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Numerical analysis and optimization study on shell-side performances of a shell and tube heat exchanger with staggered baffles

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A B S T R A C T

With a view to possessing the characteristics of the simple fabrication of the shell and tube heat exchanger with segmental baffles (STHX-SG) and the helical flow of the shell and tube heat exchanger with continuous helical baffles (STHX-CH), a shell and tube heat exchanger with staggered baffles (STHX-ST) is proposed in this work. The baffles of the STHX-ST are arranged according to a certain rule that the adjacent baffles are staggered by a constant clockwise or counterclockwise angle in sequence. Comparisons of the heat transfer performance and pressure drop among the STHX-SG, STHX-CH, and STHX-ST are firstly carried out. Results show that the comprehensive performance of the STHX-ST is superior the STHX-SG and STHX-CH. The parametric studies about the baffle cut δ and staggered angle β are conducted for the STHX-ST. Moreover, the multi-objective optimization is carried out to obtain the optimal solutions using the genetic algorithm further. The relationships between the design variables (the baffle cut δ, staggered angle β, and number of baffles n) and objective functions (the heat transfer rate Q and pressure drop Δp) are characterized by the artificial neural networks. The STHX-ST, at the $\delta = 0.45$, $\beta = 79°$, and $n = 11$, is determined as the optimal solution according to the TOPSIS selection. Meanwhile, it is proved that the STHX-SG, a special STHX-ST at the $\beta = 180°$, is not always the best choice from the view of heat transfer enhancement. The STHX-ST can provide a preferable and meaningful solution for more efficient energy utilization in industrial applications.

1. Introduction

Driven by the purpose of the energy saving and emission reduction, heat exchangers play a vital role in various fields of the modern industry, particularly in chemical processing, electric power, and waste heat recovery. The shell and tube heat exchanger (STHX) is one of the most widely used heat exchangers owing to its versatile usability, convenient maintenance, high-pressure resistance, and high-temperature resistance [1]. The flow manner of the working fluid in the shell-side of the STHX can be divided into three types roughly: the cross flow, the longitudinal flow, and the helical flow. The conventional shell and tube heat exchanger with segmental baffles (STHX-SG), of which a cross flow is presented in the shell-side as illustrated in Fig. 1(a), is the most common STHX because of its simple installation, low cost, and high heat transfer performance. However, there are some disadvantages, such as the high flow resistance, the flow induced vibration, and dead zones for the STHX-SG [2].

The CFD method is frequently used to conduct a study, which results from its convenience, low cost, and time saving. Prithiviraj and Andrews [3–5] proposed a numerical method to simulate flow and heat transfer in STHXs. Their method was proved more accurate than the other prediction methods, including Kern, Donohue, and Bell methods. Aslam Bhutta et al. [6] focused on CFD applications in heat exchangers design, and they claimed that CFD was an effective tool for predicting the behavior of various heat exchangers. Basing on the above studies, we deem the CFD method is appropriate and effective for the present research.

A variety of studies have been conducted to improve the comprehensive performance of heat exchangers by enhancing the heat transfer performance or reducing the flow resistance by researchers from all over the world [7–11]. Particularly, the shell and tube heat exchanger with helical baffles was invented by Lutcha et al. [12] and commercialized by ABB Lummus Global Inc [13]. Afterwards, more and more improved structures and measures were developed with respect to the helical flow manner [14–17]. Typically, Wang et al. [18–21] proposed a shell and tube heat exchanger with continuous helical baffles (STHX-CH), and the ideal helical flow was generated in the shell-side, as depicted in Fig. 1(b). However, the complexity of the fabrication about helical baffles was

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Nomenclature

A	heat transfer area (m^2)
c_p	specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
C	relative closeness to the ideal solution
C_1, C_2	model coefficients
d	outer diameter of tube (mm)
d_r	diameter of center rod (mm)
D	inner diameter of shell (mm)
D_{in}	inner diameter of inlet (mm)
D_{out}	inner diameter of outlet (mm)
G_k	producing item of the k by the mean velocity gradient ($kg \cdot m^{-1} \cdot s^{-3}$)
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
h_c	cut height of circular baffle (mm)
I	turbulence intensity
k	turbulent kinetic energy ($m \cdot s^{-2}$)
l	turbulence length scale (mm)
L	effective length of tube (mm)
M	mass flow rate ($kg \cdot s^{-1}$)
n	number of baffles
n_h	number of neurons in hidden layer
N_t	tube number
p_t	tube pitch (mm)
Δp	pressure drop (Pa)
P	power consumption (W)
Q	heat transfer rate (W)
Re	Reynolds number
s	the baffle spacing and helical pitch (mm)
T	temperature (K)
ΔT_m	log mean temperature difference (K)
u	velocity ($m \cdot s^{-1}$)
V	volume flow rate ($m^3 \cdot s^{-1}$)
x, y, z	Coordinate axes

Greek symbols

β	staggered angle (°)
δ	baffle cut
ε	turbulent dissipation rate ($m^2 \cdot s^{-3}$)
λ	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
μ	dynamic viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
σ_k	turbulence Prandtl number for k
σ_ε	turbulence Prandtl number for ε

Subscripts

i, *j*	tensor
in	inlet
local	local parameter
out	outlet
test	testing set
train	training set
w	tube wall

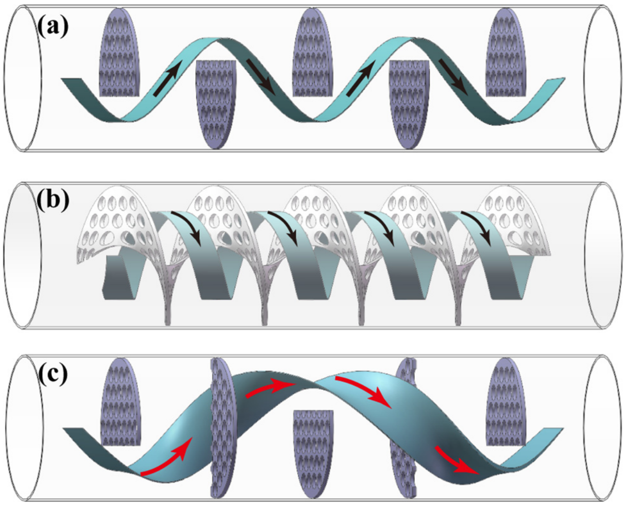

Fig. 1. Schematic diagrams of the main flow manner: (a) STHX-SG; (b) STHX-CH; (c) STHX-ST.

unavoidable, which increased the manufacturing cost relative to the STHX-SG, obviously. Mellal et al. [22] investigated the effect of the baffles orientation preliminarily for the STHX, and the results showed that the case of baffle orientation angle of 180° and baffle spacing of 64 mm, i.e., the conventional STHX-SG, is the optimal structure. Moreover, optimization algorithms were used to obtain the global optimal solution instead of the traditionally parametric study. Ge et al. [23] determined the best configurations for the tube inserted with porous media using Genetic Algorithm (GA). Cavazzuti and Corticelli [24] proposed a robust automated method for the design of two-dimensional enhanced surfaces. Abdollahi and Shams [25] determined the optimal values of selected design parameters of a channel with winglet vortex generator using the artificial neural network (ANN) and multi-objective genetic algorithm. However, the overall optimization for the whole shell-side of the STHX is uncommon because of its heavy workload.

Although many studies have been achieved for STHXs and the effects of the baffle orientation angle are investigated briefly in Ref. [22], however, an integrated research for the combination of the STHX-SG and helical flow is not discussed. Basing on the above studies, we propose a shell and tube heat exchanger with staggered baffles (STHX-ST) in view of taking the advantage of both the simple fabrication of the STHX-SG and the helical flow of STHX-CH, as outlined in Fig. 1(c). In the STHX-ST, the baffles are arrayed according to a certain rule that the adjacent baffles are staggered by a constant clockwise or counterclockwise angle in sequence. The fabrication and installation for staggered baffles are quite simple compared with those for helical baffles. Obviously, the baffle cut δ, staggered angle β between the adjacent baffles, and number of baffles n, as illustrated in Fig. 2, have a significant effect on the comprehensive performance of the STHX-ST. The baffle cut is defined as the ratio of the cut height of the circular baffle and the inner diameter of the shell. The parametric studies about the effects of the δ and β are also carried out. Moreover, the orthogonal test is determined for the design of experiment to reduce the workload of CFD simulations. The CFD, ANN, and GA are used in combination to fulfill the multi-objective optimization to obtain the optimal solutions.

This paper is organized as follows: (1) In Section 2, the numerical method, adopted to verify the advantages of the STHX-ST, is outlined. (2) In Section 3, the analysis and comparison of the simulation results are performed for the STHX-SG, STHX-CH, and STHX-ST; and then, effects of the baffle cut δ and staggered angle β are discussed for the STHX-ST; finally, the optimal STHX-STs