DRAFT: EXPERIMENTAL STUDY ON FLUIDELASTIC INSTABILITY OF ROTATED TRIANGULAR TUBE BUNDLES SUBJECTED TO TWO-PHASE CROSS FLOW

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ABSTRACT
Fluidelastic instability is one of the main vibration mechanisms that cause damage of steam generator tube. Connors relation based on quasi-static fluid forces is widely applied to research fluidelastic instability. In this paper, fluidelastic instability experiments were conducted on rotated triangular tube array subjected to air-water cross-flow. The test section was equipped with 7 columns and 15 rows straight tube bundles. The pitch-to-diameter ratio of bundles is 1.48 and the tube diameter is 17.48 mm. Two different frequencies of tube in the lift direction were tested. Critical velocity of fluidelastic instability, damping and hydrodynamic mass of tube bundle were measured in these void fraction of 0, 20%, 40%, 60%, 80% and 90%. Connors relation was fitted according to the data obtained. The results show that, critical velocity increases with the increase of void fraction for tube bundle with the same frequency. Critical velocity varies inversely with natural frequency of tube for the same void fraction. While void fraction is less than 20%, vortex shedding occurs in the tube bundles. With the increase of void fraction, the damping ratio increases first and then decreases. The damping ratio reaches the maximum value at void fraction of 60%. Fluidelastic instability constant $K$ fitted for two different frequencies of tube are both greater than 4.75.

NOMENCLATURE
- $\varepsilon_g$: flow homogeneous void fraction
- $Q_g$, $Q_a$: water flow and air flow, respectively
- $V_c$, $V_p$: freestream velocity and pitch velocity, respectively
- $V_{pc}$: critical pitch velocity
- $A_c$: free stream cross-sectional area
- $P$: pitch of tube array
- $D$: diameter of tube
- $\rho_h$, $\rho_w$, $\rho$: air density, water density and fluid homogeneous density, respectively
- $m$, $m_h$: tube mass and hydrodynamic mass, per unit length, respectively
- $f$, $f_v$: tube frequency in air and in homogeneous flow, respectively
- $V_{pc} / (fD)$: dimensionless velocity
- $2\pi \zeta m / \rho D^2$: dimensionless mass damping parameter
- $K$: Connors' constant
- $\zeta$: total damping ratio in two-phase

1 INTRODUCTION
Steam generator (SG) is one of principal components of nuclear power plants. Collision and abrasion between heat transfer tube of SG and support because of undergoing high velocity two-phase cross-flow, which make the tube wall thinned and even perforated, affect the service life and safety of the steam generator. It is well known that fluidelastic instability is one of principal two-phase flow-induced vibration mechanisms that damages the tube of SG. If fluidelastic instability occurs in tube bundles, the tube failure in a short time. The quantitative relationship between dimensionless velocity $V_{pc}/fD$ and dimensionless mass damping parameter $2\pi \zeta m / \rho D^2$ was first proposed by Connors in 1970 according to the principle of energy balance. The equation suggested by Connors is widely used in evaluation of fluidelastic instability
for SG design. The key for evaluation is to get the Connors coefficient $K$ and $n$, which depend on tube diameter, pitch, array arrangement, void fraction, velocity, density and flow direction.

For a period of time, a lot of research on the Connors coefficients was done for various tube bundles with different arrangement and pitch-to-diameter ratios. Pettigrew performed experiments for various cantilever tube bundles with different tube array types and pitch-to-diameter ratio ($P/D$) in air-water, Freon-22, and Freon-134a two-phase flows\(^1\)\(^-\)\(^3\). A guideline for evaluation of fluidelastic instability was presented\(^3\). Test on the damping ratio and the instability constant of a normal square array tube bundle at prototypical high temperature and pressure steam-water flow condition were performed\(^5\). Experimental results for rotated triangular and normal square array tube bundles were reported using Freon-11 two-phase flow\(^6\)\(^-\)\(^7\). Lots of experimental works were performed using straight tube bundles, but experiment on the fluidelastic instability of rotated square and normal square array U-tube bundles in air-water two-phase flow was performed\(^8\)\(^-\)\(^10\), and the results for U-tube bundles with p/d of 1.633 showed that the lowest fluidelastic instability constant is 6.5.

In the present study, fluidelastic instability for a rotated triangular tube bundle in air-water flow was experimentally investigated. The pitch-to-diameter ratio ($P/D$) of bundles is 1.48 and the tube diameter $D$ is 17.48 mm. Two different frequencies of tube in the lift direction were tested. Critical velocity of fluidelastic instability, damping, and hydrodynamic mass of tube bundle were measured in these void fraction of 0% to 90%.

2 EXPERIMENTS

2.1 TEST LOOP

The test loop consists of water loop and air loop (Fig. 1). The main equipment of the water loop includes pump, pressurizer, flow regulating valve, turbine flowmeter, and gas-water separation tank, etc. Water flow can be adjusted from 5 to 20000 m$^3$/h. The main equipment of the air loop is air compressor, gas storage tank, regulating valve and gas flowmeter, etc. The maximum gas supply pressure is 1.2 MPa, and the gas flow range is 1 to 900 m$^3$/h.

The air and water are homogenized with a-air water mixer. Different void fraction and different flow velocity is controlled by different water flow and air flow.

Based on the assumption of homogeneous flow, the void fraction is defined as

$$\varepsilon_g = \frac{Q_g}{Q_0 + Q_g}$$

where $Q_0$ is water flow (m$^3$/h), and $Q_g$ is air flow (m$^3$/h).

The freestream velocity $V_0$, and pitch velocity $V_P$ of tube bundles are defined as

$$V_0 = \frac{(Q_0 + Q_g)}{A_0}$$

$$V_P = \frac{V_0}{P}(P-D)$$

where $A_0$ is the free stream cross-sectional area (m$^2$), $P$ is the pitch of tube array (m), and $D$ is the diameter of tube.

The density of two-phase fluid is calculated from air density $\rho_0$, water density $\rho$ and void fraction $\varepsilon_g$ as

$$\rho = \rho_g \cdot \varepsilon_g + \rho(1 - \varepsilon_g) \quad (4)$$

![Fig. 1 Schematic diagram of the test loop](image1)

**2.2 Test Section**

The heat transfer tube in the test section is a straight tube array of 7 columns and 15 rows (total of 53), which is shown in Fig. 2(c). The diameter of tube is 17.48 mm with a pitch-to-diameter ratio of 1.48, and the length of the tube is 312 mm. The tubes were a rotated triangular arrangement. The tube were supported with a flexible cantilever beam, which was thin (5.5 mm) in one direction and thick (12.5 mm) in the other. The tube natural frequency in air was around 40 Hz in the thin direction and 80.25 Hz in the thick direction. Seven tubes were instrumented with strain gauges in the thin direction and thick direction respectively, located on the flexible beams to measure the strain-time data of the tube.

![Fig. 2 Schematic diagram of tube bundles](image2)

In order to measure critical velocity of fluidelastic instability, damping and hydrodynamic mass of tube bundle more accurately, two types of tests were performed in the thin direction and thick direction respectively. One tests were performed to research critical velocity with all tubes flexible, and another tests were to measure damping and hydrodynamic mass of tube with only one tube flexible in the tube array\(^11\). All type tests were performed at homogeneous void fractions of 0%, 20%, 40%, 60%, 80%, and 90%.
3 Results and Discussion

The tests were expected to research the fluidelastic instability of the tube both in the lift direction and the drag direction, but instability did not occurred in the drag direction. Although that, instability occurred in the thick direction which was lift direction while the thin direction was the drag direction. So the tests were performed for fluidelastic instability of two type of tube in the lift direction. For the sake of convenience, two conditions of the heat transfer tube were agreed here: thin direction as the lift direction and thick direction as the lift direction.

3.1 Critical Velocity and Vortex Shedding

Tests for critical velocity were performed using flexible tube bundles. Since the data of the 7 instrumented tubes were basically consistent, only the results of the T4 tube were given here.

The results of lift direction are showed in Fig. 3. The diagram shows that when the pitch velocity exceeds a certain value, there is a sharp change of RMS strain response in the lift direction, which mean fluidelastic instability occurred in the lift direction. The vibration behavior of water (Fig. 3(a)) is different from that’s other two-phase flow. The strain response of tube in water increases first and then decreases before the instability, but there is no such phenomenon for other two-phase flow before the instability.

The results of draft direction are showed in Fig. 4. In this case, thin direction is the draft direction, but the strain of draft direction do not occur instability. The same phenomenon was observed for rotated triangular tube bundles[11-13]. The strain of draft direction increases first and then decreases for 0% and 20% void fraction. And instability occurs in the lift direction.

The instability velocity was determined according to the method was presented[9]. Fig. 3 and Fig. 4 show that the critical velocity increases with the increase of void fraction, and the critical velocity is proportional to the frequency of the heat transfer tube under the same void fraction.

Fig. 3  RMS vibration amplitude in lift direction versus pitch velocity
In this experiment, when the void fraction is below 20%, the phenomenon about the strain of tube increases first and then decreases before the instability is probably caused by vortex shedding. It is still in dispute whether the tube bundles have periodic excitation or vortex shedding. Taylor\cite{14} pointed out that periodic signal of vortex shedding was not found in the spectrum of structural response in two-phase flow test with a void fraction of more than 15%. Feenstra\cite{6} deduced that a small amount of steam (void fraction of 5-10%) was sufficient to disturb the excitation of vortex shedding to the heat transfer tube. Referring to the method of previous scholars, taking 0% void fraction as an example, see Fig. 3 (a), this article will discuss whether this phenomenon is vortex shedding in several aspects. First of all, the definition of Strouhal number is $S=fD/V_{P}$, so $S=0.48$ at the first peak of Fig. 3(a). It was pointed out that the vortex shedding occurs when the Strouhal number is between 0.33 and 0.67\cite{16}, and $S$ at the first peak of Fig. 3(a) is in this interval. Then, Fig. 5 shows the comparison of time-histories of the tube under different pitch velocity. The beat wave phenomenon occurs at the first peak of Fig. 3(a), which indicates that the tube resonate. Last, Fig. 6 is the comparison of spectral analysis corresponding to the time-histories of Fig. 5, which shows that the main frequency of tube is the frequency of two-phase flow before strain of tube increasing, but the frequency amplitude of tube is very large at the first peak of Fig. 3(a) due to some strong force. To sum up, the phenomenon that the strain of heat transfer tube increases first and then decreases in the single-phase water is caused by the vortex shedding. A similar analysis is made to Fig. 4(a) and (b), and the same conclusion is obtained. Therefore, the vortex shedding occurred under 20% void fraction, which proved that the vortex shedding may occur in tube bundles.
3.2 Damping Ratio

The critical velocity for different void fraction was got in the test with the flexible tube bundles. Measurements of damping ratio and hydrodynamic mass in two-phase cross-flow were carried out at 1/2 critical velocity for different void fraction with only one flexible tube in rigid tube bundles\(^1\). Damping ratio of two-phase was evaluated by half power frequency band method\(^8\). Results of damping ratio are showed in Fig. 7, and the variation law and value coincide with the research results of other tube bundles\(^1,8\). The damping ratio is dependent on the void fraction as noted by Pettigrew et al\(^1\), and it is max at void fraction of 60\%.

3.3 Hydrodynamic Mass

Hydrodynamic mass was evaluated by the equation suggested by Carlucci and Brown\(^17\):

\[
m_h = m_l \left( \frac{f_l}{f} \right)^2 - 1
\]

where \(m_l\) (kg/m) is the mass per unit length of the tube, \(f_l\) (Hz) is the tube frequency in air, and \(f\) (Hz) is the tube frequency in two-phase flow.

Hydrodynamic mass ratio is an important basis to estimate the hydrodynamic mass experimental value is or is not reasonable, and its definition is the measured hydrodynamic mass in two-phase flow over the hydrodynamic mass in water flow\(^1\). Fig. 8 shows the hydrodynamic mass ratio of present and a comparison of the present results with other tube bundles\(^1,8\) and theoretical values. As showed in the figure, the present data agree well with the data of other tube bundles, except for the hydrodynamic mass ratio of thick direction is less than the previous experimental values but closer to the theoretical value at 80\% and 90\% void fraction.

3.4 Fluidelastic Instability

The test for fluidelastic instability is to get the instability constant \(K\) and the exponent \(n\) of Connors’ relation:

\[
V_{pc}/(fD) = K (2\pi \zeta m \rho D^n)^{\frac{1}{n}}
\]

(6)

Where \(V_{pc}\) is the critical pitch velocity, \(f\) is the tube natural frequency in two-phase, \(\zeta\) is the total damping ratio in two-phase, \(\rho\) is the homogeneous mixture density, and \(m\) is the total mass per unit length (including tube mass and hydrodynamic mass).

Pettigrew made a lot of research on fluidelastic instability of heat transfer tube and recommended\(^40\) to take a value of \(K=3.0\) and \(n=0.5\) to avoid fluidelastic instability for all tube bundles with pitch-to-diameter ratio \(P/D>1.47\). Many engineers use this recommendation to design steam generators. Results of fluidelastic instability are showed in Fig. 9. \(K=4.75\) for thin direction being the lift direction and \(K=4.8\) for thick direction being the lift direction. It is obvious that the \(K\) values are larger than the design criteria.
4 Conclusion

Tests of fluidelastic instability were investigated for rotated triangular tube bundles with pitch-to-diameter ratio $P/D=1.48$ in air-water two-phase cross-flow. Critical velocity of fluidelastic instability, damping and hydrodynamic mass of tube bundle were measured in these void fraction of 0% to 90%. Fluidelastic instabilities occurred in the lift direction, but not in the drag direction. Vortex shedding occurred in the tube bundles with void fraction less than 20%.

Critical velocity increases with the increase of void fraction for tube bundle with the same frequency. Critical velocity varies inversely with natural frequency of tube for the same void fraction.

The damping ratio was dependent on the void fraction. With the increase of void fraction, the damping ratio increased first and then decreased. The damping ratio reached the maximum value at void fraction of 60%.

Fluidelastic instability constant $K$ for two different frequencies of tube are both greater than 4.75.

REFERENCES


