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Numerical investigation on combined single shell-pass shell-and-tube heat exchanger with two-layer continuous helical baffles

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ABSTRACT

A novel combined single shell-pass shell-and-tube heat exchanger with two-layer continuous helical baffles (CSSP-STHX) has been proposed in the present study as an alternative solution of overcoming the drawbacks of the shell-and-tube heat exchanger with continuous helical baffles (CH-STHX). The shell-side baffles of CSSP-STHX are consisting of inner layer and outer layer continuous helical baffles, which are not on the same helical surface. There is no sleeve tube between inner and outer layers, thus complex flow field can be formed in the shell side which means inner layer fluid can rush out to the outer layer under the centrifugal force. Numerical simulations are carried out to compare thermo hydraulic performances of the three heat exchangers which are shell-and-tube heat exchanger with segmental baffles (SG-STHX), CH-STHX and CSSP-STHX. The results show that the CSSP-STHX has a higher heat transfer performance while maintaining a lower pressure drop. The CSSP-STHX might be an ideal choice to replace the SG-STHX and CH-STHX in industrial applications.

1. Introduction

Heat exchangers are widely used in many engineering applications, such as chemical engineering processes, power generation, petroleum refining, refrigeration, air-conditioning, food industry, and so on. Among different types of heat exchangers, the shell-and-tube heat exchangers (STHXs) have relatively simple manufacture and multi-purpose application possibilities for gaseous and liquid media in a large temperature and pressure range [1]. It was reported that more than 30% of the heat exchangers are of the shell-and-tube type [2,3].

However, the traditional STHXs with segmental baffles (SG-STHXs) which are the most commonly used until now have many disadvantages [4–6]: such as high pressure drop, low shell-side mass flow velocity, low heat transfer coefficient and fouling, short operation time and so on. When the traditional segmental baffles are used in STHXs, higher pumping power is often needed to offset the higher pressure drop under the same heat load. Therefore, it is essential to develop a new type of STHXs using different types of baffles to have higher heat transfer efficiency and lower pressure drop.

The problems of SG-STHXs mentioned above were improved or solved by the helical baffles. The shell-and-tube heat exchanger with discontinuous helical baffles (DCH-STHX) was firstly proposed by Lutcha and Nemcansky [7] and commercially produced by ABB Lummus Heat Transfer [8]. The discontinuous helical baffles are formed by overlapped fans or oval-shaped plates; each fan or plate occupies a certain place in the heat exchanger shell cross section and is angled to the axis of the heat exchanger. These discontinuous helical baffles can be manufactured and installed easily on the shell side of STHXs. The quadrant plates on the shell side can create a close helical flow pattern, which has higher conversion of pressure drop to heat transfer on an optimal helix angle [9–15]. Besides, helix flow manner can be closer to plug flow conditions, which can reduce fouling and flow-induced vibration significantly. So far, a sophisticated thermal design method for DCH-STHX has been developed [16–18]. Chen [19] noticed axial overlap turns a large triangle into two smaller triangles and thus seemingly reduce the leakage area, but the triangle at the periphery opens a leakage shortcut to the downstream chamber and thus seriously affects the heat transfer of the mainstream flow. Then Chen et al. [20] proposed a new structure consisting of circumferential-overlapped trisection helical baffled shell-and-tube heat exchangers (cothSTHXs). However, in the DCH-STHXs and cothSTHXs, the "triangle zones" exist between two oval-shaped plates, and fluid may leak from these triangle zones. Therefore, the flow in the shell side is not exactly "perfect" helical flow. This will result in a decrease in heat transfer on the shell side of the heat

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Nomenclature

A	heat transfer area, m^2
A_{min}	minimum transverse area, m^2
c_p	specific heat capacity, J/(kg K)
c_i	coefficients in k–ε turbulence model
d_e	equivalent diameter, mm
D_t	diameter of heat exchangers tubes, mm
D_{otl}	diameter of tube bundle-circumscribed circle, mm
D_{in}, D_{out}	diameters of inlet tube and outlet tube, mm
D_1	diameter of outer shell, mm
D_2	middle diameter of central tube of CSSP-STHX, mm
D_3	outer diameter of central tube of CSSP-STHX, mm
D_4	diameter of central tube of CH-STHX, mm
H_b	baffle pitch, mm
h	average heat transfer coefficient, W/(m^2 K)
I	turbulent intensity
k	turbulent fluctuation kinetic energy, m^2/s^2
L	total effective tube length, mm
M	mass flow rate, kg/s
N_t	number of tubes
p_t	tube pitch, mm
p_n	half of tube pitch, mm
Pr	Prandtl number
Δp_m	pressure drop, Pa
Q_m	heat transfer rate, W
Re	Reynolds number
$R_{CH,\ SG}$	maximal velocity ratio between CH-STHX and SG-STHX
$R_{CSSP,SG}$	maximal velocity ratio between CSSP-STHX and SG-STHX
T_f	average temperature of fluid, K
T_{in}	inlet temperature, K
T_{out}	outlet temperature, K
T_w	tube wall temperature, K
ΔT	log mean temperature difference, K
u, v, w	velocities in different directions, m/s
u_m	average velocity of fluid in shell side, m/s
x^+, y^+	dimensionless distance from wall
x, y, z	Cartesian coordinate

Greek Symbols

Γ	generalized diffusion coefficient
ε	turbulent kinetic energy dissipation rate, m^2/s^3
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, kg/(m s)
μ_t	turbulent dynamic viscosity, kg/(m s)
ρ	density, kg/m^3
σ_k	Prandtl number for k
σ_ε	Prandtl number for ε

Abbreviations

SG-STHX	shell-and-tube heat exchanger with segmental baffles
CH-STHX	shell-and-tube heat exchanger with continuous helical baffles
CSSP-STHX	combined single shell-pass shell-and-tube heat exchanger with two-layer continuous helical baffles

exchanger. Block plates [21] can be used to block the leakage in this region. However, the block plates will result in difficulty in manufacturing and significantly increase in flow resistance. On the other hand, it is also found that the helical baffled heat exchanger has higher heat transfer performance only under the same pressure drop. Under the identical tube arrangement, identical shell size and identical mass flow rate, the DCH-STHX and cothSTHX have relatively lower pressure drop in the shell side, but they have even lower heat transfer rate simultaneously, which is not always acceptable.

Wang et al. [22] introduced a manufacture method for continuous helical baffles. The fluid flow in the shell side of STHXs with continuous helical baffles (CH-STHX) is a complete helix in nature. And the experimental results indicated that the heat transfer coefficient of the CH-STHX was nearly 10% higher than that of the SG-STHX for the same shell-side flow rate. For the same pressure drop, the heat transfer coefficient of the CH-STHX was about 5% higher than for the SG-STHX. Lei et al. [23] carried out numerical simulations to study the impacts of various baffle inclination angles on fluid flow and heat transfer of CH-STHXs by using periodic model. From the results computed, it was observed that the best integrated performance occurs at approximately 45° helix angle. Recently, Wang et al. [24] proposed the maximal velocity ratio design method for CH-STHXs which can ensure that the CH-STHX has better heat transfer efficiency than that of the original SG-STHX in the same shell structure and same mass flow rate. As mentioned above, a central tube may have to be employed to fit the helical structure inside the shell because the helical baffle surface becomes relatively steep at portions close to the central axis. So tubes cannot be arranged at the place where the central tube is located, and thus heat transfer area will be reduced; on the other hand, part of the heat exchanger volume is occupied and cannot be used for heat exchange, which will result in decreasing of compactness.

Therefore Wang et al. [25,26] proposed the combined helical baffled STHXs (CMH-STHXs) and the combined multiple shell pass helical baffled STHXs (CMSP-STHXs). Chen et al. [27] numerically studied the heat transfer and flow performance of a DCH-STHX, a CH-STHX, and a CMH-STHX by adopting periodic boundary condition. Numerical studies have been conducted on the CMSP-STHXs by Wang et al. [28]. It was found that the pressure drop of CMSP-STHX was lower than that of SG-STHX by about 13% for the same mass flow rate and same heat transfer rate. But the shell-side pressure drop will sharply increases at the corner connecting the outer and inner shell passes.

In order to make full use of the advantage of helical baffles and to further enhance the shell-side heat transfer and resistance performance, a combined single shell-pass shell-and-tube heat exchanger with two-layer continuous helical baffles [29] (CSSP-STHX) is proposed and a photography of the CSSP-STHX used in oil refining is presented in Fig. 1. The shell-side baffles of the CSSP-STHX are consisting of inner layer continuous helical baffles and outer layer continuous helical baffles, which are not on the same helical surface. In other words, the inner layer continuous helical baffles are used to replace the central tube of CH-STHXs and occupy the central space for heat transfer, thus the CSSP-STHX structure is formed. There is no sleeve tube between the inner layer and outer layer, thus inner layer fluid can rush out to the outer layer under the centrifugal force. And this improves the heat transfer by enhancing turbulence and local mixing on the shell side of heat exchangers. In addition, the combined two-layer continuous helical baffles can reduce the pressure drop and mitigate fouling and increase compactness and prolong the service life of the STHXs.