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Research paper

Parametric optimization of overlapped helical baffled heat exchangers by Taguchi method

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HIGHLIGHTS

- Overlapped helical baffled heat exchangers were firstly optimized by Taguchi method.
- Parametric influence was evaluated by Intuitive and statistical analysis methods.
- It is shown that overlap size is the more significant parameter than the others.
- The optimal parametric combination has better comprehensive performance (*JF* factor).

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ABSTRACT

Taguchi method was firstly applied to investigate the influence of five geometric parameters on the comprehensive performance of overlapped helical baffled heat exchangers. These five geometric parameters are helix angle, overlap size, diameter of tube, central distance of tube and tube layout. Fifteen cases with different combination of geometric parameters mentioned above are modeled and analyzed with respect to the heat transfer and flow friction characteristics. Results show that the effect of overlap size on comprehensive performance is most significant among the five geometric parameters. In addition, the two analysis method (i.e. intuitive analysis and statistical analysis) are also conducted that the influence of five parameters is not clearly different and thus all the five geometric parameters should be taken into consideration in optimization design. Based on the analysis, an optimal parametric combination is obtained, which is validated to have better comprehensive performance (*JF* factor) than the fifteen models used in testing. The *JF* factor of the optimal combination is 11.81%–15.57% higher than the model with the relatively better comprehensive performance among fifteen cases.

1. Introduction

Helical baffled heat exchangers are designed based on segmental baffled heat exchangers [1]. Helix flow can lower uneven heat transfer, fouling, erosion induced by the flow dead zone, and reduce pressure drop on the shell side. Therefore helical baffled heat exchangers are suitable for fluid of large viscosity. They are widely used in the field of oil refining, chemical engineering, nuclear power energy and many other industrial fields [2–4].

Since helical baffled heat exchangers were invented by ABB LUMMUS Heat Transfer in the 1990s, optimization has been carried out to improve their performance [5–8]. Due to complexity of production, continuously helical baffles are improved by a series of sectorial or elliptic plates, which compose overlapped helical baffled heat exchangers. Past studies focused on experiment and numerical simulation into the effect of helix angle and overlap size on flow resistance and heat transfer characteristics. Results showed that comprehensive performance was enhanced by the increase of helix angle [9]. Leakage flow and local pressure drop in triangle area were reduced by the increase of overlap size [10]. Besides, tube layout and tube shape have been also verified to be important in determining the performance. Square and triangular tube layouts were suitable for the heat exchangers with different numbers of baffles [11]. Special shaped tubes such as elliptical tubes and lozenge fin tubes were applied into helical baffled heat exchangers in order to increase the mean heat transfer coefficient [12,13]. However previous researches mainly focused on single geometry parameter instead of interaction of multiple geometry parameters

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of heat exchangers. The influence of various parameters on flow resistance and heat transfer characteristics has not been analyzed in detail in literature. And also no optimal parametric combined conditions have been given.

Taguchi method is widely used in engineering experiments. This method can be applied to obtain the optimal combination of process parameters quickly and effectively, which greatly saves experiment time and ensure robustness. Jeom Yul Yun and Kwan Soo Lee [14] applied Taguchi method to systematically analyze the effect of various design parameters on the heat transfer and pressure drop characteristics of the heat exchanger with a slit fin. Qi Zhaogang et al. [15] conducted research on five experimental factors affecting the heat transfer and pressure drop of a heat exchanger with corrugated louvered fins using the Taguchi method. Kotcioglu Isak et al. [16] presented the determination of optimum values of the design parameters in a heat exchanger with a rectangular duct by using Taguchi method. Sivasakthivel, T et al. [17] employed Taguchi method to achieve the parametric optimization for only heating or only cooling mode operation.

In this paper, Taguchi method is applied to analyze five parameters which include helix angle, overlap size, diameter of tube, central distance of tube and tube layout. The influence of five parameters on comprehensive performance is detailed. The optimal parametric combination is obtained.

2. Numerical simulation for overlapped helical baffled heat exchangers

2.1. Physical model

The physical model is the overlapped helical baffled heat exchanger with quadrant sectors. The computational model is shown in Fig. 1. Geometric parameters are listed in Table 1.

2.2. Governing equation and turbulence model

The general governing equation for turbulent convective heat transfer is [18]:

$$\mathrm{div}(\rho U\phi) = \mathrm{div}(\Gamma_\phi \mathrm{grad}\phi) + S_\phi \tag{1}$$

ϕ is the general variable which can represent velocity vector, temperature and so on. Hence the general governing equation can be expressed respectively as continuity equation, momentum equation, energy equation and $k-\varepsilon$. Accordingly, generalized diffusion coefficient Γ_ϕ and generalized source term S_ϕ have been endowed with different values.

Due to helix flow in shell side is complexity, the selection of turbulence model requires higher strain rate and calculation precision of streamline with larger bent degree. Therefore, RNG $k-\varepsilon$ is chosen as the turbulence model in this manuscript.

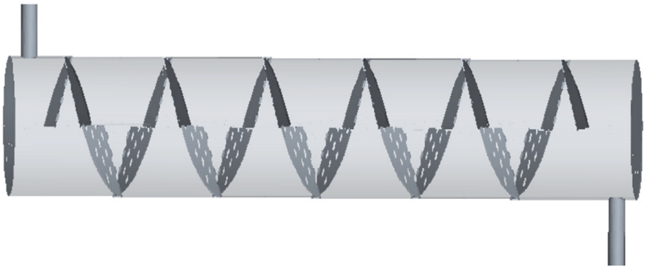

Fig. 1. Physical model of computational domain.

Table 1
Geometric parameters of heat exchanger.

Item	Size/quantity
Inner diameter of shell/mm	207
Tube length/mm	1600
Diameter of tube/mm	14, 16, 18
Central distance of tube/mm	22, 24, 26
Tube layout	Regular triangle Rhombus Square
Helix angle/(°)	20, 25, 30
Overlap size/%	0, 25, 50

2.3. Boundary conditions and basic assumptions

Shell side working medium is water. The mass flow rate is given in inlet and the temperature is 313.15 K. Fluid is free in outlet and the relative pressure is 0 Pa. Tube surface temperature keeps constant at 353.15 K. It is assumed that the turbulent flow is steady, the physical property of working medium is constant, the surface of baffles and the inner wall of shell are thermal isolation (i. e., the conduction resistance of baffles and the heat transfer between shell wall and surrounding are ignored), and that the impact of buoyancy and gravity is ignored.

2.4. Grid independence and reliability validation

In view of the complexity of overlapped helical baffled heat exchangers, tetrahedral and pyramid unstructured meshes are applied with the adaptive technology to refine meshes for three times. Through the grid independence test and considering the calculation time, 9.8×10^6 grid number is adopted.

In order to validate the reliability of numerical simulation procedure, numerical simulation was carried out at the same operating condition as the experimental study of none-block-plates helical baffled heat exchanger with helix angle 15° from literature [19]. The datum between numerical simulation and experiment were compared. Figs. 2 and 3 illustrate the comparisons between simulation results and experimental results in flow friction and heat transfer. The results show that the deviation of pressure drop is 14.7%~21.5%, and the deviation of wall heat transfer coefficient is 9.0%~14.8%. The deviation is in a reasonable range, which confirms the reliability of numerical simulation.

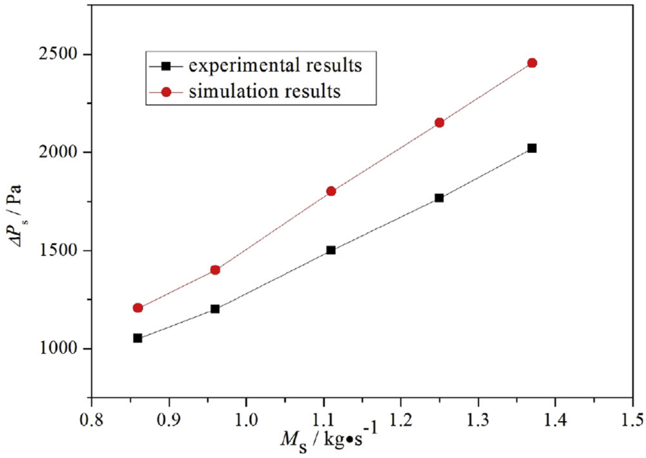

Fig. 2. Pressure drop in shell side comparisons between experimental and simulation results.