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FORCES ON HORIZONTAL TUBES OF NON-CIRCULAR CROSS-SECTION IN FLUIDIZED BEDS

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ABSTRACT

Dynamic forces were investigated on immersed horizontal tubes of various cross-sectional shapes (circular, diamond-shaped and triangular), both singly and in bundles of such tubes, in a two-dimensional fluidized bed. The transient forces induced by solids movement associated with passing bubbles were identified by frame-by-frame image analysis. The influence of surrounding tubes around a tube equipped with sensors was clarified by studying the movement of particles.

INTRODUCTION

Fluidized beds are used in a wide range of industrial applications, both for chemical reactions and for physical operations like drying and coating. In many of these applications, the fluidized particles interact with fixed objects suspended within the column. When objects are fixed in fluidized beds, they encounter substantial transient forces, with the root-mean-square magnitude increasing with increasing cross-sectional area. Most frequently the surfaces consist of horizontal tubes of circular cross-section. These have been shown [(1),(2)] to experience buffetting forces during the passage of bubbles, with an upward thrust occurring as the bubble approaches from below, and a subsequent downward force being experienced after the bubble has passed the

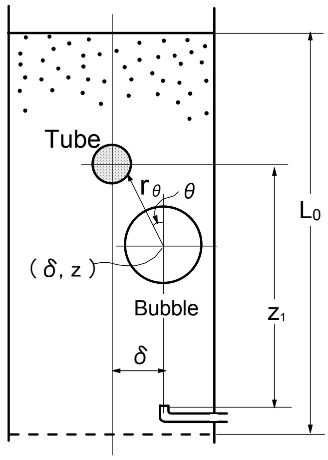


Fig.1 Coordinate for rising bubble.

object. The magnitude of these forces is proportional to the density of the dense phase and to the square of the bubble velocity [3]. The forces may also be affected by the presence of other bubbles and neighbouring tubes [4]. Previous work[5] indicates that the average force on core tubes in a bundle is reduced relative to forces on a single tube.

In some applications, suspended surfaces may be non-circular in cross-section. This includes, for example, shed baffles used in fluidized bed strippers [6],[7] and membrane panels [8] suspended in fluidized bed membrane reactors. Forces on objects of non-circular cross-section have not been investigated previously.

In this work, dynamic forces were investigated on suspended single horizontal tubes of various cross-sectional shapes – circle, diamond, upright-triangle and inverted-triangle – as well as on bundles of horizontal circular and triangular (upright and inverted) tubes in a two-dimensional fluidized bed. The transient forces induced by solids movement associated with passing bubbles were identified by frame-by-frame image analysis. In addition, the influence of surrounding tubes around a tube was clarified by studying the movements of particles.

TRANSIENT FORCE ON VARIOUS TUBES INDUCED BY PASSING BUBBLES

1) SIMPLE MODEL OF TRANSIENT FORCE INDUCED BY A PASSING BUBBLE

The theoretical net pressure forces around the tube contributing to drag is first calculated from potential flow in order to obtain fundamental understanding of the origin of the dynamic forces on the tube caused by passing bubbles, as in our earlier work [1].

The pressure, $P(r,\theta_r)$, within the fluidizing fluid at position (r, θ_r), relative to the center of a two-dimensional bubble of radius R_b, (**Figure1**) can be described [9] by

$$P(r_\theta,\theta) = -\left\{(1-\varepsilon_{mf})\ \rho_s g\left[r - \frac{R_b^{\ 2}}{r}\right]\cos\theta\right\} \qquad (1)$$

The instantaneous vertical force, $F_V(t)$, due to form drag, i.e. caused by the pressure balance, is given by:

$$F_v(t) = D_T L_s \int_0^{\pi} P(t,\theta)\cos\theta\, d\theta \cong D_T L_s \sum_i P_i \cos\theta_i\,\Delta\theta \qquad (2)$$

where D_T and L_S are the tube diameter and length exposed to the bubble, and i indicates multiple points of measuring static pressure.

Figure 2 shows pressure profiles around a cylinder. Experimental static pressures at each point are predicted well by the Davidson model. Vertical force profiles as functions of time predicted using eqs. (1), (2) are plotted in **Figure 3** for different values of the horizontal displacement, δ. Drag caused by passing bubble is

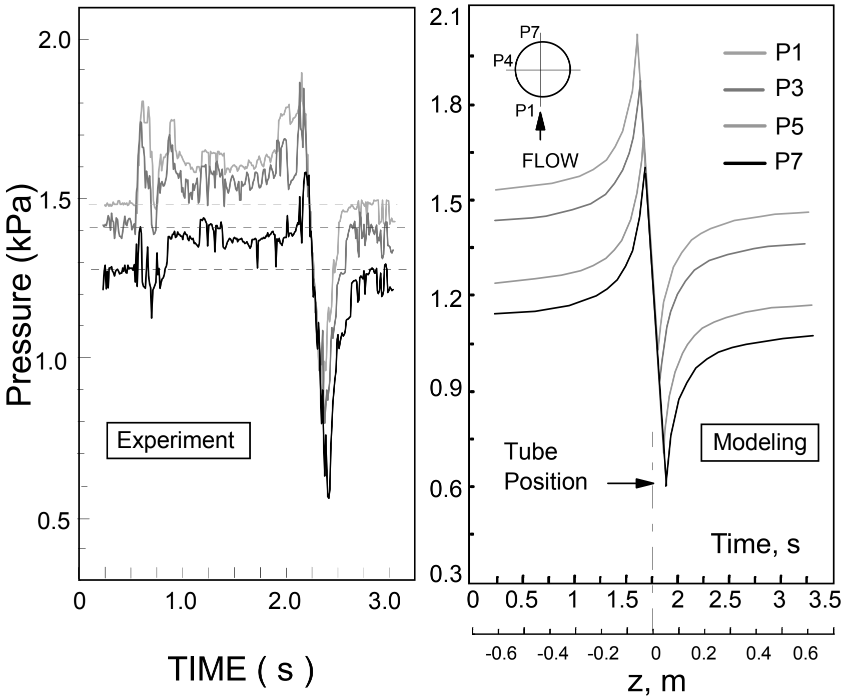


Fig.2 Comparison of pressure profile from Davidson model with experiment (D_T=30 mm, D_B=80 mm).

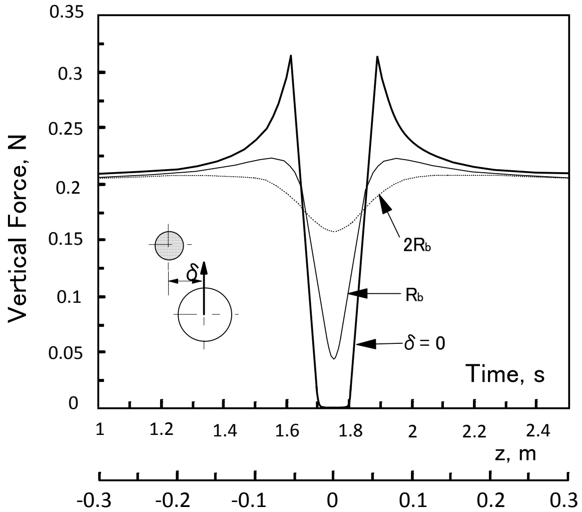


Fig.3 Drag around tube caused by passing bubble: D_T=30 mm, D_B=80 mm, δ=horizontal distance between centers of tube and bubble.

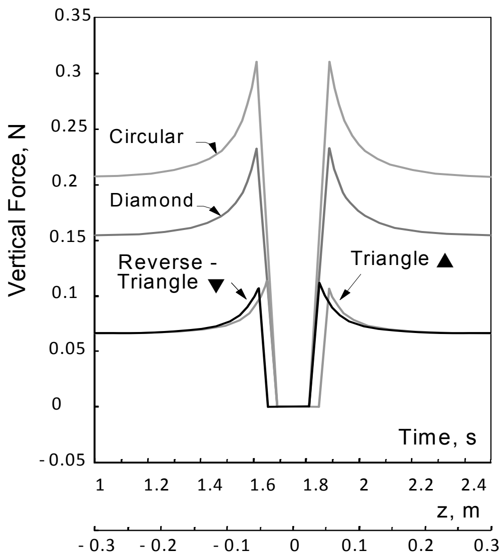


Fig.4 Drag caused by passing bubble for non-circular tubes, each with the same projected area.

compared for different tube shapes in **Figure 4**, each with the same projected area. The peak values depend on the immersed volume because of buoyancy. Note that the drag profiles for vertical-symmetric tubes circular, diamond) are symmetric for potential flow, but not symmetric for non-vertically-symmetric tubes (triangle, reverse-triangle), because of the interaction between tube surface and bubble.

2) EXPERIMENTAL TRANSIENT FORCE ON A SINGLE TUBE INDUCED BY PASSING BUBBLES

Experiments were carried out by the same method as in previous work [(2)] using a unique instrumented tube. Transient forces on a fixed horizontal tube (ϕ30 mm) were measured in 2-dimensional column (22 x 378 x 850 mm) with bed material of glass beads (ϕ0.6mm dia., density: 2450 kg/m^3). Forces on a tube induced by a passing bubbles, measured by strain gage F, pressure force $(F)_{MS}$ (integrated from measured pressure) and predicted pressure force $(F)_{TH}$ (drag from Davidson potential flow model) are indicated in **Figure 5** for a circular tube. The difference between F and $(F)_{MS}$ is the force associated with particle motion, i.e., impact force of collision of wake particle (at ③) and wake shedding (at ④) .

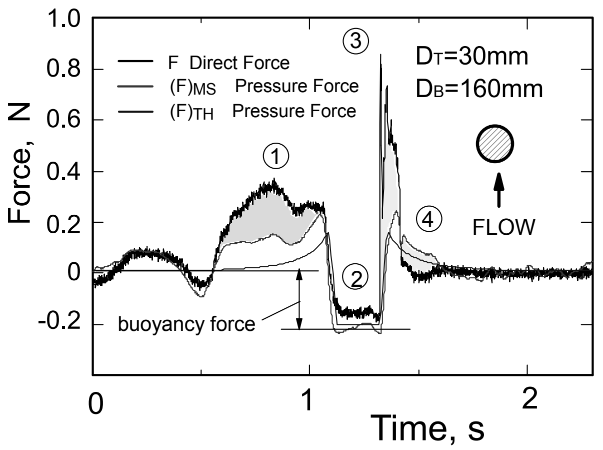


Fig.5 Experimental transient force induced by passing bubble (circular tube).

Transient forces for non-circular tubes are indicated in **Figures 6** and **7**, for a triangle-tube and a reverse-triangle tube respectively. **Figure 6** shows that severe impulses, due to collision of wake particles, appear just after bubble passage and then there are no signals corresponding to wake shedding. On the contrary, in **Figure 7** for a reverse-triangle tube, the force corresponding collision of wake particles decreases, while the force corresponding to wake shedding increases, unlike the case of triangle tube. This is mostly due to the shape of tubes. A triangle tube is easily struck by wake particles at the bottom surface and not so severely affected by wake shedding for downward movement. The reverse explanation applies for the reverse-triangle tube. This is confirmed by the frame-by-frame analysis of a vector-diagram of particle motion around a tube (**Figure 8** for a triangle tube, omitted here for reverse-triangle tube). In the case of the reverse-triangle tube (**Figure 7**), there is a large difference between the direct force and drag force (downward force associated with particle motion), when a tube is completely inside a bubble, due to the force caused by the weight of particles supported by the top of the tube.

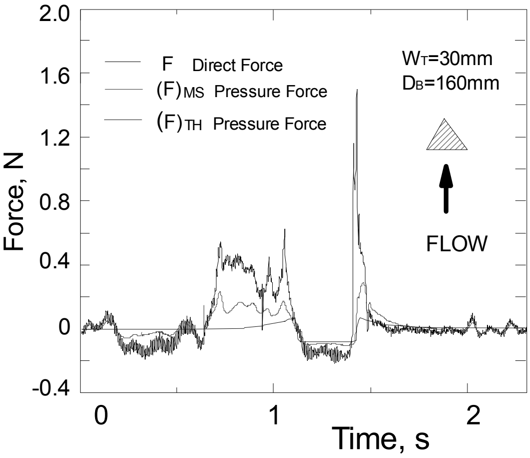


Fig.6 Transient force on triangle-tube due to passing bubble.

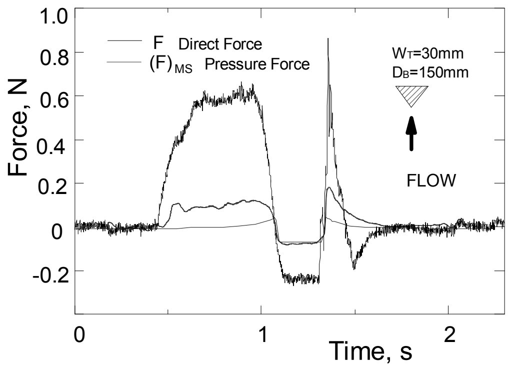
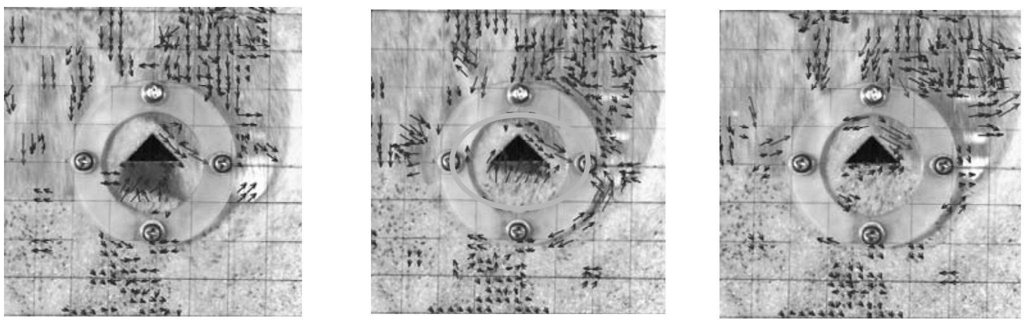


Fig.7 Transient force on reverse-triangle-tube due to passing bubble.



after bubble-in 0.936 s | 0.968 s | 0.984 s

Fig.8 Successive frames showing bubble and particle motion for a triangle-tube.

TRANSIENT FORCE ON TUBE IN A BUNDLE DUE TO PASSING BUBBLE

The configuration of the tube bundles tested is shown in **Figure 9**. Two tube arrangements were used for these experiments, a 7x7 tube array (s/D_T=1.0) and 5x5 arrays (s/D_T=2.0), staggered and in-line arrangements, for circular tubes, and 5x5 arrays (s/D_T=2.0), staggered and in-line arrangements, for non-circular tubes. In each test run, force measurements were synchronized with frame-by-frame analysis from the image of a high-speed camera. Results can be explained based on the motion of bubbles and particles around the instrumented tube.

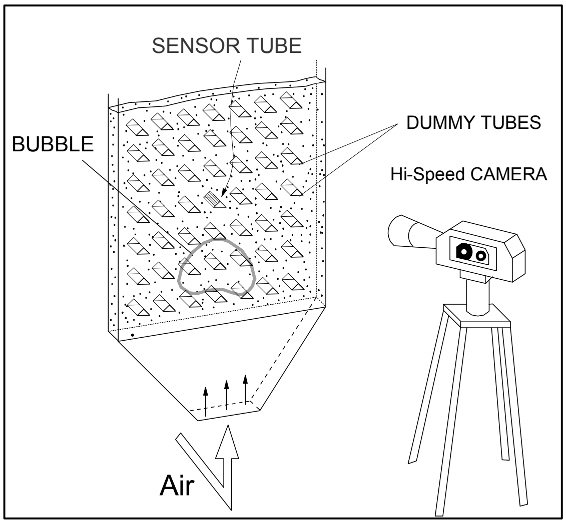


Fig.9 Experimental set-up (with tube bundle).

(1) DEPENDENCE ON TUBE ARRANGEMENT:

Results were similar to earlier experimental results on forces on tubes in bundles(4), as confirmed in **Figure 10**. When the sensor tube is shielded by an upstream tube, impulse forces are reduced (compare (b) and (c)). They are also reduced when the tube spacing becomes closer (compare (a) and (b)) because of immobilization of particles around the tubes.

(2) DEPENDENCE ON TUBE ARRANGEMENT AND SHAPE:

Similar phenomena appear for a tube bundle as for a single non-circular tube, with collision of wake particles being the predominant factor (causing an upward force), modified by friction and wake-shedding (causing a downward force).

It is explained well by visual analysis of the movement of particles around tubes (although the images are omitted here). The dependencies of transient forces on tube arrangement and tube shape are indicated in **Figure 11**. The upper figures provide the results for in-line tube

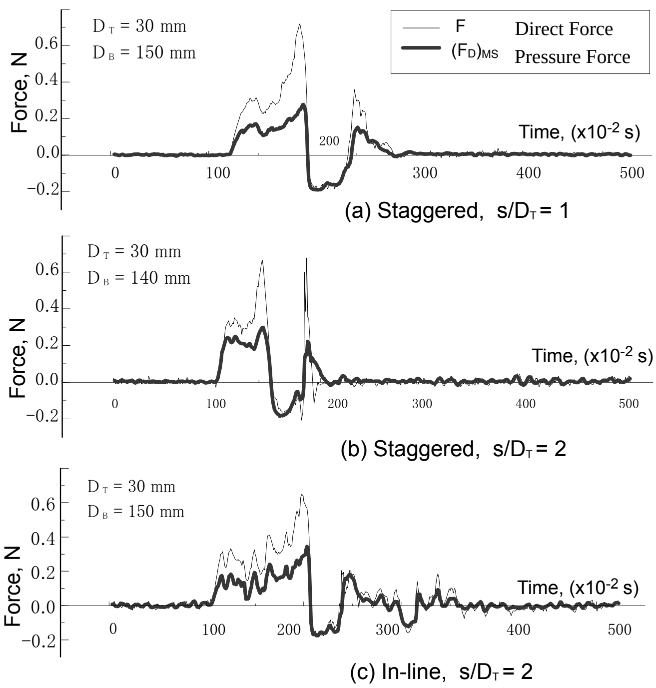


Fig.10 Transient force dependence on tube arrangement (circular tube).

arrangements, whereas the lower figures are for staggered arrangements, with similar tube spacing (s/D_T=2.0). In general, the impulse upward force is most severe for a triangle-tube array, followed by the reverse-triangle tube array, with the circular tubes giving the lowest impulse forces. The effect of tube arrangement is similar to that for the bundle of circular tubes mentioned above. Although the trend of wake shedding (downward force) is not presented here, it became predominant in the case of the staggered reverse-triangle tube bundle. The degrees of dependence on tube arrangement and tube shapes are summarized in **Table 1**.

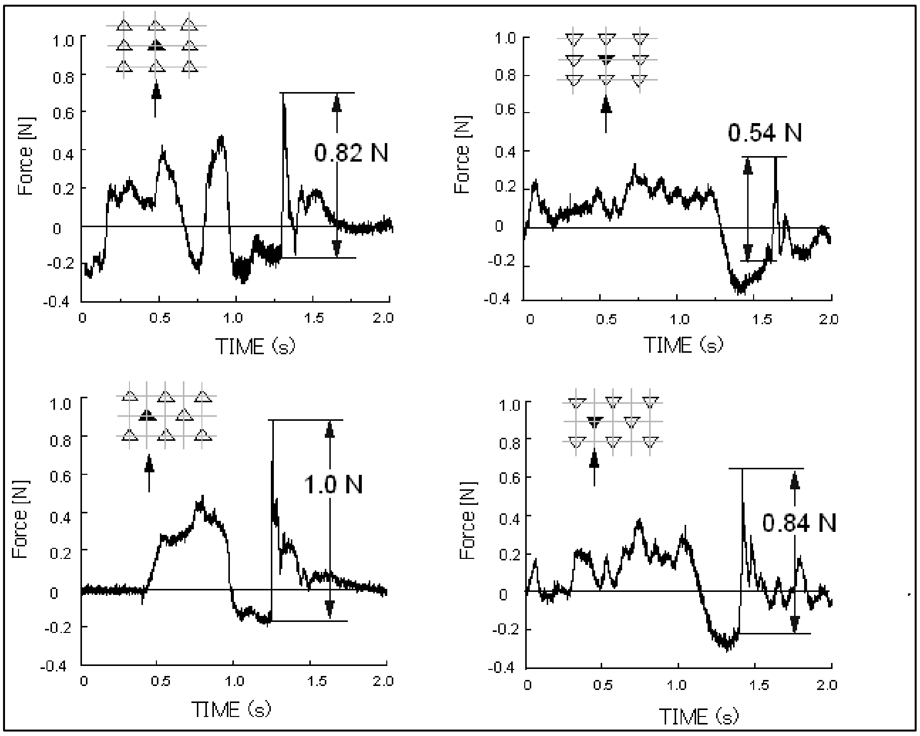


Fig.11 Relationship between transient force and tube arrangement (upper; in-line, lower staggered, left; triangle, right; reverse-triangle).

Table 1 Average peak-to-peak forces, impulse [N], (5 runs)
D_B= 140-165 mm (D_T: tube dia. (circular), width (triangle, rev-triangle)

	Single tube	*In-line (s/D_T=2)*	*Staggered (s/D_T=2)*
Circle	0.79	0.47	0.54
Triangle	1.55	0.76	1.2
Reverse-triangle	0.94	0.54	0.86

CONCLUSIONS

To clarify the influence of tube shape and tube arrangement on forces on tubes, transient forces caused by passing bubbles were investigated in 2-dimensional gas-fluidized beds. Predominant factors for the force, upward impulse force by wake particles and downward friction and wake-shedding, were identified for each case (dependent on tube shape and tube arrangement). These forces will be investigated for actual operation under the freely bubbling conditions in future work.

ACKNOWLEDGEMENT

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