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Numerical investigation of shell side performance of a double shell side rod baffle heat exchanger

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ABSTRACT

A double shell side rod baffle heat exchanger (DS-RBHX) is proposed, and comparisons between single shell side rod baffle heat exchanger (SS-RBHX) and DS-RBHX in terms of the heat transfer and pressure drop in the shell side are presented in this study. A realizable k-epsilon model is adopted to solve the turbulent flow problem. All numerical simulations are carried out under mass flow rate M ranging from 3 kg/s to 10 kg/s for the SS-RBHX and DS-RBHX. The results demonstrate that under same mass flow rate M, the heat transfer rate Q and pressure drop Δp of the DS-RBHX are higher than those of the SS-RBHX by 34.5–42.7% and 41.6–40.6%, respectively. Moreover, under same mass flow rate M, the comprehensive performance index $h/\Delta p$ of the DS-RBHX is higher than that of the SS-RBHX by a maximum of 8.9%. An efficiency evaluation criterion *EEC*, the ratio of the gain in heat transfer rate and cost in power consumption, is adopted to evaluate the comprehensive performance in the present study. The *EEC* of the DS-RBHX is approximately equal to and larger than 1, which indicates that the cost in power consumption of the DS-RBHX is offset by the gain in heat transfer rate. The DS-RBHX is demonstrated to be effective in enhancing heat transfer and improving the comprehensive performance of rod baffle heat exchangers.

1. Introduction

The heat exchanger is a device applied to transfer heat between cold and hot fluids, and it plays an important role in a number of industries such as petroleum, chemical engineering, power generation and waste heat recovery. The shell and tube heat exchanger (STHX) is one of most commonly used heat exchangers because of its high pressure resistance, simple fabrication, low cost, convenient maintenance, versatile usability, and adaptability [1]. The flow patterns in the shell side of STHXs can be roughly categorized into three types: cross flow, longitudinal flow, and helical flow. The conventional STHX is supported by segmental baffles that direct the fluid in a zigzagged and cross flow. The shell and tube heat exchanger with segmental baffle (STHXsSB) is used widely because of its convenient installation and high heat exchange performance. Nevertheless, it has a few deficiencies such as high pressure drop, flow induced vibration, and flow dead zone [2].

In view of the above facts, studies to enhance heat transfer and improve comprehensive performance have been carried out by researchers around the world [3–14]. The STHXs with longitudinal and helical flow are popular research objects. The rod baffle heat exchanger (RBHX) [15] was invented by Philips Petroleum Company in the 1970s. The RBHX modifies the cross flow in the STHXsSB to longitudinal flow, which reduces flow induced vibration and power consumption in the shell side [16]. A combined STHX with two-layered continuous helical baffles was proposed by Yang et al. [17], and it has the potential to replace the STHXsSB. Wang et al. [18,19] designed a combined multiple shell-pass STHX with continuous helical baffles, which consists of several individual shell side with different types of baffles. This type of STHX improves the heat transfer performance and simplifies the manufacturing process. Liu et al. [20] presented simulations of the RBHX with spirally corrugated tubes, and these tubes can enhance heat transfer in the tube side as well as shell side. As the STHX consists of both the tube side and shell side, appropriate measures can be taken to enhance heat transfer in tube side as well. A variety of novel tube inserts [21–25] and special shaped tubes [26–28] are proposed and studied to enhance heat transfer in tube side. In addition to the measures mentioned above, researchers have carried out studies on optimization of STHXs such as heat transfer optimization in tubes based on local exergy destruction minimization [29,30], optimization of STHXs by constructal theory [31] and exergetic optimization of STHXs [32].

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Nomenclature

A	heat transfer area (m^2)
c_p	specific heat capacity (J kg^{-1} K^{-1})
C_1	empirical constant
C_2	empirical constant
d_o	the outer diameter of tube (mm)
d_{si}	the inner diameter of sleeve (mm)
D_i	the inner diameter of shell (mm)
D_{in}	the inner diameter of inlet (mm)
D_{out}	the outer diameter of outlet (mm)
EEC	the efficiency evaluation criteria
G_k	producing item of k by average velocity gradient (kg m^{-1} s^{-3})
h	heat transfer coefficient (W m^{-2} K^{-1})
I	turbulence intensity
k	turbulent kinetic energy (m s^{-2})
l_b	baffle pitch (mm)
l_t	tube pitch (mm)
L	effective length of tube (mm)
M	mass flow rate (kg s^{-1})
N_t	tube number
Nu	Nusselt number
Δp	pressure drop (Pa)
P	power consumption (W)
Q	heat transfer rate (W)
R	the radius of shell
Re	Reynolds number
s	the spacing between tubesheet and partition (mm)
t	the wall thickness of sleeve (mm)
T	temperature (K)
ΔT_m	logarithmic mean temperature difference (K)
u	velocity (m s^{-1})
u'	root-mean-square of the velocity fluctuation (m s^{-1})
V	volume flow rate (m^3 s^{-1})
V_z	axial velocity
x, y, z	coordinate axes

Greek symbols

λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
ε	turbulent dissipation rate (m^2 s^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})
μ_t	turbulent dynamic viscosity (kg m^{-1} s^{-1})
σ_k	Prandtl number corresponded to k
σ_ε	Prandtl number corresponded to ε

Subscripts

0	comparison object
avg	average
i, j	tensor
in	inlet
max	maximum
min	minimum
out	outlet
w	tube wall

Although experimental results of studies of heat transfer performance of STHXs are considered to be convincing and accurate, the experiments are costly and time-consuming. On the contrary, numerical simulation by CFD [33,34] is convenient and efficient, and therefore, this method is popular for use in studies of STHXs. Yang et al. [35] contrasted four numerical modeling approaches with experimental results of studies on a RBHX. The results demonstrated that both the porous model and whole model provided reasonably accurate predictions of heat transfer and pressure drop when compared to the unit model and periodic model. The different CFD turbulence models, including the Spalart-Allmaras model, standard k-epsilon model, and realizable k-epsilon model are studied for the STHXsSB by Ozden et al. [36]. It is indicated that the results using the realizable k-epsilon model and fine mesh were the closest to those by Bell-Delaware method.

In this paper, a DS-RBHX, as illustrated in Fig. 1, is proposed to enhance heat transfer and improve the comprehensive performance of RBHXs. Numerical simulation by CFD is adopted to study heat transfer and pressure drop of the DS-RBHX, and a SS-RBHX is used as a reference. The SS-RBHX and DS-RBHX are meshed and simulated using commercial software Gambit and Fluent, respectively. The numerical simulations are processed on servers with 20 dual-core CPUs and 240 GB RAM.

2. Model description

2.1. Physical model

Fig. 1(a) illustrates the structure and main flow manner of the DS-RBHX. The shell side of the DS-RBHX is divided into the inner shell side and outer shell side by the sleeve and partition. After flowing into the outer shell side through the shell side inlet at one end, the fluid traverses the rod baffles and flows along the sleeve to the tube sheet at the other end. Then the fluid swerves and flows into the inner shell side along the end face of the sleeve. The fluid streams along the inside of the sleeve and then flows out through the shell side outlet. The structure of the sleeve (with rod holes) is illustrated in Fig. 1(b). The baffle rods pass through the corresponding rod holes and are fixed on the outer rings as depicted in Fig. 1(c).

The physical models and geometrical parameters of the SS-RBHX and DS-RBHX are presented in Fig. 2(a) and (b), respectively. The two heat exchangers have same inlet and outlet nozzle diameters, tube effective lengths, and inner diameters of the shell. The square arranged tube bundles are used in the RBHX as a rule for more convenient installation and more stable support in industrial applications, so they are adopted for the present SS-RBHX and DS-RBHX models. The minor alterations are made based on square arranged tube bundles to ensure the same tubes layout for two models, as illustrated in Fig. 2, because the 2 mm thick sleeve in the DS-RBHX is installed between tube bundles to divide the shell side. More specifically, the two models have same layouts with 40 identical tubes each. Identical rod baffles are adopted for the two models, and their geometrical parameters are listed in Table 1.

2.2. Numerical simulation model

2.2.1. Governing equations

To simplify the calculation, the fluid is assumed to be incompressible, flow is assumed to be steady, and influence of gravity is ignored. Based on these assumptions, the governing equations for continuity, momentum, and energy conservation are provided below [37]:

Continuity equation:

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$