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Numerical investigation on the heat transfer enhancement mechanism of planar elastic tube bundle by flow-induced vibration

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ABSTRACT

This work numerically investigated the heat transfer enhancement mechanism of planar elastic tube bundle by flow-induced vibration based on a two-way fluid structure interaction model. The unsteady, three-dimensional incompressible Navier-Stokes equation was solved with finite volume approach and the dynamic equilibrium equation of tube bundle was solved with finite element method combined with dynamic mesh scheme. Then the heat transfer performance was studied according to the field synergy principle. Synergy angle and Nusselt number were studied qualitatively and quantitatively from overall and local perspectives. Results show that improvement of field synergy and oscillating relative velocity are two crucial factors for heat transfer enhancement. Among which, the improvement of field synergy plays a dominated role on heat transfer enhancement. At the water velocity 0.15 m/s, the overall average Nusselt number is increased by 6.5%, and the overall average field synergy is improved by 6.01% with the tube vibration within the sub-millimeter level. In view of the shell-side geometry and vertical arrangement of tube bundle, the flow-induced vibration is conducive to the heat transfer enhancement of top tube bundle. The maximum heat transfer augmentation of 11.43% occurs around the fifth row tube bundle, and the maximum improvement of field synergy is 10.9% around the third row tube bundle.

1. Introduction

The occurrence of tube vibration induced by fluid flow is a common phenomenon in many engineering applications such as in heat exchangers, fluidized beds and nuclear steam generator [1–3]. The focus on suppressing flow-induced vibration attracts many researchers because of the tube fatigue failure resulted from the flow-induced vibration [4–6]. However, flow-induced vibration can be an alternative technique to enhance heat transfer with proper design. Thus it captures more and more attention to enhance heat transfer using flow-induced vibration. Go et al. [7] proposed a microfin array heat sink to enhance heat transfer using flow induced vibration in laminar flow. The dynamics of the microfin vibration was characterized by a microfin sensor. Compared to the plain-wall heat sink, the cooling enhancement was increased by 5.5% and 11.5% at the air velocity 4.4 m/s and 5.5 m/s, respectively. Park et al. [8] studied the effect of a vibrating flexible wing induced by a pulsating fluid flow on heat transfer using both numerical and experimental methods. The flexible wing was a novel milli-scale shape with a relatively large body and a narrow connecting leg. Results showed that the heat transfer coefficient of flexible wing was increased by 11.3% than that of a flat plate. Tan et al. [9] carried out a numerical simulation on the unsteady fluid flow and heat transfer performances induced by the resonating cantilever beam at different flexural modes and opening inlets. Results showed that the deformation of cantilever beam dominated the flow patterns, resulting in different heat transfer augmentation at different resonance modes. 1.7–3.1 at the first mode and 1.7–2.7 at the second mode for heat transfer augmentation ratios were achieved by comparing to the natural convective heat transfer. Shi et al. [10] numerically studied a passive heat transfer enhancement method via vortex-induced vibration based on a two-dimensional model at four different Reynolds number and two inlet temperature profiles. Results showed that the heat transfer rate was increased due to the disruption of thermal boundary layer by vortex-induced vibration. Average Nusselt number showed that the vortex-induced vibration played a significant role on heat transfer and a maximum enhancement of

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Nomenclature

R	radius of curvature [m]
A	surface area of tube bundle
D	diameter dimension [m]
u,U	fluid velocity [m/s]
E	elastic modulus [Gpa]
L	length dimension [m]
W	width dimension [m]
H	height dimension [m]
t	time [s]
k	thermal conductivity of fluid [W/K·m]
$p(P)$	static pressure [Pa]
T	temperature [K]
ΔT	period of time integration
M	mass matrix [−]
C	damping matrix [−]
K	stiffness matrix [−]
R^T	coupling matrix [−]
C_p	specific heat at constant pressure [J/(kg·K)]
$Nu = hd/k$	local Nusselt number [−]
$\overline{Nu}$	time-averaged Nusselt number [−]
$\langle Nu\rangle$	surface-averaged Nusselt number [−]
$\overline{\langle Nu\rangle}$	time-and-surface-averaged Nusselt number [−]
n	normal direction to the tube wall

Greek letters

σ	stress
ν	poisson ratio
ρ	fluid density [kg/m^3]
μ	dynamic viscosity [kg/m·s]
α	tube row spacing
θ	synergy angle/°
δ	tube pitch

Subscripts

w	tube wall
s	structure domain
f	fluid domain
t	tube bundle
E	heat exchanger
i,j	velocity vector in x,y and z direction
c	copper tube
m	mass-block
B	big mass-block
S	small mass-block
in	inlet
out	outlet

90.1% was achieved in their study.

It is noted that the above-mentioned researches mainly focus on the simple equipment or a two-dimensional numerical model. Cheng et al. [11] proposed a complex planar elastic tube bundle, which has been used in engineering, to enhance heat transfer using flow-induced vibration. Heat transfer experiment showed that the overall heat transfer coefficient was increased compared to the heat exchangers with fixed planar elastic tube bundle. Tian et al. [12] experimentally evaluated the heat transfer enhancement of planar elastic tube bundle under the pulsating fluid flow. The pulsating fluid flow was generated by a triangular pole device in the inlet region. Experimental results showed that the pulsating fluid flow dominated the vibration of tube bundle. The average heat transfer coefficient was enhanced by 30% compared to the condition without the pulsating fluid flow. Despite many works, which have studied the planar elastic tube bundle, far fewer works have focused on the overall heat transfer performance of planar elastic tube bundle by experimental method [13,14], and those many works, mostly have concentrated on the vibration characteristic of planar elastic tube bundle. Among them, experimental works of Zhang et al. [15], Jiang et al. [16], and numerical studies of Zheng et al. [17,18], Yan et al. [19,20] were noticeable. Results indicated that the vibration of planar elastic tube bundle consisted of out-of-plane vibration and in-plane vibration, both vibration modes were beneficial to heat transfer enhancement.

Clearly, many researches on planar elastic tube bundle have conducted and obtained such results by experimental and numerical method. However, the mechanism of heat transfer enhancement has not been clearly interpreted due to the complexity of flow-induced vibration, which belongs to the problem of fluid structure interaction (FSI). It is indispensable to analyze the flow-induced vibration of tube bundle using the FSI analysis procedure. This FSI evaluation involves on the one hand fluid dynamics calculation for fluid flow characteristics and on the other hand structural analyses for tube vibration [21]. Therefore, in order to gain a better understanding of the heat transfer enhancement by flow-induced vibration, a two-way FSI model of planar elastic tube bundle is presented in the present work. The unsteady, three-dimensional incompressible Navier-Stokes equation is solved by finite volume approach and the dynamic equilibrium equation of tube bundle is solved with finite element method combined with dynamic mesh scheme [22]. Then the field synergy principle is selected to study and discuss the heat transfer enhancement of planar elastic tube bundle from overall and local perspectives. The temperature field and fluid velocity distribution in fixed and vibrational tube bundle conditions are compared qualitatively. The average Nusselt number and synergy angle for overall and single-row tube bundles are presented quantitatively.

The organization of this paper is as follows: the physical mode is introduced in Section 2; the numerical approach is described in Section 3, mainly includes the conservation equations, grid system and boundary conditions, numerical procedure and validation, grid independence and field synergy principle; the result and discussion are presented in Section 4, in which the temperature field, fluid velocity distribution, overall and local average Nusselt number and synergy angle are all discussed; and final conclusions are provided in Section 5.

2. Physical model

Fig. 1 (a) shows the heat exchanger with six-rows planar elastic tube bundle, which is vertical arrangement with the row number $\alpha_{1\sim6}$ from bottom to top in shell-side. The tube-row spacing α 60 mm is used in the present work. Fig. 1 (b) indicates the planar elastic tube bundle with four curved copper tubes and two mass-blocks, a big mass-block and a small mass-block. The innermost and outermost tubes are fixed on the pipe of tube-side. The diameter of tube is D_t with the radius of innermost tube R and the tube pitch δ. The specific detailed geometry parameters of shell-side and planar elastic tube bundle are shown in Table 1.

For heat exchange, hot water enters from the bottom tube-side inlet and cold water enters from the shell-side inlet. Heat exchange

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