Interaction Between Water or Air-Water Bubble Flow and Tube Bundle—Effects of Arrangement of Tube Bundle and Void Fraction

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Abstract Water or air-water bubble flow passing through tube bundle can be seen in many industrial equipments such as heat exchanger and chemical equipment. In addition, tube bundle can be used as a flow-straightener, -mixer, -resistor, and -damping device. In this study, the effects of tube arrangement of equally or unequally spaced in-line and staggered tube bundle and of void fraction on the flow characteristics such as flow pattern and flow resistance of a tube or tube bundle are examined experimentally.

Keywords Tube bundle · Effects of tube arrangement · Water or air-water bubble flow · Flow resistance

1 Introduction

Tube bundle is used widely in many industrial fields such as heat exchanger, chemical equipment, flow-straightener, -mixer, -resistor and -damping device. There are many studies on the improvement of performance but almost all are for equally spaced tube bundle [1, 2]. It is expected that using the tube bundle with an unequal interval the flow and heat transfer characteristics are changed and the performance will be improved. Shakouchi et al. [3] studied the flow and heat transfer of gas-liquid flow passing through a single row tube bundle with unequal interval tube pitch and showed the heat transfer efficiency of an uneaqul interval could be enhanced.

In this study, the effects of tube arrangement of equally or unequally spaced in-line and staggered tube bundle and of void fraction on the flow characteristics are examined by flow visualization using tracer method, velocity measurement by

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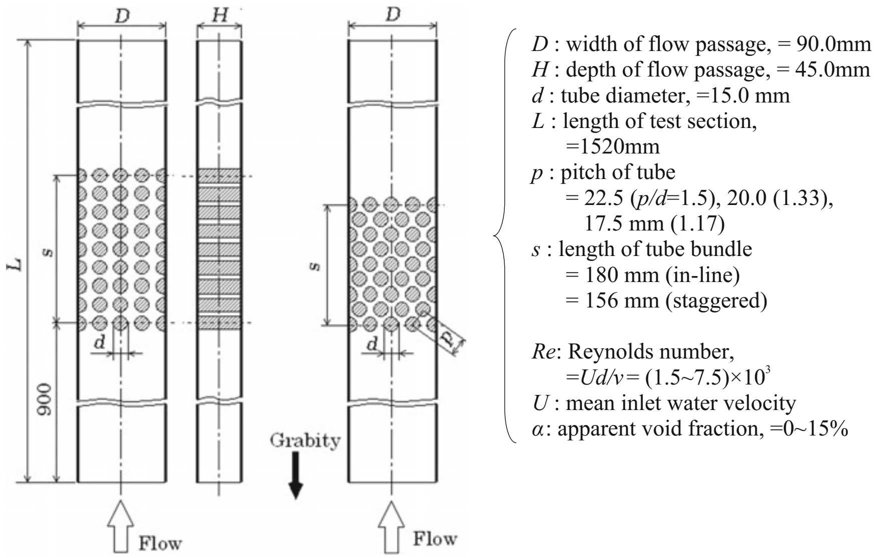
Particle Image Velocimetry, PIV, and the flow resistance of a tube and tube bundle are also examined by pressure measurement.

2 Experimental Apparatus and Procedure

Figure 1 shows the schematic diagram of experimental apparatus, test section. The test section is made of transparent acrylic resin plate and is set vertically. The width, depth and length of the test section are $D = 90.0$, $H = 45.0$, and $L = 1{,}520$ mm, respectively. The tube bundle is consisted of 5 rows and 9 lines of tube of diameter $d = 15.0$ mm. The pitch of tube is equal interval of $p/d = 1.5$, and unequal interval of $p/d = 1.33$, 1.17 which were realized by moving odd numbered rows.

Water or air-water bubble flow introduces into the test section from the bottom after passing through the inlet flow passage with an enough length. The volumetric flow rate of water or air can be adjusted using flow meter and valve (Fig. 2).

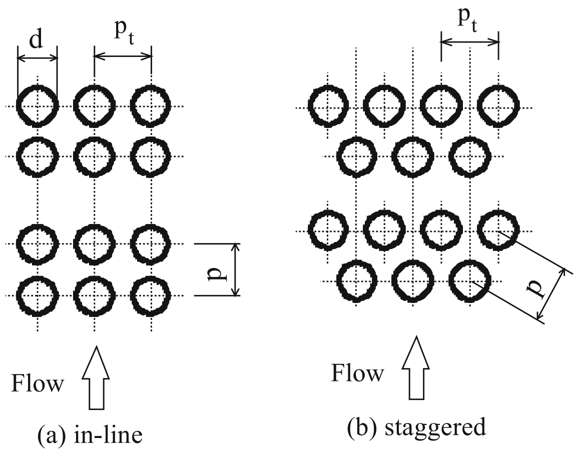
A tube has a pressure hole of diameter 0.8 mm at the half depth and which can be rotated around its own axis. Then the pressure around the tube can be measured. The pressure loss Δp_{tl} of the tube bundle was measured by the pressure holes which were located on the middle depth of the side wall of the trst section at the up- and down-stream of distance $5d$ and $27d$ from the first row, respectively.



(a) in-line (b) staggered

Fig. 1 Test section (tube bundle)

Fig. 2 Arrangement of tube bundle



The visualized flow pattern by a Tracer method was photographed by a high speed video camera. The velocity distribution was measured by Particle Image Velocimetry, PIV, and pressure was measures by pressure hole of diameter 0.8 mm and liquid column manometer or semi-conductor type pressure transducer.

3 Results and Discussions

3.1 Flow Pattern and Velocity Distribution

Figure 3 shows an example of the visualized flow pattern around the 1st to 2nd rows of staggered tube bundle with equal interval of p/d = 1.5 where are in the center region of the test section and velocity distribution around the 1st and 2nd

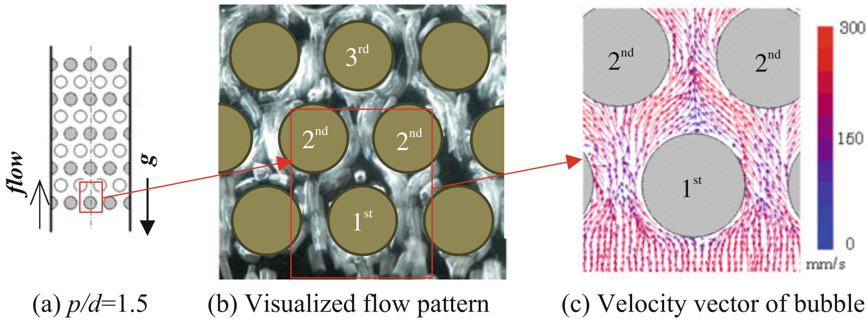


Fig. 3 Flow pattern and velocity distribution of staggered tube bundle under equal interval of p/d = 1.50, $Re = 1.5 \times 10^3$, and $\alpha = 5.0\%$ [**b** shutter speed: 1/60 s., **c** PIV using 96 photos taken by 1/240 frs. with 1/1000 s.]

tubes measured by PIV. The white part in the figure are path of air bubbles. The mean bubble size is $d_b \approx 2.5$ mm. Behind the 1st row tube there is a wake region and bubbles collide near the stagnation points of 1st and 2nd row tubes. The flow pattern for unequal interval of $p/d = 1.17$ was largely different with the equal interval of $p/d = 1.5$. The flow seemed to be hard to flow between the 1st and 2nd row tubes.

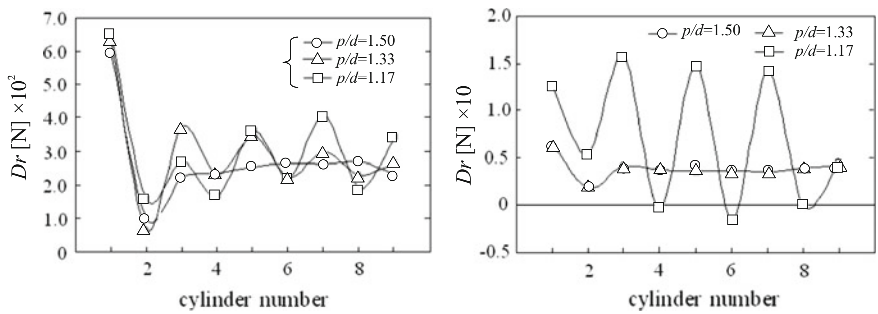
3.2 *Flow Resistance of Tube and Tube Bundle*

3.2.1 Drag of Tube

Figures 4a shows the drag *Dr* of the center tube for the in-line, $Re = 5.0 \times 10^3$, and $\alpha = 0\%$. *Dr* was obtained from the pressure distribution around the tube. For equal interval of $p/d = 1.5$ the 1st tube has a large value, but after the 3rd tube *Dr* increases a little to the downstream. But, for unequal interval of $p/d = 1.33$, 1.17, *Dr* of the even numbered tube is smaller than the tube just before because it is in the wake region of the tube just before. Figure 4b is the results for staggered array. *Dr* for $p/d = 1.17$ fluctuates much larger than the in-line array. For bubble flow of $\alpha = 5.0\%$ of the in-line and staggered arrays, *Dr* for each *p/d* showed almost the same change although the value was a little different.

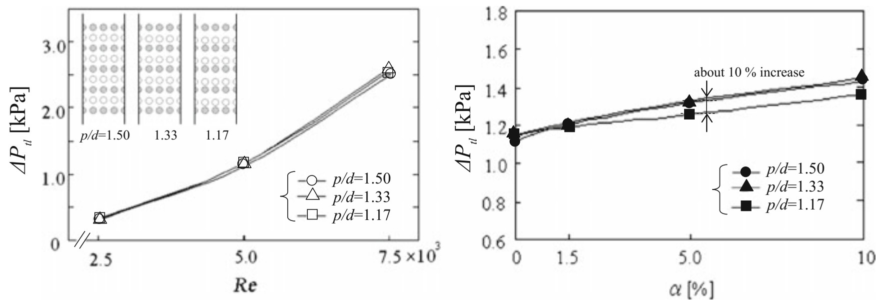
3.2.2 Pressure Loss ΔP_{tl} of Tube Bundle

Figure 5a, b show the pressure loss ΔP_{tl} of the tube bundle of the in-line array for *Re* and α, respectively. For $\alpha = 0\%$, ΔP_{tl} increases with *Re* rapidly and is almost the same regardless of *p/d*. But, for the bubble flow ΔP_{tl} of $p/d = 1.17$ becomes a smaller than the others. For example, at $\alpha = 0$, 10% for $p/d = 1.17$ it is smaller about 10, 8% than the others, respectively.



(a) in-line (b) staggered

Fig. 4 Drag of center tube, $Re = 5.0 \times 10^3$, $\alpha = 0\%$



(a) $\alpha = 0$ % (b) $Re = 5.0\times10^3$

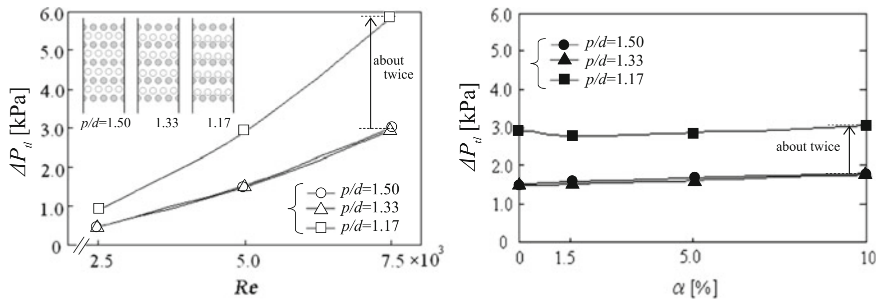
Fig. 5 Pressure loss Δp_{tl} of tube bundle (in-line)

Figure 6a, b show ΔP_{tl} of the staggered for Re and α, respectively. ΔP_{tl} increases with Re and the p/d = 1.17 is much larger than the others. For example, at Re = (5.0–7.5) × 10^3 it is about twice of the others. ΔP_{tl} for bubble flow at Re = 5.0 × 10^3 is almost constant for α = 0–10.0%, but the p/d = 1.17 is about twice of the others.

3.3 Flow Fluctuation

Figure 7 is the power spectral density of the pressure fluctuation at the center between the 2nd and 3rd tubes for the staggered, $Re = 5.0 \times 10^3$, α = 5.0%. Two dominant frequencies of f_d = 1.0 and 2.0 Hz are appeared. For α = 0%, the 2nd dominant frequency of f_d = 2.0 Hz did not appear.

For the in-line and α = 0%, two dominat frequency of f_d = 1.0 and 3.0 Hz, and for α = 5.0% two f_d of 1.0 and 2.0 are appeared. The fluctuation characteristics are different by the arrangement of tube bundle and void fraction.



(a) $\alpha = 0$ % (b) $Re = 5.0\times10^3$

Fig. 6 Pressure loss of tube bundle (staggerd)

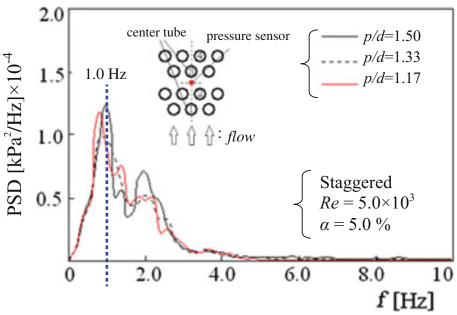


Fig. 7 Pressure fluctuation between 2nd and 3rd tube

4 Conclusions

In this study, the effects of tube arrangement with an equal or unequal interval of the tube bundle and of void fraction on the flow characteristics were examined.

The pressure loss ΔP_{tl} of the tube bundle for the in-line and $\alpha = 0\%$ was independent of *p/d*, but for bubble flow of $Re = 5.0 \times 10^3$ the $p/d = 1.17$ was about 10% smaller ΔP_{tl} than the others. ΔP_{tl} for the staggered of $p/d = 1.17$ was about twice of the others. The dominat frequency of flow fluctuation was in the range of $f_d = 1.0$–3.0 Hz, and the fluctuation characteristics were different by the arrangement of tube bundle and void fraction.

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