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Research Paper

Numerical analysis on shell-side flow-induced vibration and heat transfer characteristics of elastic tube bundle in heat exchanger

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HIGHLIGHTS

- An appropriate meshing strategy was proposed for meshing convenience.
- A step calculation method was proposed for computing efficiency.
- The flow-induced vibration responses of the elastic tube bundle were studied.
- The heat transfer characteristics of the elastic tube bundle were studied.

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ABSTRACT

Based on the sequential solution of bi-direction fluid-structure coupling method, the shell-side flow-induced vibration responses and the heat transfer characteristics of the elastic tube bundles in heat exchanger have been investigated in this paper. Taking into account the meshing convenience and computing efficiency, appropriate meshing strategy and step calculation method have been proposed. Effects of shell-side water inlet velocity on the flow-induced vibration responses and heat transfer characteristics of the elastic tube bundle have been discussed. The results indicate that the mainly vibration of each tube bundle induced by the shell-side fluid is the out-plane vibration. The vibration amplitudes of the two stainless steel blocks are basically consistent when the shell-side fluid inlet velocity is lower, and the vibration amplitude of the stainless steel block III is more intense when the shell-side fluid inlet velocity is higher. In addition, the heat transfer coefficient of each elastic tube bundle has increased significantly at low flow rate (or low Reynolds number) when the shell-side flow-induced the elastic tube bundle vibration.

1. Introduction

Heat exchangers are widely used to achieve heat exchange [1,2]. By using flow-induced vibration to achieve compound heat transfer enhancement, the elastic tube bundle heat exchanger proposes an innovative research direction in passive heat transfer enhancement technology [3,4]. Instead of the traditional rigid heat transfer elements, the elastic tube bundle is used to enhances heat transfer with flow-induced vibration driven by the fluid around it [5]. Design of the elastic tube bundle heat exchanger should comply with the following principles: Within the range of parameters to meet the enhanced heat transfer, taking into account the fatigue life of the elastic tube bundle, the elastic tube bundle should achieve heat transfer enhancement without fatigue failure by reasonable excitation and appropriate control of the flow-induced vibration. Thus, study on the flow-induced vibration responses and heat transfer characteristics of the elastic tube bundle are the fundamental problems to design the elastic tube bundle heat exchangers [6].

Because of the complexity of the structure, the shell-side fluid domain, and the working conditions, it is very difficult to obtain exact analytical solutions to the flow-induced vibration responses and heat transfer characteristics. Up to now, researches on the flow-induced vibration responses and heat transfer characteristics of the elastic tube bundle have been the mostly experimental studies. Numerous experimental studies [7–10] show that the natural vibration mode of the elastic tube bundle can be divided into in-plane vibration (vibration in the plane of elastic tube bundle) and out-plane vibration (vibration perpendicular to the plane of elastic tube bundle). The tube sectional radius and the two stainless steel

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blocks have greater effects on the natural frequency of the elastic tube bundle, while the tube wall thickness has a smaller effect on the natural frequency. The elastic tube bundles in heat exchanger vibrate with low frequency and small amplitude. In addition, under the coupling-impact of shell-side and tube-side fluids with low flow rate, the heat transfer coefficient of elastic tube bundle increases significantly based on the technology of passive heat transfer enhancement. Moreover, the elastic tube bundle heat exchanger also has such functions as avoiding fatigue damage, reducing noise and removing fouling. Based on the elastic tube bundle heat exchanger and its working principles, through the tireless efforts of researchers, improved elastic tube bundle heat exchanger [11] and conical spiral tube bundle heat exchanger [12,13] have been proposed, and the flow-induced vibration responses and heat transfer characteristics of the heat transfer elements in different heat transfer equipment have been investigated. By setting up the test-bed of shell-side flow-induced vibration, the flow-induced vibration accelerations of the single-row elastic tube bundle under the impact of shell-side fluid have been tested, and the flow-induced vibration responses of the two stainless steel blocks under different shell-side water inlet velocities have been experimental studied [14]. In the numerical simulation research, based on the sequential solution of bi-direction fluid-structure coupling method, the flow-induced vibration responses of the elastic tube bundle under the impact of uniform shell-side fluid or/and tube side fluid have been investigated [15,16]. Numerical simulation results show that the flow-induced vibration amplitude increases with increasing shell-side or/and tube-side flow rate, and flow-induced vibration of the elastic tube bundle is the mainly in-plane vibration. Compared with the changes of tube-side fluid inlet velocity, the changes of shell-side fluid inlet velocity have greater influence on the vibration responses. This indicates that the vibration of the elastic tube bundle is mainly induced by the shell-side fluid.

By using the sequential solution of bi-direction fluid-structure coupling method, the shell-side flow-induced vibration responses and heat transfer characteristics of the elastic tube bundles in heat exchanger have been investigated in this paper. Taking into account the meshing convenience and computing efficiency, appropriate meshing strategy and step calculation method have been proposed. The research has important to the study of the mechanism of heat transfer enhancement, the improvement of heat exchanger, and the effective excitation and control of the flow-induced vibration.

2. Numerical simulation

2.1. Elastic tube bundle heat exchanger

Schematic diagram of the elastic tube bundle heat exchanger and the inside shell-side fluid domain is shown in Fig. 1. In order to facilitate meshing, the entire shell-side fluid domain is divided into a plurality of subdomains, including the upper head domain, the bottom head domain, the tube bundle domain, the additional upper domain, the additional middle domain and the additional bottom domain. Thus, different grid strategies can be used in the following meshing process according to the structural characteristics of each subdomain. In Fig. 1, x refers to the direction of the shell-side fluid.

In the following study, the inner diameters of the heat exchanger, the shell-side fluid inlet pipe and the shell-side fluid outlet pipe are 305 mm, 54 mm and 60 mm, respectively. The outer diameters of the tube-side fluid inlet and outlet standpipes are 45 mm. In addition, in order to facilitate analysis of the calculation results, the elastic tube bundles inside the heat exchanger are numbered sequentially as 1, 2, 3, . . . , 6 from the bottom head domain to the top head domain.

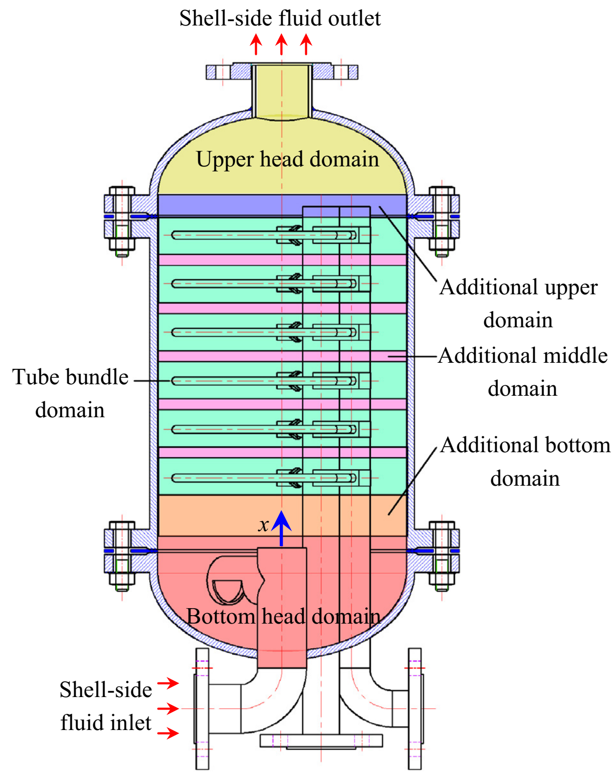

Fig. 1. Schematic diagram of the elastic tube bundle heat exchanger and the inside shell-side fluid domain.

Structures of the elastic tube bundle and the bottom head are illustrated in Fig. 2. The elastic tube bundle is composed of four bend copper tubes (bend radii: R_1, R_2, R_3 and R_4), and two stainless steel blocks (III and IV). I and II are two fixed ends, and they are mounted on the tube-side fluid inlet and outlet standpipes respectively. A_i and B_i are two monitor points on the ith row of elastic tube bundle, and they are applied to detect the displacements which are induced by the shell-side fluid. φ_1 is the position angle of block III. φ_2 and φ_3 are the installation angles of the two fixed ends. Detailed structural parameters of the elastic tube bundle during the study are shown in Table 1. In Table 1, l, w and h refer to the length, width and height of the stainless steel block respectively. In order to ensure that all components of the heat exchanger meet the installation rules, the size of the elastic tube bundle is less than that of the inner wall of the heat exchanger.

As shown in Fig. 2, the shell-side fluid inlet pipe is installed in the bottom head of the heat exchanger, and the inlet fluid has downward trend in the impact on the inner wall of the bottom head. m_1 and m_2 are the mounting positions of the tube-side fluid inlet standpipe. n_1 and n_2 are the mounting positions of the tube-side fluid outlet standpipe. y and z mean the Cartesian coordinates in the elastic tube bundle plane. o refers to the coordinate origin. θ is the position angle of the shell-side fluid inlet pipe. s is the distance between the shell-side fluid inlet pipe and the coordinate origin o. In the following study, m_1 = 85.0 mm, m_2 = 75.5 mm, n_1 = 48.0 mm, n_2 = 23.0 mm, θ = 45°, s = 76.25 mm.

2.2. Mathematical model and boundary condition

Based on the research questions in this paper, the whole solution domains are divided into fluid domain and structural domain. The sequential solving method of the bi-direction fluid-structure