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A study of the enhanced heat transfer of flow-induced vibration of a new type of heat transfer tube bundle—The planar bending elastic tube bundle

Yancai Su *, Mengli Li, Mingliang Liu, Guodong Ma

School of Mechanical & Automotive Engineering, Qilu University of Technology, Jinan 250353, China

HIGHLIGHTS

- This tube bundle's vibration modes contain transverse and longitudinal vibration modes.
- The fluid can induce this tube bundle vibration along all directions.
- The heat transfer enhancement effect of flow-induced the tube bundle vibration is obvious.

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ABSTRACT

Based on the idea of fully using flow-induced transverse vibration to enhance heat transfer, this paper proposes a new type of elastic heat transfer element—the planar bending elastic tube bundle. This elastic tube bundle has a large heat transfer area per unit volume and a small gap between the transverse and longitudinal stiffness. The inherent characteristics are numerically studied. The results showed that the natural vibration forms of the elastic tube bundle include the longitudinal vibration forms and the transverse vibration forms, and the two types of vibration modes appear alternately. In addition, the characteristics of flow-induced vibration and heat transfer are researched. Because the first two orders of the natural vibration modes are longitudinal vibration and transverse vibration, respectively, and the two vibration frequencies are low and similar, at the low flow velocity, the cross flow could induce the elastic tube bundle vibration along the three-dimensional directions. Along the *X* and *Z* axis directions, the two monitoring points *A* and *B* have the same vibration amplitude value and phase, whereas in the *Y* axis direction, the two monitoring points have a 180-degree phase difference, which is determined by the first-order and second-order natural vibration forms. The range of amplitudes of monitoring points *A* and *B* is from 2.3 mm to 5.3 mm, in agreement with the amplitude range of the heat transfer enhancement by flow-induced vibration. The effect of heat transfer enhancement of flow-induced tube bundle vibration is obvious. With the increase in flow velocity, the influence of tube vibration on heat transfer enhancement decreases greatly. Within the scope of this research, compared with the heat transfer of the still tube bundle in the same condition, the average heat transfer coefficient of the flow-induced planar bending elastic tube bundle vibration is 2.64 times that of the static tube bundle.

1. Introduction

Quite a large number of studies of flow-induced vibration showed that flow-induced vibration played a positive role in enhancing heat transfer. Because of the vibration of the heat transfer element, the turbulence of the flow field increases and the temperature layer thins, thereby greatly improving the heat transfer effect (Jiang et al., 2013; Cheng, 2001; Yan et al., 2016). With the parameters of flow field and vibration within a certain range, the vibration of the heat transfer element could enhance heat transfer, and the same heat transfer effects were obtained, regardless of which direction the heat transfer element vibrates along (Su et al., 2011). In some conditions, the heat transfer enhancement is up to 9 times (Yu et al., 2006). As a result, to optimally use enhancement heat transfer theory via flow-induced vibration in engineering practice, the most important issue is to study the structure of an elastic heat transfer element. This elastic

* Corresponding author.
E-mail address: boboxuanxuan1@163.com (Y. Su).

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Nomenclature

L	the length of the pipes, mm
d	the pipe diameter, mm
t	the wall thickness, mm
m	the weight of the joint body, kg
M	the mass matrix
C	the damping matrix
K	the stiffness matrix
P	the fluid dynamic pressure
u'	the velocity, m/s
R^T	the fluid solid coupling matrix
F_p	the structure internal force
F_f	the force fluid acting on the structure
the subscript f	is the fluid
the subscript p	is the structure
$C_{\varepsilon 1}$	$C_{\varepsilon 2}, \sigma_k, \sigma_\varepsilon$ the turbulent model constant
μ_t	the viscosity of turbulent flow
u_1	the viscosity laminar flow
k	the turbulent kinetic energy
ε	the turbulent kinetic energy dissipation rate
the subscripts o, p, w	are the three directions of the right angle coordinate
U	the flow velocity
h_0	the average heat transfer coefficient of the outer surface of the static tube bundle, W/(m^2·°C)
h	the period average heat transfer coefficient of the vibrating elastic tube bundle, W/(m^2·°C)
δ	the effect of heat transfer enhancement

heat transfer element can not only vibrate under the cross flow but also meets the requirements of fatigue strength. For this purpose, the structure of a planar elastic tube bundle is proposed (Cheng et al., 2009; Mao-cheng et al., 2000; Lin and Yan, 2003). The heat transfer and vibration characteristics of the bundle have been studied experimentally. The results showed that the heat transfer effect increased with the increase in the vibration frequency and amplitude when the vibration parameters were in a certain range. The characteristics of vibration and heat transfer of the planar elastic tube bundle in a heat exchanger have been studied via experimental and numerical methods. It was shown that the multiple rows of the planar elastic tube bundle could continuously vibrate along the transverse direction with the dominant frequency and a small amplitude, while the vibration along the longitudinal direction was random and weak, and the maximum heat transfer enhancement was 5.7% (Su, 2012). The vibration characteristics of the planar elastic tube bundle under the combined induction of shell-side and tube-side cross flows at different inlet water velocities have been studied using the weak coupling method of fluid-structure interaction (Ji et al., 2015). It can be concluded that the vibration of the planar elastic tube bundle was mainly induced by the shell-side cross flow, and its vibration forms were mainly determined by the low-order vibration modes. The transverse vibration amplitudes were found to be much larger than that in the longitudinal direction in the velocity range from 0.6 m/s to 1.2 m/s. Based on this, the reports in the literature (Ke et al., 2013, 2010; Ge et al., 2011a,b) proposed a new form of elastic tube bundle structure—the conical spiral tube bundle—and studied the characteristics of the inherent and flow-structure coupling vibration. It showed that the first-order natural vibration mode of this tube bundle was the out-of-plane vibration, and the second-order vibration mode was in-plane vibration. At low flow, its low-order natural frequencies were decreased by 30%, and the flow-induced vibration frequency was between the 1st and the 2nd natural frequency. In addition, no specific study on the effect of heat transfer enhancement is found in these literature studies. The above-mentioned several types of elastic tube bundles all have high lateral stiffness and low longitudinal stiffness. It is desirable to strengthen the heat transfer through flow-induced vibration with sustained, stable and reasonable vibration parameters. Through relevant research, we found that the transverse vibration has a higher contribution to the heat transfer enhancement of the elastic tube bundle relative to the longitudinal vibration. In addition, a large number of literature reports showed that the amplitude, frequency and vibration band width of flow-induced vibration along the transverse direction were larger than those of the longitudinal direction (Jauvtis and Williamson, 2003; Goncalves et al., 2013; Fang and Gu, 2008). From the discussion above, is it possible study a type of elastic tube bundle structure that makes full use of the transverse vibration to enhance the heat transfer and to promote the development of the research field of elastic tube bundle structure?

Based on the above discussion, a new type of elastic tube bundle—the planar bending elastic tube bundle—is proposed, as shown in Fig. 1. This elastic tube bundle has a large heat transfer area per unit volume and a low transverse stiffness. We can control the low-order natural frequency with the transverse mode of the tube bundle between 10 Hz and 20 Hz by modifying the parameters of the pipe, such as the outer diameter, wall thickness and space of the tubes. We also may control the flow-induced vibration amplitude value by adjusting the joint quality. The purpose is to cause the flow to induce the elastic tube bundle transverse vibration with the best amplitude and frequency to enhance heat transfer while meeting the requirements of the fatigue strength. Here, the characteristics of inherent, flow-induced vibration and heat transfer of the planar bending elastic tube bundle will be studied via a numerical calculation method to reveal its own rules.

2. The structure of the new heat transfer device

The structure of this new elastic tube bundle, named the planar bending elastic tube bundle, is shown in Fig. 1. The planar bending

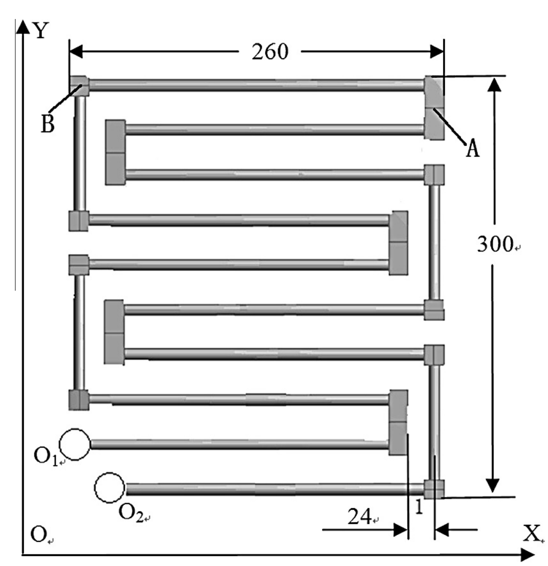

Fig. 1. Sketch of the planar bending elastic bundle.