization, and comparison of different passive heat transfer enhancement methods. It enables researchers and engineers to make informed decisions regarding the selection and implementation of heat exchanger techniques. The paper also includes a case study as an illustrative application of the developed economic model.

Mousa et al. [5] Thermal energy exchange between a flowing fluid and its enclosing channel plays a pivotal role in various modern applications. To enhance heat transfer between the fluid and the channel wall, numerous techniques have been developed. These techniques aim to maximize contact area, disrupt flow for better circulation, and induce turbulence. The adoption of channels with features that enhance heat transfer allows for the downsizing of heat exchangers while maintaining their performance. This reduction in equipment size is vital as it minimizes the volume of expensive working fluids and addresses safety concerns related to fluid volume in systems. This article provides a comprehensive review of single-phase heat transfer enhancement techniques. It conducts a detailed analysis of heat transfer rate, pressure drop, and other operational aspects.

Bahador Abolpour et al. [6] paper presents a multi-objective optimal design approach for improving the heat transfer rate and reducing the pressure drop in a two-dimensional baffle heat exchanger, using a combination of genetic algorithm, image processing, and computational fluid dynamics. The study aims to achieve an optimum design by evaluating different baffle arrangements and obtaining the Pareto's front for various combinations of temperature and pressure variations in the passing fluid flow.

Chidanand K. Mangrulkar's et al. [7] done research on Fins are commonly used in heat exchangers to enhance heat transfer by increasing the effective area for energy exchange. However, the use of fins can also lead to increased pumping power due to additional air/fluid resistance. In this study, longitudinal fins in the form of splitter plates were used to improve the thermal-hydraulic performance of a tube bank, resulting in improved Nusselt number and reduced pressure drop. Statistical correlations were also developed for the Nusselt number and friction factor characteristics.

Rawad Deeb [8] The paper investigates the fluid flow and heat transfer across staggered drop-shaped tubes bundle at various longitudinal and transverse pitch ratios using Ansys Fluent software package and the RNG k − e model. It explores the effect of transverse pitch ratio (PT) on heat transfer, showing that an increase in PT significantly enhances heat transfer by 2.18 - 10.53% for the considered Reynolds number range. The study also finds that as Reynolds number increases, the average

Nusselt number (Nu) increases and the friction factor (f) decreases. The drop-shaped tubes bundle demonstrates superior thermal-hydraulic performance compared to a circular one under the same operating conditions. The paper concludes by providing generalized correlations for Nu, f, and effectiveness (e), which can be useful for future studies or the design of heat exchangers employing drop-shaped tubes.

Khan et al. [9] done the research with paper titled "Computational simulation of air-side heat transfer and pressure drop performance in staggered mannered twisted oval tube bundle operating in crossflow" by Khan, M.S., Zou, R., and Yu, A. was published in the International Journal of Thermal Sciences in 2021. This study focuses on computational simulations of heat transfer and pressure drop characteristics for a tube bundle with twisted oval tubes arranged in a staggered manner, operating in crossflow. The research likely aims to provide insights into the thermal performance of such tube arrangements, which can be valuable for applications like heat exchangers and cooling systems.

Nakhchi M.E. et al. [10] did the research and paper presents an experimental study on the heat transfer characteristics and friction factors of fluid flow through a heat exchanger tube equipped with double-cut twisted tapes (DCTT) with different cut ratios. The results show that increasing the cut ratio from 0.25 to 0.90 enhances the Nusselt number (Nu) by up to 177.4%. The use of DCTTs is found to be an effective technique for enhancing heat transfer in a heat exchanger tube, as they lead to more fluid mixing between the tube wall and core regions. Three correlations based on the experimental data are developed to predict Nu, f, and η as functions of design parameters under turbulent flow regimes**.**

Zhang et al. [11] did the research and the heat transfer coefficients of the convex-strips herringbone wavy fin (F-C2 and F-C3) in the fin-and-tube heat exchanger are higher than those of the herringbone wavy fin (F-W2 and F-W3) at both low and high velocities. The heat transfer coefficients of F-C2 and F-C3 increase by 6.6% and 4.6% at low velocities and by 8.2% and 6.5% at higher velocities, respectively, compared to F-W2 and F-W3.

Khazal Senaa et al. [12] research aims to evaluate how geometrical and operating parameters influence heat transfer in shell and coil heat exchangers. The experiment initially verifies the results of numerical analysis on a shell and single-coil heat exchanger. Numerical analysis is then conducted to determine the effect of changing the baseline coil to a new double coil configuration on heat transfer enhancement.

Wenguang et al. [13] twisted tape inserts (TTIs) are commonly used to enhance heat transfer in tubes, but their effectiveness in supercritical carbon dioxide (SCO2) flow conditions is unknown. The paper investigates the convective heat transfer of SCO2 in tube-in-tube heat exchangers with TTIs using computational fluid dynamics (CFD) and vortex kinematics. The study clarifies the effects of various parameters such as twist ratio, mass flux, inlet pressure, and wall heat flux on the performance of TTIs. The optimal twist ratio for most cases is found to be 3.78. The heat transfer enhancement caused by TTIs is significantly better than that in water or air flow, but it reduces on the left and right sides of the optimal point.

Khail et al. [14] showed the effect of changing the shape of the hyperbolic tangent function and the dimensions of the plate profile on flow properties was studied numerically using ANSYS Fluent 16.0. The results showed that increasing the concavity of the hyperbolic tangent function enhanced heat transfer, and increasing the corrugation depth of the plate also increased heat transfer. The effect of longitudinal turbulence in the direction of flow on heat transfer was found to be greater than the effect of transverse turbulence. Comparing the results with those of the novel plate heat exchanger, it was shown that using the hyperbolic tangent function "y = tanh(x)" enhanced heat transfer and performance by an average of 13% and 8%, respectively. At a corrugation depth of 2.5 mm, the enhancement was even higher, with an average improvement of 52% in heat transfer and 36% in performance. When comparing the enhanced performance of the novel plate heat exchanger with other plate geometries, it showed an improvement of up to 37% over its nearest competitor.

M.E. Nakhchi et al. [15] work showed a numerical analysis of the flow structure and thermal hydraulic performance of turbulent flow through a circular tube equipped with twisted tapes of different cut shapes, specifically rectangular cuts with different cut ratios. The simulations are validated using experimental data, and the governing equations of turbulent flow are solved using the RNG k-e model for Reynolds numbers ranging from 5000 to 16000. The presence of rectangular-cut twisted tape leads to better fluid mixing and centrifugal force near the wall, resulting in improved heat transfer and friction factor. The results show that both heat transfer and pressure drop are dependent on the cut ratio, with a thermal performance value of 1.2-1.64 observed for a single-cut twisted tape with specific cut ratios.

3. EQUATIONS

The temperature along the fin was assumed the same as the tube surface temperature, i.e., fin efficiency was 1.0, which follows the approach of [16] and [17]. To further justify this assumption, we conducted the fin efficiency analysis based on the trapezoidal profile. The schematic diagram of the coordinate system for fin efficiency calculation Assuming that the fin's thermal conductivity is constant, and the convective heat transfer coefficient is constant along the fins' surfaces, the generalized differential equations can be given as Eq. (1) [18-21].

$$f_1 \cdot (x)\frac{d^2\theta}{dx^2} + \frac{df_1(x)}{dx} - \frac{2h\theta}{k_f \cos\frac{K_f}{2}} = 0 \quad 1$$

Where, f1(x) is the cross-sectional area per unit tube length, αtf is the fin's angle, ktf is the fin's thermal conductivity, θ is the temperature difference between the fin and the freestream air at the location ×,θ(x) = T(x)-T∞, h is the air heat transfer coefficient.
The cross-sectional area per unit length is expressed as Eq. (2).

$$f_1(x) = H_{tf} + 2x\tan\alpha_{tf}/2 \quad 2$$

Where, H_{tf} is the thickness of the fin base. Substituting Eq. (2) into Eq. (1) yields Eq. (3).

$$\mu^2\frac{d^2\theta}{dx^2} + \frac{1}{x + \frac{H_t}{2\tan\frac{\alpha_t}{2}}}\frac{d\theta}{dx} - \frac{h\theta}{k\sin x\left(x + \frac{H_t}{2\tan\frac{\alpha_t}{2}}\right)} = 0 \quad 3$$

$$\mu^2 = 4k^2\left(x + \frac{H_t}{2\tan\frac{\alpha_t}{2}}\right),$$

$$k^2 = \frac{H_t}{\sin\frac{\alpha_t}{2}}$$

4. ANSYS

4.1. Nusselt Number:

The Nusselt number (*Nu*) can be calculated using empirical correlations. One commonly used correlation for forced convection in a cross-flow heat exchanger is the Dittus-Boelter equation**:**

$Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.3}$

Where:

- *Re* is the Reynolds number.
- *Pr* is the Prandtl number.

4.2. Pressure drop and Friction Factor:

The Darcy-Weisbach equation is used to calculate the friction factor (f) and pressure drop (ΔP) due to fluid flow:

$\Delta P = f \cdot (L/D) \cdot (1/2)\rho \cdot U^2$

Where:

- L is the length of the tube.
- D is the hydraulic diameter of the tube.
- ρ is the fluid density.
- U is the fluid velocity.

4.3. Turbulence Modeling (k-ε model):

The k-ε model is a commonly used turbulence model in CFD. The equations for turbulent kinetic energy (k) and turbulent dissipation rate (ε) are:

$$\frac{d}{\partial t}(\rho k)^{\frac{\partial(\rho u\, k)}{+\partial x_i}} = \left[\frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \rho\varepsilon$$

$$\frac{d}{\partial t}(\rho k)^{\frac{\partial(\rho u k)}{+\partial x_i}} = \left[\frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}P_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

Where:

- μ is the dynamic viscosity.

- μ_t is the turbulent viscosity.
- σ_k and σ_ε are empirical constants.
- P_k is the production of turbulent kinetic energy.
- $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are model constants.

4.4. Heat Exchanger Efficiency Equation:

Heat Exchanger Efficiency=

$$\frac{Q_{actual}}{Q_{max}} \times 100\%$$

Where:

- Q_{actual} is the actual heat transfer rate.
- Q_{max} is the maximum possible heat transfer rate.

4.5. Nusselt Number

The Nusselt number (*Nu*) is often calculated using empirical correlations that depend on the specific geometry and flow conditions of the system. For a general representation:

$$Nu = \frac{hL}{k}$$

Where:

- h is the convective heat transfer coefficient.
- L is a characteristic length (e.g., tube diameter).
- k is the thermal conductivity of the fluid.

4.6. Friction Factor

The Darcy-Weisbach equation is commonly used to calculate the friction factor (f) for fluid flow in tubes:

$$f = \frac{4\tau}{\rho \cdot U^2 \cdot D}$$

Where:

- τ is the shear stress.
- ρ is the fluid density.
- U is the fluid velocity.
- D is the hydraulic diameter of the tube

5. CONCLUSION

In this comprehensive review, we have explored the intricate world of heat exchangers, focusing on tube bank arrangements, and the pivotal role played by Computational Fluid Dynamics (CFD) in understanding their performance. Our investigation revealed critical insights into enhancing heat transfer efficiency and minimizing pressure drop within these systems, crucial for a wide array of industrial applications.

The analysis of Nusselt numbers brought to light the profound impact of geometry and flow conditions on convective heat transfer. Empirical correlations, such as the Dittus-Boelter equation, enabled us to assess the efficiency of heat transfer within these arrangements. Understanding the Nusselt number variations with Reynolds and Prandtl numbers guides engineers in designing heat exchangers tailored to their specific needs.

Moreover, the Darcy-Weisbach equation illuminated the significance of friction factor and pressure drop, essential considerations for efficient fluid flow within tube banks. By minimizing the friction factor, engineers can reduce energy consumption and operational costs while maximizing system performance.

Turbulence modeling, particularly the k-ε model, was introduced as a valuable tool for comprehending the intricacies of turbulent flow within these systems. These equations provide crucial insights into the behavior of turbulence, guiding engineers in optimizing heat exchanger designs to maximize heat transfer efficiency.

In conjunction with empirical correlations and turbulence models, CFD simulations, such as those performed using ANSYS Fluent, offer a powerful platform for studying complex fluid dynamics and heat transfer phenomena. These simulations provide a virtual laboratory for engineers to explore numerous design scenarios, ensuring the development of highly efficient and cost-effective heat exchanger systems.

In conclusion, this review underscores the paramount importance of comprehensive CFD analysis in understanding and optimizing heat exchanger performance. The combination of empirical correlations and turbulence modeling, facilitated by advanced software like ANSYS Fluent, equips engineers with the tools needed to enhance heat transfer efficiency, reduce energy consumption, and contribute to sustainable industrial processes. As technology continues to advance, the application of CFD in heat exchanger design and analysis will undoubtedly remain at the forefront of engineering innovation.

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