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Numerical Simulation of Thermal Performance of a Novel Spiral Plum-Blossom Perforated Plate Heat Exchanger Postprint

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Date: 2018-01-02T00:00:00+00:00

Abstract

Drawing upon vortex flow heat transfer enhancement technology, traditional straight-flow-channel plum-blossom-shaped support orifice plates are transformed into spiral-flow-channel plum-blossom-shaped support orifice plates, thereby designing a novel spiral plum-blossom-shaped orifice plate heat exchanger. A corresponding mathematical model is established, and its heat transfer and flow characteristics are simulated. Through comparative analysis with the plum-blossom-shaped orifice plate heat exchanger, the shell-side heat transfer enhancement mechanism of the novel heat exchanger is demonstrated, and the influence of the spiral flow channel' s spiral angle on the novel heat exchanger is further explored. The calculation results indicate that: within the studied range, the average shell-side convection heat transfer coefficient of the novel heat exchanger exceeds that of the conventional heat exchanger, while the shell-side pressure drop increases correspondingly; within a certain Reynolds number range, the comprehensive performance parameter of the novel heat exchanger surpasses that of the conventional heat exchanger. When the spiral angle is 27° and the Reynolds number is less than 19672, its comprehensive performance is superior to that of the conventional heat exchanger. The investigation into different spiral angles reveals that a larger spiral angle results in greater pressure drop for the novel heat exchanger, accompanied by stronger heat transfer capability.

Full Text

Preamble

The Simulation on Thermal Performance of a Novel Shell-and-Tube Heat Exchanger with Screw Cinquefoil Orifice Baffles

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Abstract

Based on vortex flow heat transfer enhancement technology, this study transforms traditional straight-flow cinquefoil orifice baffles into spiral-flow configurations, proposing a novel shell-and-tube heat exchanger with screw cinquefoil orifice baffles (STHX-SCOB). The corresponding mathematical and physical models were established to simulate the shell-side flow and heat transfer characteristics. Comparative analysis with conventional cinquefoil orifice baffle heat exchangers (STHX-COB) reveals the heat transfer enhancement mechanism of the novel design, while further investigating the influence of helical angle on thermal performance. Simulation results demonstrate that within the studied range, the novel heat exchanger achieves higher average convective heat transfer coefficients on the shell side, albeit with correspondingly increased pressure drop. The comprehensive performance parameter of the novel design surpasses that of conventional heat exchangers within certain Reynolds number ranges. Specifically, when the helical angle is 27° and Reynolds number is less than 19,672, the novel heat exchanger exhibits superior overall performance. Additionally, larger helical angles correlate with greater pressure drop and enhanced heat transfer capability.

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

Introduction

Shell-and-tube heat exchangers are widely employed in chemical engineering due to their low cost, structural simplicity, durability, and capability to handle large fluid flow rates [1]. However, conventional designs suffer from significant shell-side pressure drop, flow dead zones, and vulnerability to flow-induced vibration [2], necessitating research into alternative configurations.

Among various novel shell-and-tube heat exchangers, orifice baffle designs have gained prominence in nuclear power and other industries because their longitudinal shell-side flow patterns yield 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 flow and heat transfer characteristics in 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 orifices effectively scour tube walls, enhance turbulence intensity, accelerate mainstream mixing, and reduce boundary layer thickness, thereby significantly augmenting heat transfer. However, previous studies reveal that heat transfer enhancement in orifice baffle heat exchangers concentrates near support plates, with heat transfer capability diminishing in regions distant from baffles, indicating untapped potential for improvement. In addition to investigating conventional structural parameters such as baffle spacing, modifying orifice geometry offers a promising avenue for performance enhancement.

Helical baffle heat exchangers have attracted increasing industry attention because their baffle-guided shell-side flow eliminates dead zones, reduces pressure losses, and effectively suppresses fouling and tube bundle vibration [7-9]. Du et al. [10] proposed a sextant sector helical baffle heat exchanger, conducting numerical simulations with ANSYS CFX and experimental validation. Their findings indicate that the quasi-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. Nevertheless, the angular configuration between helical baffles and tube sheets complicates manufacturing processes and increases costs relative to conventional segmental baffles [7].

To address these challenges, this study proposes a novel screw cinquefoil orifice baffle heat exchanger based on traditional cinquefoil orifice baffles, transforming straight flow channels into spiral configurations. This innovation expands the research scope of longitudinal-flow orifice baffle heat exchangers and provides a new solution for practical applications. Through numerical simulation of 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 effect of helical angle on the novel heat exchanger' s performance, providing theoretical guidance for structural optimization.

1.1 Geometric Model

The screw cinquefoil orifice baffle is a full-circular support plate featuring six fluid passage holes around each tube hole, forming spiral flow channels that alter fluid direction. The structure is illustrated in Figure 1: see original paper(b). In contrast, conventional cinquefoil orifice baffles employ straight flow channels, as shown in Figure 1: see original paper(d). Detailed geometric parameters for both configurations 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 exchanger

inlets were specified as velocity inlets at 360 K, while outlets were defined as pressure outlets with 0 Pa gauge pressure and 101,325 Pa reference pressure. Tube walls were set as constant temperature surfaces at 300 K. 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] under steady-state conditions. The SIMPLE algorithm was employed for pressure-velocity coupling, and physical variables were solved using a second-order upwind scheme.

Due to flow complexity near support plates, the computational domain was divided into three regions: areas distant from baffles, regions adjacent to baffles, and inlet/outlet sections [1], as illustrated in [Figure 3: see original paper]. Meshing was performed using ANSYS ICEM with block-structured grids.

Grid independence verification was conducted for all models [1, 5, 12]. For the screw cinquefoil orifice baffle heat exchanger at a helical angle of =38° and Reynolds number Re=5,802, 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 was selected considering computational resources, while the conventional cinquefoil orifice baffle heat exchanger used 3.09×10 cells.

Model validation was performed by comparing simulation results against Ozden et al.' s heat exchanger model [13]. As depicted in [Figure 5: see original paper], the red line represents results from the present numerical method, while the black line shows Ozden et al.' s data. The maximum deviation in heat transfer coefficient h is within 5%, and the maximum deviation in pressure drop Δp is 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 velocity distribution in the conventional cinquefoil orifice baffle heat exchanger shown in Figure 6: see original paper, Figure 6: see original paper reveals that the shell-side fluid in the novel design exhibits intense rotational flow. At the cinquefoil orifices, the fluid generates not only jet effects but also continuous vortices that enhance mixing among fluid microelements, strongly scouring both the boundary layer and fouling layer to achieve heat transfer augmentation.

[Figure 7: see original paper] further demonstrates that conventional designs exhibit large low-velocity regions near the shell wall, whereas the novel heat exchanger maintains more uniform velocity distribution with smaller flow dead zones. The higher fluid velocity in the novel design disrupts 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 significantly improved compared to conventional designs.

2.2 Heat Exchanger Performance Comparison

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

Figure 9: see original paper shows that the novel heat exchanger' s h exceeds that of the conventional design, with an average improvement of 9.2% across five operating points. This advantage is more pronounced at low Reynolds numbers. At Re=2,322, the novel heat exchanger achieves h=754.9 $W \cdot m^{2} \cdot K^{1}$ compared to 610.9 $W \cdot m^{2} \cdot K^{1}$ for the conventional design—a 23.6% difference. As Re increases, the conventional heat exchanger's turbulence intensity improves, narrowing the performance gap to 6.9% at Re=23,220. This confirms the novel design' s superior performance at low Reynolds numbers.

Regarding pressure drop, Figure 9: see original paper indicates that the novel heat exchanger' s Δp is higher than the conventional design. At Re=2,322, the novel design' s Δp is 21.4% higher, with this difference increasing to an average of 36.0% across the studied range. Overall, the novel heat exchanger demonstrates stronger applicability under low Reynolds number conditions.

2.3 Effect of Helical Angle on Novel Heat Exchanger Performance

In helical baffle heat exchangers, the baffle helical angle directly affects performance [7, 9]. Similarly, in screw cinquefoil orifice baffle heat exchangers, the helical angle significantly influences thermal performance. Three helical angles were investigated: 27°, 38°, and 46°, with identical boundary conditions applied. As shown in [Figure 10: see original paper], larger helical angles produce stronger spiral flow patterns and better heat transfer performance.

Figure 11: see original paper presents the heat transfer coefficient h for the three configurations, revealing that h increases with . Within the studied range, the h values for =46° and =38° differ by 6.2%, while those for =38° and =27° differ by 7.1%. However, enhanced heat transfer comes with increased pressure drop. Figure 11: see original paper shows that the Δp difference between =46° and =38° is 36.9%, while that between =38° and =27° is 31.6%.

Many industrial applications in power engineering and petrochemical processes involve high-viscosity or low-velocity fluids operating at low Reynolds numbers, making low-Re heat exchanger research critically important [16].

To comprehensively evaluate performance, a comprehensive performance parameter [14] was introduced. As shown in [Figure 12: see original paper], the comprehensive performance CP increases as decreases. Therefore, the novel heat exchanger with =27° was selected for comparison with the conventional design. [Figure 13: see original paper] demonstrates that the novel heat exchanger' s CP exceeds that of the conventional design within a certain Reynolds number range. When =27° and Re<19,672, the novel design shows superior comprehensive performance, achieving CP=4.3 at Re=2,322–5.7% higher than the conventional heat exchanger.

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 intense rotational flow on the shell side. At cinquefoil orifices, the fluid generates both jet effects and continuous vortices that enhance microelement mixing and strongly scour boundary and fouling layers, achieving significant heat transfer augmentation.

(2) Under identical structural parameters and boundary conditions (except for baffle design), the novel heat exchanger exhibits higher average convective heat transfer coefficients and pressure drop on the shell side. However, its comprehensive performance surpasses that of conventional designs within certain Reynolds number ranges. Specifically, when the helical angle is 27° and Reynolds number is less than 19,672, the novel heat exchanger demonstrates superior overall performance.

(3) With other parameters held constant, larger helical angles produce stronger spiral flow patterns but also greater energy losses, resulting in higher shell-side heat transfer coefficients and pressure drop. For instance, heat exchangers with =38° and =27° show a 7.1% difference in heat transfer coefficient but a 31.6% difference in pressure drop. Therefore, selection of this novel heat exchanger requires careful consideration of specific heat transfer and pressure drop requirements for the intended application.

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