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Numerical investigation on baffle configuration improvement of the heat exchanger with helical baffles

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ABSTRACT

An improved structure of ladder-type fold baffle is proposed to block the triangular leakage zones in original heat exchangers with helical baffles. The numerical results showed that the shell-side tangential velocity and radial velocity in improved heat exchanger increase significantly and the shell-side fluid becomes approximately continuous spiral flow. And the configuration of ladder-type fold baffles was optimized. The numerical results showed that the shell-side heat transfer coefficient of the improved heat exchanger increases by 82.8–86.1%, when the folding ratio φ is 0.3, the baffle height ω is 60%, and the folding angle α is 37°. The associated pumping power penalty is about 21–549 W due to the increased shell-side pressure drop. The thermal performance factor *TEF* enhances by 28.4–30.7%, which demonstrates that the ladder-type fold baffle effectively improves the heat transfer performance of heat exchangers with helical baffles. The results of this paper are of great significance in the optimal design of heat exchanger.

1. Introduction

Shell-and-tube heat exchangers (STHXs) are widely used in the power plant, chemical engineering, environment engineering, and waste heat recovery due to their robust geometry construction, reliable operation, easy maintenance and possible upgrades [1]. The segmental baffles are commonly used in STHXs, which force the shell-side fluid to go through in a zigzag manner. But this type of heat exchanger has some inherent drawbacks, such as a large pressure drop in the shell side and a dead zone in the back of the segmental baffles, and leading to a serious fouling and high risk of vibration failure on tube bundles [2–6]. A number of new methods were proposed to overcome the above-mentioned drawbacks in shell-and-tube heat exchangers with segmental baffle [7–13]. STHX with helical baffles (STHXsHB) was firstly proposed by Lutcha and Nemcansky [14]. They found that the shell-side spiral flow of STHXsHB is closer to plug flow which can lead to an increase in the heat transfer temperature difference. Furthermore, the shell-side spiral flow will cause the radial velocity gradient, therefore thinning the boundary layer and increasing the heat transfer coefficient. Bashir et al. [1] found that STHXsHB are able to reduce shell-side fouling. Stehlik et al. [15] and Butterworth [16] have reported that STHXsHB can reduce the flow-induced vibration. Stehlik et al. [15] used experiment methods to compare the STHXsHB with the STHXsSB. Results showed that the performance of heat transfer and pressure drop of STHXsHB was considerably enhanced. Kral et al. [17] compared the performance among five STHXsHB with different helical angles and one STHXsSB. The result showed that the heat transfer coefficient of STHXsHB was higher than that of the STHXsSB, and the helix angle of 40° was the best.

Ideally, the helical baffle is made by continuous helical baffles, while the manufacture is very difficult, especially for heat exchangers with a large diameter. Consequently, conventional STHXsHB are usually made by four elliptical sector-shaped plates joined end to end to form a helical pitch. However, obvious triangle leakage zones exist between two adjacent baffles, which cause a short-circuit leakage in the shell-side. The leakages can shunt the main spiral medium and decrease the medium flow velocity, which in turn degrades the heat transfer performance of STHXsHB [18,19]. A lot of researchers devoted themselves to the heat transfer enhancement in STHXsHB. However, most of efforts were focused on the effect of helical pitch, helix angle and connection type of baffles [17,20–25]. Hajmohammadi et al. proposed a conductive thick plat between a heat source and a cold flowing fluid to improve the heat transfer [26–30]. Only few attempted to the

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Nomenclature

Latin symbols

S	the distance of bend to the center (m)
R	radius (m)
L	cutting height (m)
κ	turbulent kinetic energy ($m^2\ s^{-2}$)
x, y, z	coordinate (m)
u	fluid velocity in shell side ($m\ s^{-1}$)
I	turbulent intensity
Re	Reynolds number, $\rho u_m d_t/\mu$
q_s	volume flow rate ($m^3\ s^{-1}$)
A_m	the minimum transverse area (m^2)
B	baffle pitch (m)
D_s	diameter of inner shell (m)
D_{otl}	diameter of the tube bundle-circumscribed circle (m)
d_t	diameter of outer tube (m)
t_p	tube pith (m)
L_{bb}	gap between tube bundle and shell (m)
h_s	heat transfer coefficient, W ($m^{-2}\ k^{-1}$)
A	heat transfer area, m^2, $N{\cdot}\pi d_t L_s$
Δt_m	logarithmic mean temperature difference, K, $\frac{\Delta t_{max}-\Delta t_{min}}{\ln(\Delta t_{max}/\Delta t_{min})}$
N	number of tubes
L_s	length of tube, m
$t_{s,in}$, $t_{s,out}$	temperature of inlet tube and outlet tube, K
t_w	tube wall temperature (K)
Nu	Nussle number, hd/λ
ΔP	pressure drop (kPa)
F	flow resistance coefficient

Greek symbols

Θ	baffled angle (°)
α	bend angle (°)
φ	bending degree (°)
ω	cutting percentage (%)
ε	turbulent kinetic dissipation, kg ($m^{-1}\ s^{-1}$)
c_p	specific heat J ($kg^{-1}\ K^{-1}$)
μ	dynamic viscosity of viscosity ($m^2\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
λ	thermal conductivity W ($m^{-1}\ K^{-1}$)
β	helix angle (°)
Φ_s	heat exchanger quantity

Subscripts

in	inlet
out	outlet
s	shell side
t	tube side
w	wall

decrease of leakage flow [18,31–33]. Peng et al. [31] used the continuous helical baffle to block triangle gaps and found that continuous helical baffle increased the heat transfer coefficient about 10%. However, such design of continuous baffles causes difficulty in manufacture, especially for the heat exchanger with a large diameter. Wang et al. [32] proposed the triangular plates to stuff the triangle gaps. The experimental results demonstrated that the heat transfer coefficient was almost unchanged, while the shell-side pressure drop increased significantly. Song et al. [33] designed an anti-shortcut baffle structure that widened the straight edges of the elliptical sector-shaped baffles to accommodate one or two rows of tube pitch. Experimental results showed that this structure could decrease the triangle leakage and improve the heat transfer performance. Wang et al. [18] used the fold baffle to replace the plane baffle to block the shell-side triangle leakage of STHXsHB. It was found that the overall heat transfer coefficient of heat exchanger increased by 7.9–9.7%. The triangle leakage of STHXsHB would change the flow pattern in the shell-side fluid from a spiral flow to an axial flow, which will reduce the shell-side flow distance of the medium and thus weaken the heat transfer.

Triangle leakage zones in the shell side of STHXsHB need to be addressed properly for further improvement of the performance of STHXsHB. In this paper, a novel ladder-type fold baffle is proposed to block the triangle leakage zones. In addition, four elliptical sector-shaped plates are required to form a helical pitch in the conventional STHXsHB, and therefore location and installation would become difficult. However, there are only two ladder-type fold baffles required in the improved design. The numerical investigation on performance of STHXsHB was carried out. The shell-side flow patterns of the STHXs with ladder-type fold baffles and the original STHXsHB were firstly compared. Then, the effects of the configuration parameter of ladder-type fold baffles on the heat transfer performance of the heat exchanger were studied and the optimum baffle design was also identified. Finally, discussion is focused on evaluating the shell-side heat transfer coefficient, pressure drop and the comprehensive performance among the improved STHXsHB, the original STHXsHB and the STHXsSB. under the same operation conditions.

2. Mathematical and model

2.1. Physical models

As shown in Fig. 1. The original elliptical sector-shaped plate is cut off a standard ellipse, symmetrically with respect to the minor axis. The cutoff angle of the baffle sector should be larger than 90° and vary with the helix angle β (Fig. 1a). While, the projected angle of the baffle onto the normal cross-section of the heat exchanger is 90°. As shown in Fig. 1b, the novel ladder-type fold baffle is formed from folding a flat panel twice, which consists of three planes. The plane A and C are perpendicular to the axis of the tube bundle. The folding angles between different planes are the same, denoted as α. The folding ratio φ is the ratio of the distance S to the projection radius R ($\varphi = S/R$). The baffle height ω is ratio of the baffle height H to the projection diameter D ($\omega = H/D$).

Fig. 2 demonstrates the installation of the baffles in the tube bundle of heat exchanger. The straight edges of the two adjacent ladder-type fold baffles are overlapped to accommodate several rows of tube pitch and two fold planes are made by bending both sides of the baffle, making the two adjacent ladder-type fold baffles connected closely. The shell-side diameter of the heat exchanger is 250 mm and is 2000 mm in length. Tube bundle consists of 57 tubes with the diameter of 19 mm and in a square layout with a tube pitch of 25 mm.

To simplify numerical simulation but with a reasonable accuracy in the model, assumptions are as follows: (1) the tube-side is simplified and the tube wall temperature is set as constant; (2) the thickness of the baffles is neglected to reduce the number of grids; (3) the gaps between tubes and baffles and those between baffles and the shell are neglected; (4) the fluid flow and heat transfer processes are turbulent and in steady-state; and (5) heat