Postprint: Numerical Simulation of Thermal Performance of a Novel Spiral Quincunx Perforated Plate Heat Exchanger

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Abstract

Drawing upon vortex flow heat transfer enhancement technology, this work transformed the traditional straight-flow plum blossom-shaped support orifice plate into a spiral-flow configuration, thereby designing a novel spiral plum blossom-shaped orifice plate heat exchanger. A corresponding mathematical model was established, and numerical simulations were conducted on its heat transfer and flow characteristics. Through comparative analysis with conventional plum blossom-shaped orifice plate heat exchangers, the shell-side heat transfer enhancement mechanism of the novel heat exchanger was demonstrated, and the influence of the spiral flow channel' s spiral angle was further explored. Computational results indicate that within the studied range, the shell-side average convective heat transfer coefficient of the novel heat exchanger exceeds that of the traditional design, while the shell-side pressure drop increases correspondingly. Within a certain Reynolds number range, the comprehensive performance parameter of the novel heat exchanger is superior to that of the traditional heat exchanger. When the spiral angle is 27° and the Reynolds number is less than 19672, its comprehensive performance is better than that of the traditional heat exchanger. Investigation of different spiral angles reveals that larger spiral angles lead to greater pressure drops while simultaneously enhancing heat transfer capability.

Full Text

Preamble

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Simulation on Thermal Performance of a Novel Screw Cinquefoil Orifice Baffle Heat Exchanger

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Abstract

Based on vortex flow heat transfer enhancement technology, this study transforms the traditional straight-flow cinquefoil support orifice baffle into a spiral-flow configuration, thereby designing a novel shell-and-tube heat exchanger with screw cinquefoil orifice baffles (STHX-SCOB). The corresponding mathematical model was established, and its heat transfer and flow characteristics were simulated numerically. Through comparative analysis with conventional cinquefoil orifice baffle heat exchangers (STHX-COB), the shell-side heat transfer enhancement mechanism of the novel design is revealed, and the influence of the spiral flow channel' s helical angle on the heat exchanger performance is further investigated. The results demonstrate that within the studied range, the novel heat exchanger exhibits higher average convective heat transfer coefficients on the shell side than traditional designs, albeit with correspondingly increased pressure drop. The comprehensive performance parameter of the novel heat exchanger surpasses that of conventional designs within a certain Reynolds number range. When the helical angle is 27° and Reynolds number is less than 19,672, the comprehensive performance is superior to traditional heat exchangers. The investigation of different helical angles reveals that larger angles result in greater pressure drop but also stronger heat transfer capability.

Keywords: screw cinquefoil orifice baffles; heat transfer; numerical simulation; flow field; heat exchanger

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Shell-and-tube heat exchangers are widely employed in the chemical industry due to their low cost, simple and robust construction, and ability to handle large fluid flow rates [1]. However, conventional designs suffer from significant shell-side pressure drop, flow "dead zones,"and susceptibility to flow-induced vibration [2], making the exploration of alternative configurations critically important.

Among various novel shell-and-tube heat exchangers, orifice baffle heat exchangers have gained prominence in nuclear power and other industries because their longitudinal shell-side flow pattern yields low pressure losses, high heat transfer efficiency, minimal flow dead zones, and excellent anti-vibration characteristics [3]. Current research on orifice baffle heat exchangers remains limited. Dai et al. [4] analyzed a simplified unit model of a cinquefoil orifice baffle heat exchanger using FLUENT and derived a Nu-Re correlation. Dong et al. [5] numerically investigated the flow and heat transfer characteristics of trefoil orifice baffle heat exchangers, examining the effects of shell-side flow rate, orifice height, and baffle spacing on performance while comparing comprehensive performance across different designs. You et al. [6] experimentally studied trefoil orifice baffle heat exchangers, obtaining empirical correlations and demonstrating through numerical analysis that jets and strong recirculation formed by the orifices effectively scour tube walls, enhance turbulence intensity, accelerate mainstream mixing, and reduce boundary layer thickness, thereby significantly augmenting heat transfer.

Nevertheless, previous studies reveal that heat transfer enhancement in orifice baffle heat exchangers concentrates primarily near the support plates, with fluid heat transfer capacity diminishing in regions distant from the baffles, indicating untapped potential for improvement. In addition to investigating conventional structural parameters such as baffle spacing, modifying the orifice shape on the baffle plates offers another avenue for performance optimization.

Helical baffle heat exchangers have attracted increasing industry attention because their baffle configuration eliminates flow dead zones, reduces shell-side resistance losses, and effectively suppresses fouling and tube bundle vibration [7-9]. Du et al. [10] proposed a sextant sector helical baffle heat exchanger and conducted numerical simulations using ANSYS CFX, validating the results experimentally. They concluded that the approximate spiral channel formed by helical baffles induces rotational flow through combined centrifugal and centripetal forces, yielding superior comprehensive performance compared to conventional segmental baffle designs. However, the angular relationship between helical baffles and tube sheets complicates manufacturing processes and increases costs [7].

To address these challenges, this study proposes a novel screw cinquefoil orifice baffle heat exchanger based on traditional cinquefoil orifice plates, transforming the straight flow channels into spiral configurations. This innovation broadens the research scope of longitudinal-flow orifice baffle heat exchangers and provides a new solution for practical applications. Through numerical simulation of the shell-side flow fields in both conventional and novel designs, this paper analyzes the underlying reasons for their different thermal performances and further investigates the influence of helical angle on the novel heat exchanger’ s performance, providing a theoretical basis for structural optimization.

1.1 Geometric Model

The screw cinquefoil orifice baffle is a circular support plate featuring six fluid passage holes around each tube hole, which serve as shell-side flow channels. These channels adopt a spiral configuration that alters fluid flow direction. The structure is illustrated in Figure 1: see original paper(b). In contrast, the conventional cinquefoil orifice baffle employs straight flow channels, as shown in Figure 1: see original paper(d). Detailed geometric parameters for both heat exchangers are provided in .

1.2 Governing Equations and Boundary Conditions

The governing equations were modified appropriately for the numerical methodology, comprising steady-state continuity, momentum, energy, and state equations. Water was selected as the shell-side working fluid. Both heat exchangers employed velocity inlets at 360 K and pressure outlets with 0 Pa gauge pressure (reference pressure 101,325 Pa). Tube walls were modeled as constant temperature surfaces at 300 K, while shell inner walls and baffle surfaces were treated as adiabatic, impermeable, no-slip boundaries.

1.3 Numerical Solution Method and Model Validation

Three-dimensional solid models of both heat exchangers’ shell sides were constructed, as shown in [Figure 2: see original paper], and the entire flow field was simulated using ANSYS CFX with the RNG k- turbulence model [9, 11]. The SIMPLE algorithm coupled pressure and velocity, while physical variables were solved using second-order upwind schemes.

Considering the flow complexity near support plates, the computational domain was divided into three regions: areas far from baffles, regions near baffles, and inlet/outlet sections [1], as illustrated in [Figure 3: see original paper], using ANSYS ICEM for multi-block meshing.

Grid independence verification was performed for all models [1, 5, 12]. For the screw cinquefoil orifice baffle heat exchanger at $\alpha = 38°$ and Re = 5802, four mesh densities were tested for pressure drop Δp and heat transfer coefficient h. As shown in [Figure 4: see original paper], a mesh count of 3.67$×10^{6}$ was selected considering computational resources, while the conventional design used 3.09$×10^{6}$ cells.

Model validation was conducted by comparing results from the present numerical methodology with Ozden et al.’ s data [13]. As depicted in [Figure 5: see original paper], the maximum deviation in heat transfer coefficient h is within 5% and pressure drop Δp within 3%, confirming the reliability of the numerical approach.

2.1 Heat Transfer Enhancement Mechanism Analysis

[Figure 6: see original paper] presents flow streamlines for both heat exchangers at identical Reynolds numbers. Compared with the flow distribution in the conventional design [FIGURE:6(a)], the screw cinquefoil orifice baffle heat exchanger exhibits significantly stronger rotational flow on the shell side [FIGURE:6(b)]. In the novel design, fluid passing through the cinquefoil orifices generates not only jet effects but also continuous vortices that intensify fluid micro-mixing, strongly scouring both the boundary layer and fouling deposits to achieve heat transfer enhancement.

[Figure 7: see original paper] further reveals that conventional heat exchangers contain large low-velocity regions near the shell wall, whereas the novel design maintains more uniform velocity distribution with smaller flow dead zones. The higher fluid velocities in the new configuration disrupt boundary layer formation. As shown in [Figure 8: see original paper], the novel heat exchanger achieves higher and more uniform average heat transfer coefficients at tube walls. Consequently, the shell-side heat transfer capability is substantially improved compared to conventional designs.

2.2 Heat Exchanger Performance Comparison

Variations of heat transfer coefficient h and pressure drop Δp with Reynolds number Re under identical boundary conditions are presented in [Figure 9: see original paper]. Within the investigated Re range, both h and Δp increase significantly with Re, with Δp increasing at a faster rate than h.

Figure 9: see original paper demonstrates that the novel heat exchanger' s h exceeds that of the conventional design by an average of 9.2% across five operating points, with more pronounced advantages at low Re. At Re = 2322, the novel design achieves h = 754.9 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ versus 610.9 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ for the conventional design—a 23.6% difference. As Re increases, the conventional design' s turbulence intensity improves, narrowing the performance gap to 6.9% at Re = 23220. This confirms the novel heat exchanger' s superior performance at low Reynolds numbers.

However, Figure 9: see original paper shows that the novel design' s Δp also exceeds the conventional design' s, being 21.4% higher at Re = 2322 and increasing with Re. Across the studied range, the novel heat exchanger' s Δp averages 36.0% higher than the conventional design. Overall, the novel configuration demonstrates stronger applicability in low Reynolds number regimes.

2.3 Effect of Helical Angle on Novel Heat Exchanger Performance

In helical baffle heat exchangers, the baffle angle directly affects performance [7, 9]. Similarly, the helical angle α of the screw cinquefoil orifices significantly influences the novel heat exchanger' s performance. Three angles were investigated: $\alpha = 27°$, 38°, and 46°, with identical boundary conditions. As illustrated in [Figure 10: see original paper], larger α values produce stronger spiral flow patterns and better heat transfer performance.

Figure 11: see original paper shows that heat transfer coefficient h increases with α, with a 6.2% difference between $\alpha = 46°$ and 38°, and a 7.1% difference between $\alpha = 38°$ and 27°. However, enhanced heat transfer comes at the cost of increased pressure drop. Figure 11: see original paper indicates that Δp differs by 36.9% between $\alpha = 46°$ and 38°, and by 31.6% between $\alpha = 38°$ and 27°.

Research on low-Reynolds-number heat exchangers is particularly significant for power engineering and petrochemical applications where high fluid viscosity or low flow velocities are common due to pumping limitations or process constraints [16].

To comprehensively evaluate performance, a comprehensive performance parameter was introduced [14]. As shown in [Figure 12: see original paper], the comprehensive performance CP increases with decreasing α. Therefore, the $\alpha = 27°$ configuration was selected for comparison with the conventional design. [Figure 13: see original paper] reveals that the novel heat exchanger' s CP exceeds that of the conventional design within a certain Re range. At $\alpha = 27°$ and Re $<$ 19,672, the novel design demonstrates superior comprehensive performance, achieving CP = 4.3 at Re = 2322—5.7% higher than the conventional design.

This study reveals that velocity gradients in spiral channels affect boundary layer formation, substantially enhancing heat transfer coefficients, particularly at low Reynolds numbers—a conclusion supported by previous research [15-17].

Conclusions

(1) The heat transfer enhancement mechanism of the novel heat exchanger stems from strong rotational flow on the shell side. At the cinquefoil orifices, both jet effects and continuous vortices are generated, intensifying fluid micro-mixing and strongly scouring boundary and fouling layers to achieve heat transfer enhancement.

(2) Under identical structural parameters (except baffles) and boundary conditions, the novel heat exchanger exhibits higher shell-side average convective heat transfer coefficients and pressure drop than the conventional design. However, its comprehensive performance parameter is superior within a certain Reynolds number range. When the helical angle is 27° and Reynolds number is less than 19,672, the novel heat exchanger outperforms the conventional design.

(3) Under identical structural parameters (except baffles) and boundary conditions, larger helical angles produce stronger spiral flow patterns but also greater energy losses, resulting in higher shell-side average convective heat transfer coefficients and pressure drop. For example, heat transfer coefficients differ by 7.1% between $\alpha = 38°$ and 27° configurations, while pressure drop differs by 31.6%. Therefore, application of this novel heat exchanger requires careful consideration of specific heat transfer and pressure drop requirements.

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Note: Figure translations are in progress. See original paper for figures.