Experimental investigation on the flow-induced vibration of spatial bended section of heat exchanger tubes

Guangdong Song *, Lina Zhu, Mengmeng Liu, Huajin Yu, Lijun Zhou and Xiuyan Gong

China Institute of Atomic Energy, Beijing, China

*Corresponding author e-mail: songguangdong1986@ciae.ac.cn

Abstract. Flow induced vibrations in heat exchanger tubes have led to numerous accidents and economic losses in the past decades. The vibration characteristics of traditional heat tubes have been studied comprehensively through experiment, numerical simulations and theoretical analysis. Special tubes with spatial bended forms possess the great performance in nuclear engineering. The present work is motivated to understand the unclear flow-induced vibration features of these original heat exchanger tubes. An experimental system including of the tested objects are designed in water environment. The vibration responses and frequencies of spatial bended section of the heat exchanger tubes are tested and analysed. The results show that the spatial-bended tubes are safe enough to suffer the water flow within the velocity of 1m/s. The considerable vibration responses are in the bended areas with square configure, which should be specifically designed. The present work can be a guide for the special heat exchangers in nuclear engineering.

1. Introduction

Flow-induced vibrations in heat exchangers have been a major cause of concern in the nuclear industry for several decades. Many incidents of failure of heat exchangers due to apparent flow-induced vibration have been reported. Some examples of tube failures in commercial steam generators are reported in the review by Pettigrew and Taylor [1, 2] and Paidoussis [3]. Mechanisms underlying fluidelastic instability were elucidated in the theoretical work of Chen [4, 5]. Shell and tube type heat exchangers experience flow-induced vibration due to high velocity flow over the tube banks. Flow-induced vibration in these structures is caused by three mechanisms: vortex shedding that leads to vibration due to vortices shed when a fluid flows over a bluff structure, fluid-elastic instability where vibrations are caused as a result of the competition between the energy input by the fluid and the energy expended in damping by the structure, and turbulent buffeting.

There are many experiments were carried out to investigate the flow-induced vibration of tubes, including of U-bend tubes and normal straight tubes [6, 7]. Visual observation of tube motion in single phase flow was made by Chen and Jendrzejcyk [8]. They observed the motion of the tubes in an array in synchronous orbits. Lever and Weaver [9] showed that relative motion of tubes was not necessary for fluid-elastic instability except for cases where neighboring tubes were very slightly detuned from each other.
The spatial bended tubes are arranged in concentric-circle configures with a mixed cross-flow and in-flow operating condition, which are in good heat exchanger ability and strong mechanical performance. These typical tubes are gradually wide used in nuclear equipment. However, to the author’s knowledge, the flow-induced vibration of special spatial bended tubes has not been reported. The vibration responses and features need to be tested actually, especially in the bended area. Moreover, the safety margins of this typical structure should be estimated before it is applied in nuclear engineering. Therefore, the current experiment is conducted to answer the question, and it will contribute to the design of such heat exchangers.

2. Experimental setups

2.1. Model tests
In order to obtain the natural vibration characteristics of heat exchange tubes, modal tests are carried out on heat exchange tubes in air. The heat exchange tube structure tested in this experiment is light and small, and the excitation energy and frequency width of force hammer can meet the requirements, so the force hammer excitation is selected in the modal test. In order to avoid the excitation point being a node, the multi-point excitation measurement method is adopted. In the modal test, four measuring points are set at the middle of the second~fifth span of the heat exchange tubes. Two acceleration sensors are arranged at each measuring point to test the horizontal and vertical vibration respectively. The test system and the location of the test points are shown in Figure 1.

Figure 1. The test system and the location of the test points of model test

2.2. Flow-induced vibration tests
The test loop is a special test device for fluid-induced vibration response under normal temperature water condition as shown in Figure 2. The experimental device consists of main circulation system, mixed flow and voltage stabilizing system, vibration measuring system, instrument and meter system, control and data acquisition system, electrical system and other branch systems.
Figure 2. Flow-induced vibration test loop

The Flow-induced vibration sample in the test section and the location of test points are shown in Figure 3, and the section is a fan section. Manholes should be set at the bottom of the flow passage in the test section so as to realize the accurate connection and installation of the lower tube plate. Windows should be opened in key parts of the test section to observe the condition of tubes and test elements. Acceleration sensors and strain gauges are used in this test for evaluate vibration characteristic of the bended section of the tubes. In order to reduce the influence of sensors on the flow field morphology between tubes, acceleration sensors were installed inside the heat exchange tube.

Figure 3. Flow-induced vibration test section and the location of the test points
3. Results and discussions

3.1. Natural frequency
A total of 6 heat exchange tube bundles arranged in a square were carried out modal test this time. Generally speaking, the first-order natural frequency is the smallest, and the first-order vibration mode shows that maximum amplitude of the first-order vibration at the time appear in the second cross the cross position, and in the radial direction. Therefore, when hitting the second cross by the direction of the acceleration sensor 1, the resulting frequency value is its first natural frequency. The first natural frequency of the heat exchange tube tested is 107.12Hz.

3.2. Damping ratio
After analysis and calculation of the experimental data, statistical data of the damping ratio were obtained, as shown in Table 1, where "-" indicated that the data effect of the channel was poor and the corresponding damping ratio could not be obtained. In the modal test of fluid induced vibration sample, the damping ratio of each order should decrease gradually in theory, and be influenced by material properties, structural characteristics, constraints, models and environmental noise, and other factors. Therefore, the modal analysis to identify the damping ratio is high uncertainty and randomness, get the damping ratio of discrete degree is far higher than the natural frequency of the discrete degree. In this experiment, the random subtraction method (RDT) was used to calculate and analyze the first-order damping ratio of the heat exchange tube beam.

Table 1. Damping ratio of heat exchanger tube in air environment

| Span/direction | 1  | 2  | 3  | 4  | 5  | 6  |
|---------------|----|----|----|----|----|----|
| Location      | 1  | 2  | 1  | 2  | 1  | 2  |
|               | 2  | 3  | 4  |    |    |    |
| 1             | 0.005 | 0.0049 | 0.0048 | 0.0054 | 0.0031 | 0.0054 | - | 0.0053 |
| 2             | 0.0033 | 0.003 | 0.0023 | 0.0034 | 0.0018 | 0.0033 | 0.0028 | 0.0029 |
| 3             | 0.012 | 0.0126 | 0.0086 | 0.0088 | 0.0089 | 0.0084 | 0.0076 | 0.0131 |
| 4             | 0.0048 | 0.0061 | 0.0051 | 0.0049 | 0.0043 | 0.0025 | 0.0044 | 0.0059 |
| 5             | 0.0084 | 0.0032 | 0.0061 | 0.0087 | 0.0073 | 0.0072 | - | 0.0024 |
| 6             | 0.0069 | - | 0.0041 | 0.006 | 0.0052 | 0.0057 | 0.0068 | 0.0052 |

3.3. Vibration responses in spatial bended parts
The measuring points are arranged in the middle of the span and the bend section of the seven tube bundles in the square arrangement. Among them, the mid span measuring points are uniaxial strain gauges to measure the strain in the main vibration direction, and the bending section measuring points are biaxial strain gauges to measure the strain in two orthogonal directions (the number of measuring points is (1) and (2)). A total of 45 effective measuring points were obtained in this experiment. The axial position and naming of each measuring point are shown in Figure 4 (e). Based on the simply supported beam model, the converted RMS amplitude values of all measuring points are shown in figure 4 (c) ~ (d).
According to the criterion: the maximum amplitude of heat exchange tube in the spatial part is calculated as:

$$\frac{y_{\text{max}}}{d_0} = \frac{180 \times 10^{-6} \text{m}}{16 \times 10^{-3} \text{m}} = 0.011 < 0.02$$

Therefore, the vibration amplitude of the tube is very small and will not cause damage to the tubes. The maximum vibration amplitude of the flow-induced vibration of the heat exchange tube meets the design requirements.

### 3.4. Vibration frequency analysis

Spectral analysis was performed on all acceleration sensor signals, and the frequency range of analysis was 0–200Hz. Corresponding characteristic frequency points were obtained through frequency domain analysis and statistics. When analyzing the characteristic frequency of the bundle, the filter method was adopted to remove the noise vibration brought by additional systems such as pipelines and pumps. The frequency domain results of noise vibration are shown in Figure 5. The response frequency in the transverse flow direction at the outlet of tube 7-8 at the flow rate of 449 m3/h in the inlet is taken as an example, as shown in the following Table 2.

![Figure 4. The mid-span amplitude response of the square arrangement bundle](image)

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Table 2. Response frequency of heat exchange tube bundle and pipeline

| Location          | Tube 7-8                          | Piping and pump |
|-------------------|-----------------------------------|-----------------|
| Frequency/Hz      | 24.62864                          | 24.64294        |
|                   | 131.4402                          | 49.31946        |
|                   | 147.7766                          | 73.99292        |
|                   | 183.6395                          | 123.6868        |
|                   | 186.6841                          | 172.8964        |
|                   | 188.179                           | 131.4402        |
|                   | 190.5131                          | 147.7766        |
|                   | 192.1415                          | 183.6395        |
|                   | 193.5959                          | 186.6841        |
|                   | 196.7883                          | 188.179         |
|                   | 197.3844                          | 190.5131        |
|                   | 199.7828                          | 192.1415        |

It can be seen from the Figure 6 that the vibration frequency of square arrangement is basically distributed in three regions, which are about 149Hz, 160Hz and 200Hz respectively, and it is mainly distributed in the high frequency region in the case of large flow rate.

Figure 6. Characteristic frequency of vibration caused by square arrangement flow

4. Conclusion
The flow-induced vibration characteristics of the spatial-bended tubes arranged in concentric circle are experimentally investigated. The tubes of the heat exchanger are arranged in approximate square configure. The vibration responses and frequencies in the bended areas are tested and analyzed. Main conclusions are summarized as follows:

1) The first natural frequency of the heat exchange tube spatial bended section is 107.12Hz and the natural frequency of different layers of the same heat exchanger has little difference.

2) The max ratio of vibration amplitude to pipe diameter in spatial bended areas of square arrangements is the 0.011, which meets the design requirements and should be most concentrated while operating at larger flow range.

3) As for the vibration frequency distributions, the frequencies in square configure concentrate on three bands, 149 Hz, 160 Hz and 200Hz, respectively that should be considered in heat exchanger design.
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