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Research Paper

Numerical investigation on synthetical performance of heat transfer of planar elastic tube bundle heat exchanger

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HIGHLIGHTS

- It is possible to improve heat transfer by arranging the tube bundle layout.
- The effects of Reynolds number and geometry parameter on heat transfer are studied.
- A prediction correlation of average Nusselt number is obtained.
- Comprehensive heat transfer performance of heat exchanger is reviewed.
- Tube pitch 20 mm is the optimal selection for the heat transfer in the present work.

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ABSTRACT

This paper studied the synthetical performance of heat transfer in the shell-side of planar elastic tube bundle heat exchanger using numerical simulation. The temperature distribution in shell-side was studied. The relation of average heat transfer coefficient, pressure drop and comprehensive heat transfer performance were also discussed considering varying Reynolds number and geometry parameters. Results demonstrate that the temperature distribution provides a possibility to improve heat transfer by arranging the tube bundle layout to produce a fully heated fluid within full-scale shell-side. For the effect of geometry parameter, tube pitch has a greater effect on heat transfer compared to the tube-row spacing. However, Reynolds number dominates the heat transfer and fluid flow in shell-side. As a result, a prediction correlation of average Nusselt number is developed based on Reynolds number using the multiple-regression analysis of MATLAB software. A quite outstanding comprehensive heat transfer performance can be obtained in the case of tube pitch 20 mm. However, the high Reynolds number is more acceptable in the industry to enhance the heat transfer rate without considering the heat transfer difference caused by geometry parameter.

1. Introduction

Heat transfer enhancement has been the focus of solving energy problem in the industry. Compared to the straight tube, curved tube provides a large heat transfer surface area per unit volume no matter the heat exchange inside or outside the tube bundle [1]. Therefore, the curved tube plays an active role in heat transfer enhancement, such as the form of coiled [2], helical [3] and spiral [4].

Concerning the heat transfer outside the curved tube, Jamshidi et al. [5] experimentally investigated the heat transfer enhancement in shell and helical tube heat exchangers with varying mass flow rates and geometry parameters. The optimum condition for the whole heat exchanger was found according to the overall heat transfer coefficient. Results showed that the mass flow rate and geometry parameter were important design parameters in the coiled heat exchangers. Alimoradi and Veysi [6] investigated the effect of physical properties of fluid, operational parameters and geometrical parameters on Nusselt number of shell and helically coiled tube heat exchangers using both numerical and experimental methods. Results indicated that the doubled pitch generated an increase of 10% in shell-side Nusselt number. It was found that an increase of 50% in the height and diameter of the shell led to a decrease of 34.1% and 28.3% in the shell-side Nusselt number, respectively. At last, two correlations were developed to predict the shell-side and tube-side Nusselt numbers based on the results.

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Nomenclature

R	radius of curvature (m)
D	diameter dimension (m)
L	length dimension (m)
W	width dimension (m)
H	height dimension (m)
u, v, w	velocity components (m/s)
T	temperature (K)
T_0	reference temperature
$p(P)$	static pressure (Pa)
U	fluid velocity (m/s)
ΔT	temperature difference (K)
ΔP	pressure drop (Pa)
t	time (s)
k	thermal conductivity of fluid (W/K·m)
C	correction factor (–)
c_p	specific heat at constant pressure (J/(kg·K))
m	exponent of Reynolds number (–)
h	convective heat transfer coefficient (W/K·m^2)
q	wall heat flux
Pr	Prandtl number (–)
$Nu = hd/k$	Nusselt number (–)
$Re = \rho UD/\mu$	Reynolds number (–)

Greek letters

ρ	fluid density (kg/m^3)
δ	tube pitch
μ	dynamic viscosity (kg/m·s)
β	thermal expansion coefficient (K)$^{-1}$

Subscripts

1,2,3,4	serial number of tube bundles
m	mean value
R	tube-row spacing
in	inlet
out	outlet
B	big mass-block
S	small mass-block
E	heat exchanger
w	tube wall
t	tube bundle

Unlike the above-mentioned curved tubes, Cheng et al. [7] proposed the planar elastic tube bundle, which is a novel horizontal curved tube to enhance heat transfer. They consist of four horizontal curved tubes and two mass-blocks, a big mass-block and a small mass-block. Tian et al. [8] experimentally investigated the effect of pulsating flow on the heat transfer performance of planar elastic tube bundle. It was found that the augmentation of average convective heat transfer coefficient was about 30% by comparing the case without the pulsating flow. In addition to these two heat transfer experiments, most research was concerned with the vibration characteristic of planar elastic tube bundle [9–12]. In Yan's study [13], it was found that the complex three-dimensional vibration of tube bundle contained out-of-plane vibration and in-plane vibration. The amplitude of vibration indicated that the cross section diameter and mass-blocks dominated the vibration characteristic of planar elastic tube bundle.

As mentioned above, it is observed that the Reynolds number and geometry parameter play a significant role on the heat transfer. However, only two experiments are conducted on heat transfer in the shell-side of planar elastic tube bundle heat exchangers. Little attention has been paid to the effects of Reynolds number and geometry parameter on the shell-side heat transfer, especially the study on geometry parameter. Obviously, the manufacturing cost caused by the change of geometry parameter is a big obstacle in the heat transfer experiment. Compared to experiment, it has been proved that the numerical simulation is a convenient method to investigate the heat transfer [14]. Therefore, the aim of this work is to study the effects of Reynolds number, tube pitch and tube-row spacing on the shell-side heat transfer of planar elastic tube bundle heat exchanger using the numerical method. Variations of average convective heat transfer coefficient, pressure drop and comprehensive heat transfer performance are discussed. As a result, a correlation is developed to predict the shell-side Nusselt number using the multiple-regression analysis.

This paper is structured as follows: the shell-side geometry structure is presented in Section 2. Section 3 introduces the mathematical approach to solve this problem, mainly includes the conservation equations, boundary condition, data reduction. The numerical code is validated by comparing the numerical result with the experimental result. Then the results are presented and discussed in Section 4, in which the average heat transfer performance, average fluid flow performance and the comprehensive heat transfer performance are all studied in detail. As a result, a prediction correlation of average Nusselt number is obtained based on Reynolds number. At last, the conclusions are summarized in Section 5.

2. Physical model

The shell-side geometry of planar elastic tube bundle heat exchanger is shown in Fig. 1. The medium of heat exchange enters shell-side from the bottom inlet and outflows from the upper outlet. The heat exchange occurs when the medium cross-flow the planar elastic tube bundle. Six rows of planar elastic tube bundle are vertical arrangement in the shell-side. As shown in Fig. 1(b), planar elastic tube bundle is assembled with four curved tubes and two mass-blocks, a big mass-block and a small mass-block. The tube 1–4 is represented from inner to outer. The changes in geometry parameter are tube pitch δ and tube-row spacing H_R. Tube pitch varies from 20 mm to 30 mm and Tube-row spacing varies from 50 mm to 70 mm. In the present study, the main specific geometry parameters of the heat exchanger are shown in Table 1.

3. Mathematical approach

The fluid flow and heat transfer were analyzed using commercial computational fluid dynamics code (ANSYS CFX). Thus, the numerical simulation was conducted under following assumptions. The fluid flow and heat transfer within shell-side were fully developed. The thermal property parameter of fluid remained constant.

3.1. Conservation equations

This section provides the basic equations that must be solved to describe the velocity field and temperature distribution in the shell-side. The conservation equations are formulated in the Cartesian coordinate system because the Cartesian system is used in