Study on Vibration and Heat Transfer Performances of a Modified Elastic Tube Bundle Heat Exchanger

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Abstract. Based on the bi-directional fluid-structure coupling method, the vibration and heat transfer performances of a modified elastic tube bundle heat exchanger are studied. The vibration frequency and amplitude of tube bundle are compared between different directions and tube row spacing. Furthermore, the Nusselt number of tube bundle are studied in vibrational and non-vibrational cases. The numerical results represent that the vibration amplitude of tube bundle is the largest in the $z$ direction, which is 7.25 times that in the $y$ direction (direction of the smallest amplitude). In the calculation scope, the vibration frequency and amplitude increase with tube row spacing. From 50 mm to 90 mm spacing, the vibration frequency and amplitude increase by 21.88% and 10.65%, respectively. The Nusselt number under the fluid-induced vibration increases up to 11.67% compared with non-vibration. Besides, the Nusselt number of tube bundle in the middle part is lower than that at the two ends. Within 50-90 mm interval, the enhanced heat transfer effect rises along with tube row spacing. The rising rate of the Nusselt number increases by 52.4% in the range of computation.

1. Introduction

As an energy exchange equipment, heat exchanger [1-2] is widely used in energy, machinery, chemical industry and other fields. When traditional shell-and-tube heat exchanger works, shell-side and tube-side fluid impact on the internal stainless steel tubes. This will cause the vibration of the stainless steel tubes, and then affect its service life [3-4]. To solve this issue, by replacing stainless steel tubes with copper ones, Cheng et al. [5-6] proposed an elastic tube bundle (ETB) heat exchanger. The ETB heat exchanger does not focus on preventing vibration caused by fluid media, but makes highly use of this vibration to improve heat transfer performance. However, because of the structural limitations of the ETB, the vibration performance is not obvious at low flow velocity. Therefore, it is of great significance to modify the structure of the ETB. And also, further research on the vibration and heat transfer performances of the modified elastic tube bundle (METB) heat exchanger induced by the internal fluid media has important theoretical significance and practical value.

Yan et al. [7] proposed a space cone-spiral ETB heat exchanger, and the vibration characteristics under induction of shell-side fluid were studied. The study showed that the vibrational unevenness of the space cone-spiral ETB promoted with the growing of the entrance flow velocity. For the purpose of improving the general heat transfer characteristics of ETB heat exchanger, Ji et al. [8-10] put forward a spiral elastic tube bundle suitable for ETB heat exchanger. In addition, the fluid-induced vibration (FIV) and heat transfer properties of that were studied. The results showed that the vibration
was most violently in the middle parts and mainly out-plane vibration. Su [11] tested the FIV response of the single-row ETB by setting up a vibration test bench. The test indicated that the vibration of ETB had obvious harmonics at low flow velocity. On the other hand, by studying the temperature field, Duan et al. [12-14] found that proper arrangement of ETB in the heat exchanger could improve its heat transfer performance and efficiency.

On the basis of the traditional ETB, the structure of the tube bundle is modified. Then, based on the bi-directional fluid-structure coupling method, the vibration and heat transfer performances of the METB heat exchanger are analyzed in this paper.

2. Model and method

2.1 METB heat exchanger model
Figure 1 manifests the overall structure of the METB heat exchanger. Meanwhile, the specific structural model of the METB is also shown in that. It can be seen from the Fig. 1 that the METB consists of four copper coils, which are connected by three stainless steel blocks (I, II, III).

![Figure 1. The specific structure of the METB heat exchanger](image)

When the METB heat exchanger is working, the shell-side fluid flows into the inside of heat exchanger from the shell-side entrance at the bottom, then impacts each METBs in turn, and finally flows out from the shell-side exit at the top. Meanwhile, the tube-side fluid flows into the inside of heat exchanger from the tube-side entrance on the left, then goes into the inside of the METBs, and finally flows out from the tube-side exit on the right. When the shell-side and tube-side fluid have different temperatures, the heat exchange can be realized through the copper METBs. Owing to the coupling impact of the shell-side and tube-side fluid, the METBs vibrated slightly and the heat transfer performance is promoted. Compared to the traditional ETB, the METB has a lower natural frequency, therefore, it's easier to vibrate at low flow velocity. Studies [2, 8] have shown that shell-side fluid is the major factor of FIV, thus this paper only considers the vibration and heat transfer performances under the influence of shell-side fluid.

2.2 Calculation model
Figure 2 is the calculation domain model of the shell-side flow field. For ease of expression, METBs are numbered 1 to 6 from right to left. Each METB is installed on the horizontal pipes at the same tube row spacing (H). The tube row spacing used in the calculations includes 50mm, 70mm, and 90mm. The specific structural parameters in this paper are shown in Table 1.

2.3 Calculation method
Considering the shell-side fluid would take some time to reach a stable state, the method of first rough calculation and then accurate calculation is adopted. The rough calculation total time is 300 seconds to make sure the shell-side fluid can flow fully in the fluid domain. In the accurate calculation process,
the results obtained above are used as the initial conditions of this calculation. At the same time, the structure field and fluid field are calculated in 1200 steps with 1.2s total time and 0.001s time step.

![Figure 2. The calculation model of the METB heat exchanger](image)

| Parameter                     | Value           | Parameter                     | Value           |
|-------------------------------|-----------------|-------------------------------|-----------------|
| Shell-side space length $L_f$ | 540 mm          | Radius of curvature $R_1, R_2, R_3, R_4$ | 70, 90, 110, 130 mm |
| Shell-side space diameter $D_f$ | 300 mm          | Stainless steel dimensions, (length, width, height) | 40, 20, 20 mm   |
| Entrance diameter $D_i$       | 34 mm           | Installation angle $\phi$     | 30°             |
| Exit diameter $D_o$           | 34 mm           | Tube bundle radius $r$        | 5 mm            |
| Horizontal tube length $L_c$  | 495 mm          | Tube bundle thickness $\delta$ | 1.5 mm          |
| Horizontal tube diameter $D_c$| 30 mm           |                               |                 |

Figure 3 shows the specific calculation process. Firstly, the elastic bundle is modeled and messed. Then incipient boundary condition is applied to the fluid domain and the CFX solver is used to finish the rough calculation. The obtained force is transferred to structural domain through FSIs as initial condition. ANSYS solver calculates the vibration equations of METBs and transfers the bundle displacements to fluid domain through FSIs to obtain the new flow field distribution. Then the CFX solvers recalculate the new bundle force, and so on repeatedly until the end of entire calculation.

![Figure 3. Fluid-structure coupling calculation process](image)

The boundary conditions of the structural domain are set as the followings: the two extremities of METB are fixed supports, and the outer surface is used as fluid-structure interaction (FSI). The gravity direction is setting up -y direction, meanwhile, the gravitational acceleration is 9.8 m/s². On the other
hand, fluid domain boundary conditions are the following: the entrance boundary provides the entrance flow velocity and temperature. The relative pressure of the exit surface is set to 0 Pa. The internal walls of fluid domain are set to fluid-structure interactions, which are consistent with the structural domain. The shell-side fluid is set to be incompressible and its turbulence intensity is 0.048.

2.4 Grids and numerical code validation

Figure 4 signifies the grid division of the calculation model. In Fig. 4 (a), the shell-side fluid domain is divided into tetrahedral grids. To improve the accuracy of the calculation results, ten boundary layers are set in the near-wall domains. In Fig. 4 (b), the METB is divided into hybrid grids. The grid type of the bent copper bundle is hexahedron, while the stainless steel block mesh is tetrahedral.

![Grid division of the calculation model](image)

In order to select the appropriate grid density, three different grid conditions are selected to study the relative errors of pressure drop and the Nusselt number. Grid independence verification results are shown in Table 2. When the number of grids is 823.96 million, the relative errors of pressure drop and the Nusselt number are less than 1.0%, however, the calculation time is 1.87 times that of Case II. Therefore, considering the calculation precision and calculation time comprehensively, the grid division method of Case II is applied for the after study.

| Case | Mesh number | Pressure drop Value | Error (%) | The Nusselt number of tube Value | Error (%) |
|------|-------------|---------------------|-----------|---------------------------------|-----------|
| I    | 5,145,726   | 213.15              | 2.88      | 8.925                           | 2.37      |
| II   | 6,970,920   | 219.47              | -         | 8.946                           | -         |
| III  | 8,239,582   | 217.39              | 0.94      | 9.010                           | 0.72      |

So as to ensure the accuracy of this analysis method, new calculation domain grids are divided in view of the meshing strategy in this paper. Comparing with the experiment of Su Yancai on single-row elastic bundle [11], vibration frequency and y-direction acceleration of the two monitor points under two flow velocities are shown in Table 3. And that signifies the simulation results are generally in consistency with the experimental ones. In particular, relative errors are less than 10%. Therefore, the accuracy of the analysis method used in this paper can be confirmed.

| Velocity (m/s) | Monitor point | Vibration frequency (Hz) | Vibration acceleration (m/s²) |
|---------------|---------------|--------------------------|------------------------------|
|               | | Simulation result | Experimental data | Error (%) | Simulation result | Experimental data | Error (%) |
| 0.2           | A             | 28.8                     | 28.0                   | 2.78      | 0.094             | 0.088               | 6.38      |
|               | B             | 29.5                     | 29.0                   | 1.69      | 0.088             | 0.082               | 6.82      |
| 0.4           | A             | 28.6                     | 28.0                   | 2.10      | 0.365             | 0.340               | 6.85      |
|               | B             | 29.8                     | 29.0                   | 2.68      | 0.396             | 0.375               | 5.30      |
3. Results and discussion

3.1 Vibration performances of the METB heat exchanger

For studying the vibration of the METB in different directions, take the stainless steel III of the fourth row bundle as an example to make its vibration spectrum in the $x$, $y$, $z$ directions. At this time, the entrance flow velocity is 0.5 m/s and tube row spacing is 90mm. The study results are shown in Fig. 5.

![Figure 5. Vibration spectrum of the fourth row bundle](image)

Figure 5 shows the vibration amplitude of METB is the largest in the $z$ direction (0.413 mm) and the least in the $y$ direction (0.057mm). Moreover, the vibration frequency in the $y$ and $z$ direction are both 16.84 Hz, but that in the $x$ direction changes to 20.2 Hz, increasing by 19.95%. The occurrence of this situation is related to the impact of shell-side fluid, because the main impact direction is the $z$ direction and the force of tube bundle is the largest in this direction, thus its amplitude value is the largest among all the three directions. As the stainless block III is close to fluid domain boundary, its vibration is influenced by the backflow impact of shell-side fluid. As a result, the vibration frequency in the $x$ direction is increased.

Figure 6 demonstrates the variation of FIV frequency and amplitude under the conditions of 0.5m/s entrance flow velocity and different tube row spacing ($H=50-90$mm). The following conclusions can be drawn from that figure:

![Figure 6. Influence of tube row spacing on vibration frequency and amplitude](image)

(1) Within 50-90 mm row spacing, the vibration frequency increase with the rising of the spacing. At 50mm spacing, the vibration frequency of the METB is 17.96 Hz. From 70 mm to 90 mm spacing, vibration frequency enhances from 21.89 Hz to 22.28 Hz, increased by 21.88%.

(2) In the calculation range of this paper, the vibration amplitude keeps the same trend with frequency. When the spacing is 50 mm, vibration amplitude of the METB is 0.0836 mm. While the spacing rises to 90 mm, the amplitude increases with a 10.65% change rate.
(3) The reason for above phenomenon is that: as the spacing increases, the difference between the FIV and inherent frequency of the METB becomes smaller and smaller. At 50mm spacing, the vibration frequency (17.96 Hz) is far away from the first-order inherent frequency (16.88 Hz), so that the vibration amplitude is the least at this time. At 90mm spacing, the vibration frequency (21.89 Hz) nears the fourth-order inherent frequency (22.28 Hz) with a difference of 1.75%, therefore, the vibration amplitude is the largest at this spacing.

3.2 Heat transfer performances of the METB heat exchanger

Figure 7 expresses the Nusselt number changes with the number of the METB under the condition of 0.5 m/s entrance flow velocity and 90mm tube row spacing. As shown in Fig. 7, after the influence of FIV, the Nusselt number of METB increases in different degrees, where the enhanced heat transfer effect (11.67%) of the second row is the most obvious. Furthermore, the Nusselt number of tube bundle in the middle part is lower than that at the two ends. Because the METB at the two ends is close to the entrance and exit of the fluid domain, whose field distribution is more concentrated than the middle part. Hence, two ends of the METB heat exchanger have higher heat transfer performances.

![Figure 7. Nu with the number of METB under vibration and non-vibration](image)

Figure 8 indicates the influence of tube row spacing on the vibration Reynolds number (\(Re_v\)) and change rate of the Nusselt number (\(Nu\)) at 0.5 m/s entrance flow velocity. As can be seen from that, within 50-90 mm tube row spacing, the change rate of the Nusselt number shows a rising trend. At 50 mm spacing, the Nusselt number rises by 2.9% while the change rate becomes into 6.1% at 90 mm spacing. Vibration Reynolds number sizes the influence of vibration amplitude and frequency, and previous studies [15, 16] have shown that it’s extremely significant in enhancing heat transfer. The \(Re_v\) of 90mm row spacing is the largest, which means FIV at this time is the most violent. The surface of METB cannot form a stable boundary layer, thereby greatly reducing the thermal conductivity of the surface layer. Consequently, the enhanced heat transfer effect is the most obvious.
4. Conclusions

Based on the bi-directional fluid-structure coupling calculation method, the vibration and heat transfer performances of the METB heat exchanger under the influence of shell-side fluid are studied. In addition, the influences of tube row spacing on the vibration frequency, amplitude and enhanced heat transfer effect are researched respectively. The research conclusions are the followings:

(1) The vibration of METB is most violently in the z direction, which is 7.25 times that in the y direction. Besides, the vibration frequency is 20.2 Hz in the x direction and 16.84 Hz in the others.

(2) Within 50-90 mm tube row spacing, the frequency and amplitude of FIV advanced with a rate of 21.88% and 10.65% respectively.

(3) After the influence of FIV, the Nusselt number promotes inordinately. Furthermore, the enhanced effect of the second row is the most obvious. Besides, the Nusselt number at two ends of the METB exchanger is higher than the middle part.

(4) In the calculation scope of this paper, the enhanced heat transfer effect promotes with the row spacing. The rising rate of the Nusselt number from 50 mm to 90 mm spacing increases by 52.4%.

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