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Research Paper

Application of response surface method and multi-objective genetic algorithm to configuration optimization of Shell-and-tube heat exchanger with fold helical baffles

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HIGHLIGHTS

- A novel shell-and-tube heat exchanger with fold helical baffles was proposed.
- Effects of helical angle and overlapped degree on performance were studied.
- An effective algorithm combining RSM and MOGA was adopted.
- Empirical correlations of the Nusselt number and friction coefficient were fitted.

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ABSTRACT

A kind of shell-and-tube heat exchangers with fold baffles was proposed to eliminate the triangular leakage zones between adjacent baffles. An effective algorithm combing second-order polynomial response surface method and multi-objective genetic algorithm was adopted to study the effect of fold baffle configuration parameters on the performance of flow and heat transfer. The helical angle, overlapped degree and shell-side inlet velocity were chosen as design parameters, and the Nusselt number and shell-side pressure drop were considered as objective functions. The results show that both the Nusselt number and shell-side pressure drop increase with the decrease of helical angle and shell-side inlet velocity, and increase with the increasing overlapped degree. A set of Pareto-optimal points were obtained, and the optimization results illustrate a good agreement with CFD simulation data with the relative deviation less than ±3%. And the empirical correlations of Nusselt number and friction coefficient were obtained based on response surface method, the helical angle and overlapped degree were fitted into empirical correlations as correction factors for the first time. It is found that the adjusted coefficient of determination of the Nusselt number and friction coefficient is 0.943 and 0.999, respectively, which illustrate the fitting is correct and reliable.

1. Introduction

Heat exchangers play an important role to heat and mass transfer in engineering applications, for instance, petrochemical progress, electric power production, food industry, environmental protection, waste heat recovery, refrigeration and so on. What's more, shell-and-tube heat exchangers (STHXs) hold the dominant position with more than 35–40% of heat exchangers in the world [1–3]. STHXs have many advantages, for example, simple manufacturing, robust construction and adaptability operation conditions. Baffles, installed in shell side of STHXs, are used to support heat transfer tubes and control shell-side flow distribution, which have a significant effect on heat transfer enhancement and thermal-hydraulic performance of heat exchangers.

The shell-and-tube heat exchangers with segmental baffles (STHXsSB) are typical in conventional STHXs, which have been produced by standard in designing institutes and factories. STHXsSB are characterized by high pressure drop, flow dead zone, leakage flow in large quantities, easy fouling and flow induced vibration under high velocity, etc. [4–6], which have a negative effect on flow and thermal performance of heat exchangers. In order to overcome the above-mentioned weakness in STHXsSB, a lot of methods were put forward based on segmental baffles [7–10]. Particularly, a new

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Nomenclature

A_m	minimum flow sectional area, m^2
B	helical pitch, m
b	Regression coefficient
c_p	specific heat, $J\,kg^{-1}\,K^{-1}$
C	fitting coefficient
D_i	inner diameter of shell, m
D_1	diameter of tube bundle, m
d_0	outer diameter of tubes, m
e	overlapped degree
f	friction coefficient
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
k	turbulence pulsation kinetic-energy, $m^2\,s^{-2}$
l_c	effective length of tubes, m
m	polynomial order
Nu	Nusselt number
P	pressure, Pa
R^2	the coefficient of determination
Re	Reynolds number
T	temperature, K
t_p	tube pitch, m
u_i	velocity in x, y, z direction, $m\,s^{-1}$
u_e	mean velocity in shell side, $m\,s^{-1}$
V	volume flow rate, $m^3\,h^{-1}$
v	Shell-inlet velocity, $m\,s^{-1}$
x	input variable
Δp	pressure drop in shell side, Pa
Y	output variable

Greek symbols

β	helical angle, °
ε	Turbulent pulsating kinetic energy dissipation rate, $kg\,m^{-1}\,s^{-1}$
λ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
μ	dynamic viscosity, Pa s
μ_{eff}	effective viscosity, Pa s
ρ	fluid density, $kg\,m^{-3}$

Subscript

1,2	inlet, outlet
0,i,j	polynomial power

type of shell-and-tube heat exchangers with helical baffles (STHEsHB) was proposed by Lutcha and Nemcansky in 1990 [11] and realized industrialization by ABB Lummus in 1994. At present, STHXsHB are mainly discontinuous helical baffles with four fan-shaped plain baffles form one helical pitch due to the difficult manufacture of continuous helical baffles. STHXsHB have plenty of advantages, such as: enhancing shell-side heat transfer, decreasing pressure drop, reducing shell-side fouling, prolonging the running time and avoiding flow-induced vibration [6,12–14].

As a consequence, STHXsHB are most possibly considered to replace STHXsSB, hence, researchers have investigated the influence factors of heat and mass transfer performance and compared with STHXsSB. Zhang et al. compared the thermal-hydraulic performance of shell-and-tube oil coolers with overlapped helical baffles and segmental baffles, the results suggested the heat transfer coefficient per unit pressure drop of oil coolers with overlapped helical baffles is higher relatively [15]. Gao et al. experimentally studied and compared five helical angles of 8°, 12°, 20°, 30° and 40° when overlapped degree is 0.1. The results demonstrated that the comprehensive performance with helical angle of 40° is best [16]. Taher et al. studied the influence of different baffle spaces with helical angle of 40° on flow and heat transfer performance using numerical simulation method. The results presented that longer baffle spaces have better thermal-hydraulic performance under same flow rate [17]. Nevertheless, it is noteworthy that the triangle leakage zones between two adjacent baffles decreases radial flow rate and reduces the flow and heat transfer performance in discontinuous STHXsHB.

To solve the problem of triangle leakage zones, there are many useful methods. Wang et al. inserted plates to block triangle leakage zones, but experimental results showed heat transfer coefficient of STHXsHB with block plate is lower than that without block plate, and pressure drop is increased significantly [18]. Chen et al. proposed a new type of shell-and-tube heat exchangers with circumferential overlap trisection helical baffles, it was found that heat transfer coefficient per pressure drop of novel heat exchanger is about 0.5 higher than that of STHXsSB by experiment, and circumferential overlap trisection can block triangle leakage effectively [19–21]. Du et al. used six quadrant fan-sector baffles to form a cycle, and arranged baffles circumferentially every 60°, this method is also based on circumferential overlap to eliminate leakage zones [22,23]. Wen et al. came up with a novel shell-and-tube heat exchangers with ladder-type fold baffles, the results indicated that the comprehensive performance evaluation factor TEF is 1.148–1.242, which exceeds 1.0, that is to say, the thermal-hydraulic performance of novel heat exchangers is better than STHXsHB [24,25].

In this paper, on account of triangle leakage zones, a novel shell-and-tube heat exchanger with fold helical baffles (STHXsFHB) was proposed, which are used to reduce outer fringe triangle gaps between adjacent baffles. Based on numerical simulation, optimization for shell-and-tube heat exchangers with fold helical baffles was carried out using an improved algorithm combing second-order response surface method and multi-objective genetic algorithm. And the configuration parameters (helical angle and overlapped degree) were fitted into the correlations of the Nusselt number and friction coefficient for the first time.

2. Mathematical model

2.1. Physical models

The schematic diagrams of plain and fold baffles are shown in Fig. 1. There are two key configuration parameters, which are helical angle and overlapped degree, respectively. Helical angle β is angle between the normal lines of fold helical baffles and the axis of cylindrical shell. Overlapped degree e is expressed as, $e = l/R_i$, where l is vertical dimension from overlapped point to shell and R_i is radius of cylindrical shell. As shown in Fig. 2, the geometrical models of STHXsPHB and STHXsFHB are presented. The shell diameter of STHXs is 250 mm and tube bundle is 2500 mm in length. There are 40 tubes with the diameter of 19 mm, which are arranged squarely with the tube pitch of 25 mm. Besides, 12 spacer tubes are set to fix baffles and increase flow disturbance, in which there are no fluid.

To simplify numerical simulation, assumptions are demonstrated as follows: (1) the thickness of baffles, tubes and shell are all neglected; (2) the leakage zones between baffles and shell and those between baffles and tubes are neglected; (3) the fluid flow is turbulent and in steady state and the heat loss to the environ-