Study on a Countermeasure of Self-Sustained Tone by a Baffle Plate in Boiler Tube Banks

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***Abstract*- In heat exchangers such as boilers and gas heaters, tube banks are set in a duct such that water passes through inside the tubes and warm gas outside the tubes. Due to the external flow, the resonance phenomenon called the self-sustained tone occurs at a certain velocity. The self-sustained tone might cause noise problems in the surroundings, cause losses due to plant shutdown, etc. The insertion of baffle plates in the duct is one of a few countermeasures of the self-sustained tone. However, the mechanism of suppression of the self-sustained tone is not understood. Therefore, the use of the baffle plate in the tube bank has unclear points for instance baffle plate length and the insertion conditions. Thus, the purpose of this study is to clarify a new mechanism of suppression of the self-sustained tone by baffle plate insertion and the best insertion conditions for baffle plates in tube banks**.

Keywords- Self-Sustained Tone; Baffle Plate; Boiler Tube Bank

I. INTRODUCTION

In heat exchangers, such as boilers and gas heaters, tube banks are set in a duct and the water passes through inside the tube and warm gas outside the tube. When the flow velocity increases Karman vortex shedding occurs behind the tubes. The vortex shedding frequency is proportional to the velocity. On the other hand, the duct has an acoustic natural frequency (natural frequency hereafter) determined by the duct size and the sound speed. The acoustic natural frequency is independent of the flow velocity. A resonance phenomenon occurs at a certain velocity when the two frequencies coincide [1-5]. If the acoustic damping is small, a high level sound continues with increasing flow velocity. This phenomenon is called the self-sustained tone [6-8]. The self-sustained tone might cause the surrounding noise problem, and also cause plant shutdown and hence production losses, etc. A countermeasure involving the insertion of a baffle plate in the duct is generally adopted to suppress the self-sustained tone. This is based on the idea that the baffle plate can prevent the resonance within the range of the usage flow velocity by introducing a new partition, thus raising the natural frequency of the duct [9]. However, it was clarified that the natural frequency of the duct became lower by the baffle plate insertion in a past study [10] and the forecast of the self-sustained tone suppression by the existing idea became difficult [11-12]. Thus, the purpose of this study is to clarify a new mechanism of suppressing the self-sustained tone by the baffle plate insertion.

II. PROBLEM OF EXISTING IDEAS OF POLICY ACTS TO A SELF-SUSTAINED TONE BY A BAFFLE PLATE

Karman vortex shedding occurs in a tube bank when there is a flow in the duct. The vortex shedding frequency increases in proportion to the flow velocity. On the other hand, the natural frequency of the duct is a constant value determined by the duct size and the sound speed, and it is independent of the flow velocity. Therefore, the noise, called a self-sustained tone, is generated when these two frequencies approach by increasing of the flow velocity. The countermeasure of inserting a partition board called a baffle plate in the duct is generally adopted to suppress the noise. This is based on the idea that the baffle plate changes the size of the duct cross section, and can raise the natural frequency of the duct. As a result, it has been considered that the flow velocity at which the vortex shedding frequency approaches the natural frequency of duct shifts to higher values. According to our previous study, it has been found that the natural frequency of the duct decreases on inserting the baffle plate. As a result, the existing idea cannot explain the suppression mechanism of the self-sustained tone by the baffle plate.

Therefore, the suppression mechanism of the self-sustained tone by the baffle plate will be described in the following sections.

III. CONTROL MECHANISM OF A SELF-SUSTAINED TONE BY A BAFFLE PLATE

The sound power which the vortices add to the acoustic field of the duct is given by the following expression (1) from Howe [13]. The parameters are: W : sound power [W], ρ: gas density [kg/m^3], $\vec{\omega}$: vorticity [rad/s], $\vec{U}$: flow velocity [m/s] and $\vec{\xi}$: particle velocity [m/s].

$$W = \rho \int \left(\vec{\omega} \times \vec{U} \right) \cdot \dot{\vec{\xi}} dV \tag{1}$$

The particle velocity in the duct is given by the gradient of the sound pressure. Moreover, the phase of the particle velocity relative to the sound pressure progresses by 90 degrees. The particle velocity is therefore maximum at the node of the acoustic pressure. In addition, the particle velocity is the largest at the center of the duct width. In addition, Karman vortices are strong in the tube bank. Each parameter is controlled by inserting the baffle plate in the part where these two parameters are large, and the sound power decreases. However, the flow velocity, which is the remaining parameter, increases to recover the sound power. This idea is a new mechanism described in the present study. An experiment will be described in the following sections to verify this mechanism.

IV. EXPERIMENTAL SETUP AND METHODOLOGY

The experimental setup is shown in Fig. 1 (a) and the duct used in this experiment is shown in Fig. 1 (b). The size of the duct is 1720mm in length, 200mm in height, and 222mm in width. The tube bank is set as shown in Fig. 1 (b). The microphone is put on the tube bank outside duct as shown in Fig. 1 (a). The flow is driven through the duct by a blower and the flow rate can be controlled by an inverter. The tube bank consists of an array of bronze tubes of 6mm diameter. The array geometry is square with spacing T/D=2.0 and L/D=2.0, where T is the transverse center-to-center spacing, L the longitudinal center-to-center spacing and D the tube outside diameter as shown in Fig. 2. The flow velocity in the duct is measured by using a hot wire anemometer and the sound pressure level of the self-sustained tone is measured using the sound level meter.

One tube bank is installed in the duct in the present experiment as shown in Fig. 1 (b). The baffle plate with a length of 60mm, thickness of 3mm and height of 200mm is inserted in the center of the tube bank as shown in Fig. 1 (b). The position of this baffle plate is varied in the flow direction in increments of a row pitch (12mm) in the tube array. The patterns of the baffle plate position are shown in Fig. 3. An effective position of the baffle plate to suppress the self-sustained tone is derived from this experiment.

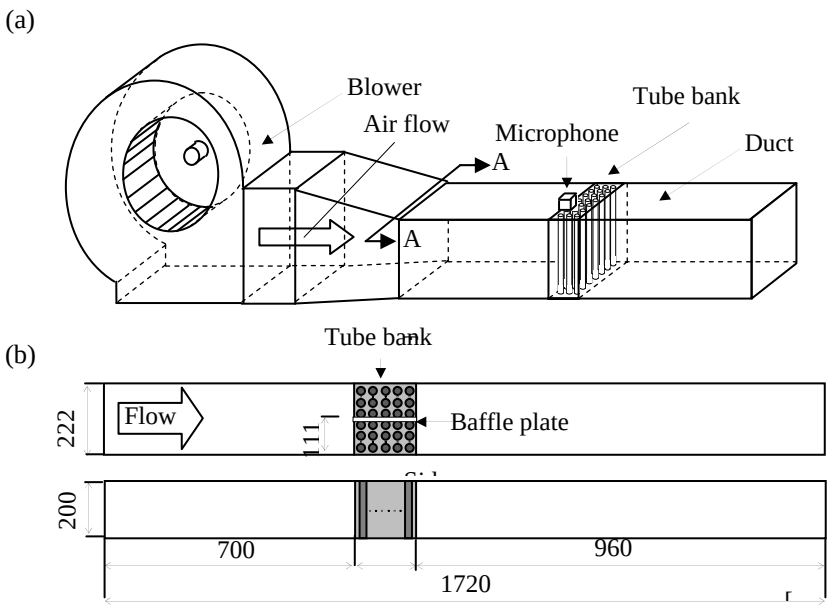


Fig. 1 Experimental setup

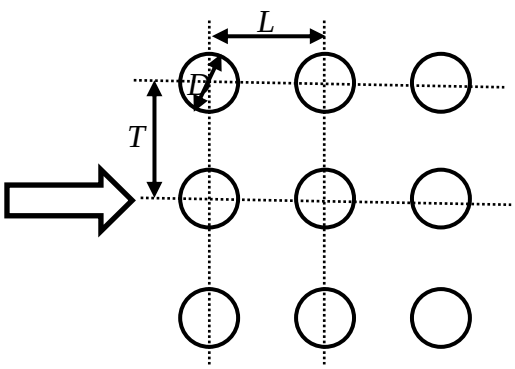


Fig. 2 Array geometry

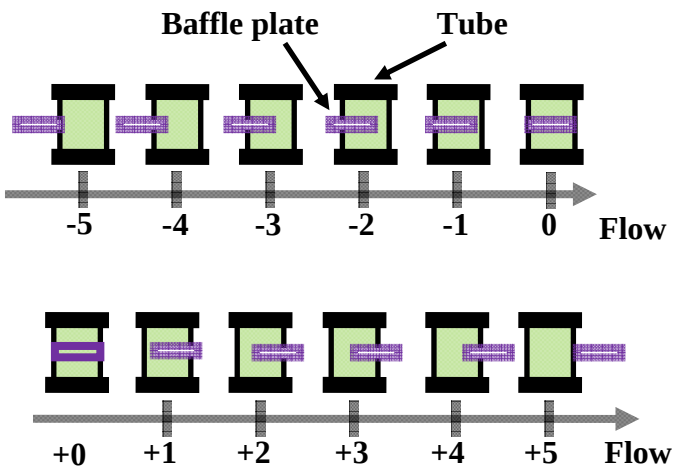


Fig. 3 Pattern of baffle plate positions

V. EXPERIMENTAL RESULTS

A. *Natural Frequency of Duct and Peak Frequency of a Self-Sustained Tone*

The natural frequency of the duct can be obtained by the speaker test. The speaker test is conducted by using the same experimental setup. The speaker is set in the duct downstream side and the natural frequency is obtained by the sweep test with sin wave. Fig. 4 shows the acoustic mode in case of the baffle plate obtained by the FEM analysis in case of no baffle plate. The natural frequency of the duct and the peak frequency of the self-sustained tone are shown in Fig. 5. The vertical axis shows the frequency while the horizontal axis shows the pattern of the baffle plate positions as shown in this figure. The natural frequency of the duct was obtained by a speaker test mentioned above, and the peak frequency of the self-sustained tone was obtained by the ventilation experiment.

The symbol Δ shows the peak frequency in case of with baffle plate. In this case, the self-sustained tone was not generated when the baffle plate positions are –1, 0, and +1. So we cannot see the symbol Δ in these positions. It is confirmed that the natural frequency of the duct corresponds to the peak frequency of the self-sustained tone as can be seen from this figure. Moreover, it is found that the natural frequency of the duct decreases by the insertion of the baffle plate regardless of the position. This is because that the baffle plate cannot divide into two parts of the acoustic field of the duct due to a small length. If the baffle plate length is the same with the length of the duct, then the natural frequency becomes higher and doubles.

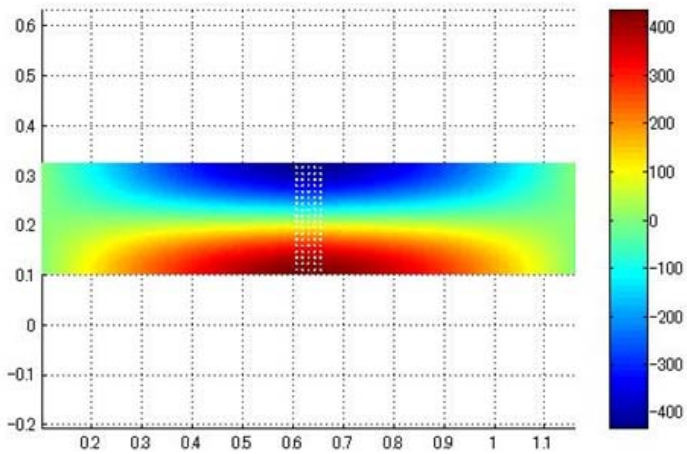


Fig. 4 Acoustic mode in case of without baffle plate

B. *Onset Flow Velocity of a Self-Sustained Tone*

The onset flow velocity of the self-sustained tone is shown in Fig. 6. The vertical axis shows the gap velocity of the tube bank when the self-sustained tone occurs and the horizontal axis shows the pattern of the baffle plate positions as shown in this figure. From this figure, in patterns (-1, 0 and +1) where the baffle plate is inserted in the entire tube bank, it was found that the self-sustained tone was not generated in the limited velocity of the experimental setup. It can be considered that vortices become very small as described after in patterns (-1, 0, +1), as a result, the sound power decreases from the equation (1) and

the self-sustained tone is not generated. Moreover, it is clear that the tendency of the onset flow velocity of the self-sustained tone is significantly different for the upstream and the downstream positions. In general, the Karman vortex shedding frequency f_v is proportional to the flow velocity and the natural frequency of the duct f_a is constant value determined by the duct size and the sound speed. When the flow velocity increases the f_v approaches f_a. Before the f_v reaches the f_a, the vortex shedding frequency suddenly locks on to the natural frequency of the duct. The resultant high level sound occurs at or nearly at the natural frequency duct. This is a Lock-in phenomenon.

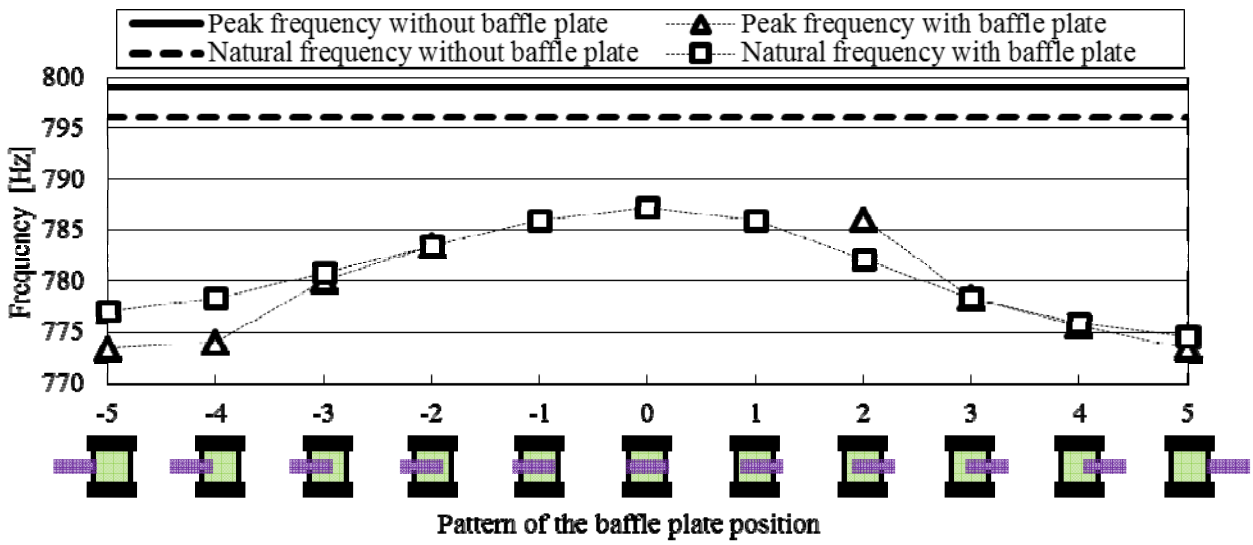


Fig. 5 Natural frequency and peak frequency

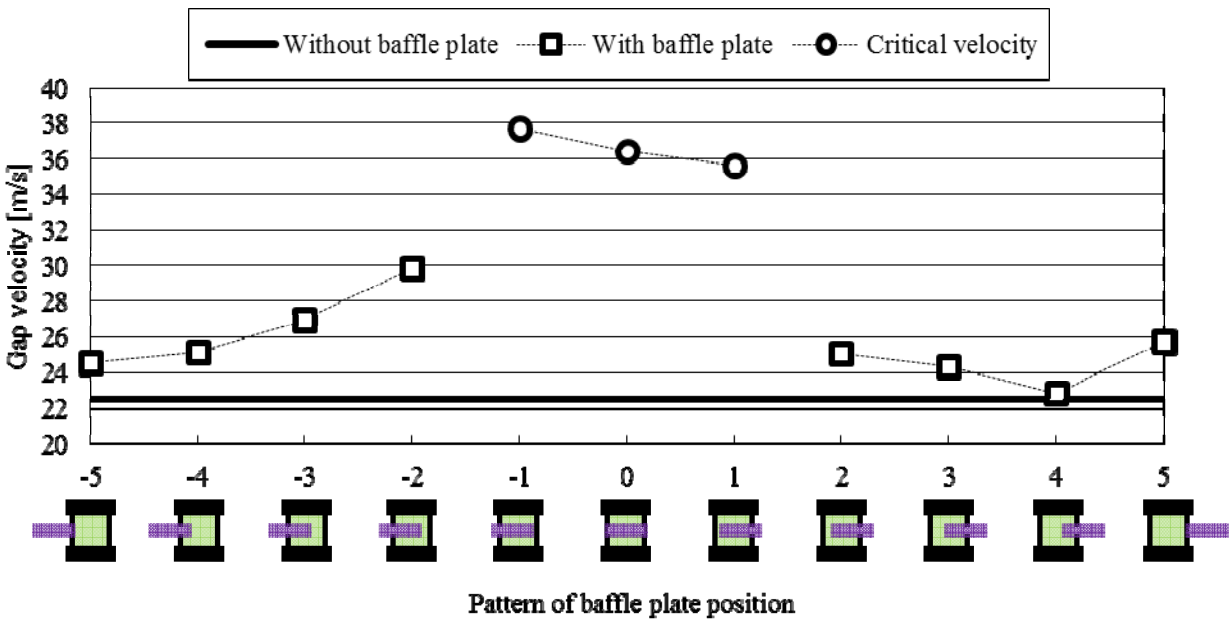


Fig. 6 Gap velocity and pattern of baffle plate positions

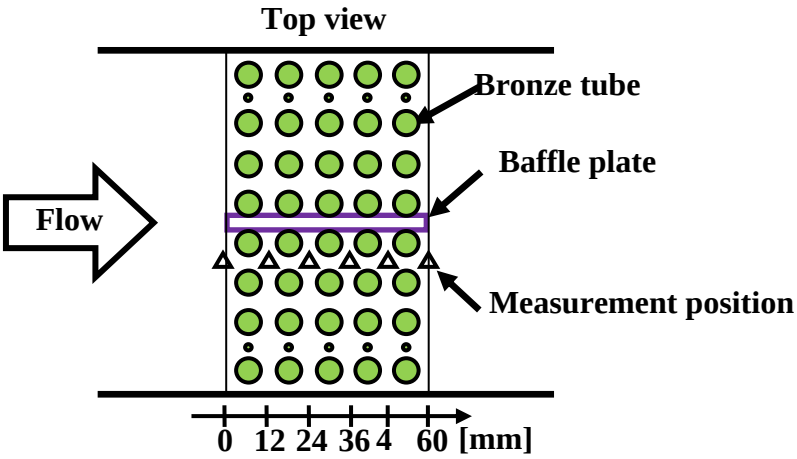
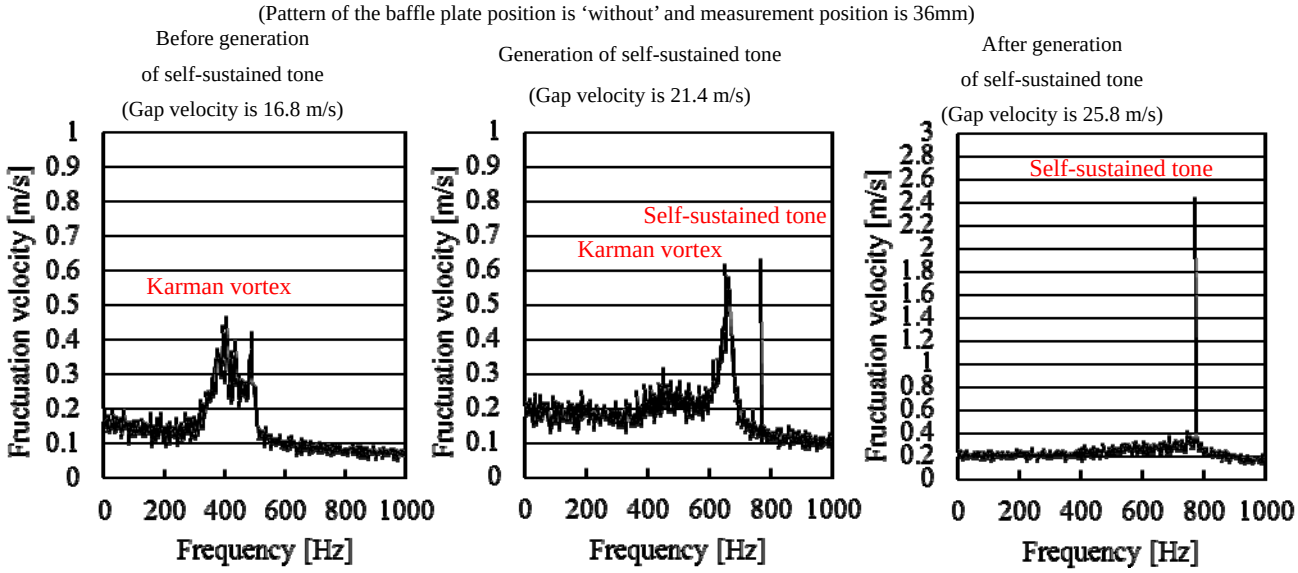


Fig. 7 Measurement position of fluctuation velocity in tube bank

The condition that the self-sustained tone is generated

(Pattern of the baffle plate position is 'without' and measurement position is 36mm)



The condition that the self-sustained tone is not generated

(Pattern of the baffle plate position is '0'and measurement position is 36 mm)

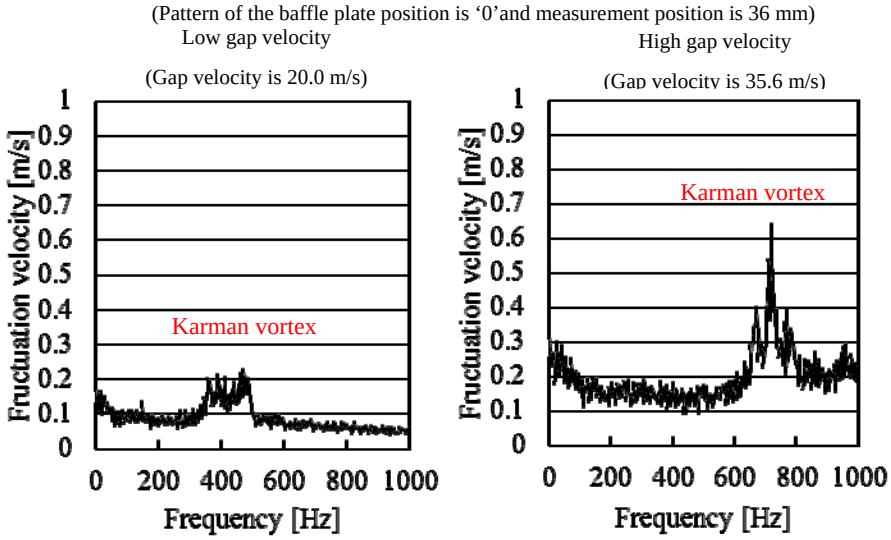


Fig. 8 Fluctuation velocity of flow

C. Fluctuation Velocity of Flow

The measurement position of the fluctuation velocity in the tube bank by the hot-wire anemometer is shown in Fig. 7. Because the baffle plate is inserted at the center of the tube bank, the hot wire probe is inserted in the neighboring flow channel. Additionally, the fluctuation velocity is measured between each tube row (12mm interval). A measurement example (the measurement position is 36mm) of the fluctuation velocity of the flow in the tube bank is shown in Fig. 8. The vertical axis shows the fluctuation velocity of the flow and the horizontal axis shows the frequency. From these figures, two peaks (one needle and the other mountain) can be seen. The peak like a needle is due to the self-sustained tone and the peak like a mountain is due to Karman vortex shedding as shown in Fig. 8. The peak frequency of Karman vortex shedding increases in proportion to the flow velocity and the Strouhal Number is 0.13～0.19; the Karman vortex occurs within the tube bank. On the other hand, the peak frequency of the self-sustained tone coinciding with the natural frequency of the duct, it can be seen that the sharp peak like a needle corresponds to the flow fluctuations related to the generation of the self-sustained tone. To distinguish the peak from other peaks, this is called 'Excitation flow fluctuation' in this study. However, Karman vortices are generated and the excitation flow fluctuation is not generated when the self-sustained tone is suppressed by inserting the baffle plate in the entire tube bank.

Next, the distribution of the excitation flow fluctuation in the tube bank when the self-sustained tone is generated is examined. Here, it has been non-dimensionalized as shown in equation (2) below because the excitation flow fluctuation is a value depending on flow velocity.

$$u = \frac{U}{V_{g1}} \tag{2}$$

The distribution of the excitation flow fluctuation in the tube bank is shown in Fig. 9. The vertical axis shows the baffle plate positions. The circle shows the dimensionless excitation flow fluctuation and its radius indicates the value of the excitation flow fluctuation while the horizontal axis shows the measurement position of the flow fluctuation velocity in the tube bank.

From this figure, it can be seen that the excitation flow fluctuation is not generated in the entire tube bank under the condition where the self-sustained tone is not generated. On the other hand, it can be confirmed that it is generated in the entire tube bank under the condition of the self-sustained tone being generated. Therefore, the effect of the baffle plate insertion controls two parameters, the particle velocity and the excitation flow fluctuation. It is therefore thought that it is the suppression mechanism of the self-sustained tone to decrease the sound power by controlling these two parameters.

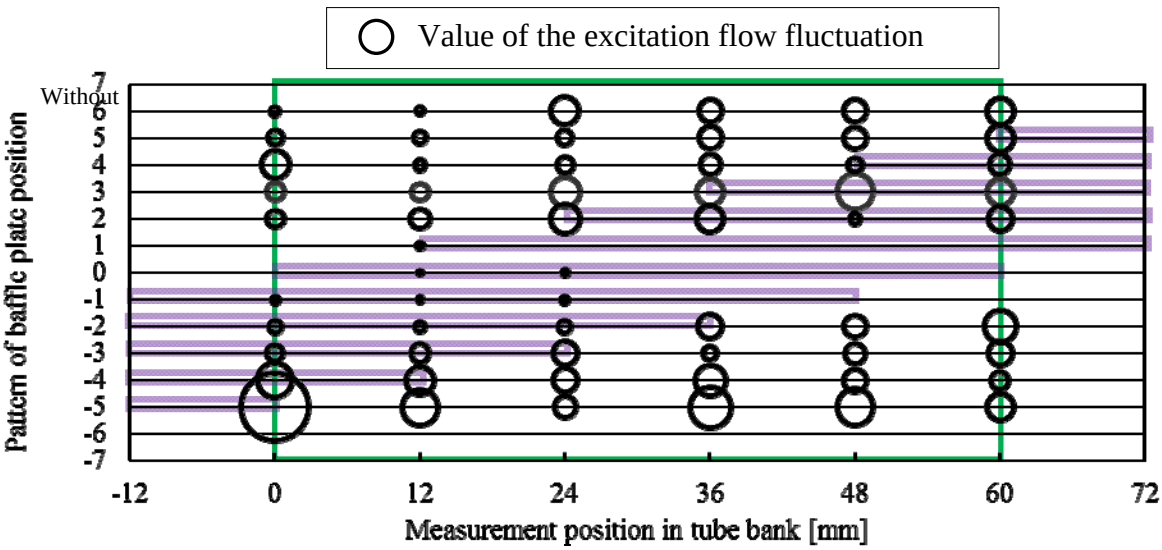


Fig. 9 The fluctuation velocity of flow on tube bank and the measurement position

VI. CONCLUSIONS

The following findings were obtained from the present experiment.

(1) The natural frequency of the duct decreases and the onset flow velocity of the self-sustained tone increases by inserting the baffle plate. Therefore, it is concluded that the natural frequency of the duct and the suppression of the self-sustained tone are irrelevant.

(2) The baffle plate insertion in the entire tube bank is the most effective for the suppression of the self-sustained tone. Moreover, the onset flow velocity of the self-sustained tone when the baffle plate is inserted on the upstream side is different from the case where it is inserted downstream.

(3) Two peaks, one for Karman vortex shedding and the other related to the excitation flow fluctuations can be seen in the tube bank. Furthermore, the excitation flow fluctuation is observed in the entire tube bank under the condition that the self-sustained tone has been generated. However, it is not observed under the condition that the self-sustained tone has not been generated.

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REFERENCES

[1] R. C. Baird, "Pulsation-Induced Vibration in Utility Steam Generation Unit", *Combustion*, vol. 25, iss.10, pp. 38-44, 1954.

[2] R. D. Blevins and M. M. Bressler, "Acoustic Resonance in Heat Exchanger Tube Bundles-Part I: Physical Nature of the Phenomena, Part II: Prediction and Suppression of Resonance", *Journal of Pressure Vessel Technology*, vol. 109, pp. 275-288, 1987.

[3] M. Funakawa, "The Acoustic Resonance in a Tube Bank", *Journal of the JSME*, vol. 13, pp. 348-355, 1970.

[4] M. Funakawa, "The Acoustic Resonance in a Tube Bank", *Journal of the JSME*, vol. 13, pp. 348-355, 1970.

[5] H. Hamakawa, "Effect of Cavities inside of In-line Tube Banks on Acoustic Resonance", *Transactions of the Japan Society of Mechanical Engineers* 76-764-B, pp. 580-587, 2010.

[6] K. Ishihara, "Study on High SPL Sound of Gas Heater Composed of Two Parallel Located Ducts with Tube Bundles(1st Report, Understanding of Phenomenon) ", *Transactions of the Japan Society of Mechanical Engineers* 70-689-B, pp. 126-132, 2004.

[7] K. Ishihara, "Study on High SPL Sound of Gas Heater Composed of Two Parallel Located Ducts with Tube Bundles (2nd Report, Acoustic Damping of Perforated baffle Plate and Its Effect) ", *Transactions of the Japan Society of Mechanical Engineers* 70-689-B, pp. 133-139, 2004.

[8] K. Ishihara, "On Generating Mechanism of High Level Sound Generated in Boiler and Heat Exchanger: Effect of Tubes and Acoustic Damping on SPL", *Transactions of the Japan Society of Mechanical Engineers* 76-763-C, pp. 572-579, 2010.

[9] K.SHIRAKI, "The noise control design and simulation", Ouyougijutsu Publisher, pp. 179-183, 1987.

[10] K. Ishihara, M. Tsuji, T. Tamehira, "On Effect of Baffle Plate Insertion on Acoustic Natural Frequency of Duct in Boiler Tube Banks", *Transactions of the Japan Society of Mechanical Engineers* 77-784-C, pp. 4468-4478, 2011.

[11] T. Tamehira, "Study on Countermeasure of Self-Sustained Tone by Baffle Plate in Boiler Tube Banks with Cavity", *the 49th term general meeting lecture meeting lecture collected papers of JSME Tyugokushikoku branch division*, p. 367, 2011.

[12] T. Tamehira, "Study on Countermeasure of Self-Sustained Tone by Baffle Plate in Boiler Tube Banks with Cavity", *the 86th term general meeting lecture meeting lecture collected papers of JSME Kansai branch division*, vol. 1, p. 14, 2011.

[13] M. S. Howe, "THE DISSIPATION OF SOUND AT AN EDGE", *Journal of Sound and Vibration*, vol. 70, iss.3, pp. 407-411, 1980

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