Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-18, 2012

An Experimental Study on Spiral Motion of Free Rising Oblate Spherical Bubble

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1. Introduction

In the two phase bubbly flow, the dynamics of bubbles are complicated due to its moving interface and simultaneous deformation. Among those interfacial forces, prediction about lift force acting on a single bubble has been remained as the one of important problems of two phase flow analysis. Numerous studies have been made about kinematical and dynamical characteristic of free rising bubble from theoretical prediction of Saffman[1] based on potential theory. However, it needs experimental evaluation. Also the lift force in the linear shear flow is not directly applicable to the free rising bubbles which occur frequently in the fluidized bed. Therefore the present study aims to measure the trajectory of free rising bubbles in various sizes (equivalent diameter d_{eq} = 3~10*mm*), and to quantify the spiral number for Saffman's model and the lift force coefficient for free rising bubble.

2. Experimental Methods

2.1 Experimental Facility

Experiments have been performed in the vertical rectangular water chamber of 120 *cm* height with a squared cross section of 25 *cm* width as shown in Fig. 1. Images were captured from 70 *cm* above the bubble release location. The spiral motion of a bubble was captured by the high speed camera (1000 *frame/sec*, Photron Fastcam ultima 512) with the conventional digital camera (30 *frame/sec*). Instantaneous positions of the bubble and the bubble aspect ratio χ which is the length of the major axis divided by the length of the minor axis were obtained from pixel coordinates of the camera image. Then, so as to reconstruct the smooth horizontal trajectory of a bubble, discrete Fourier transform and partial sum of the Fourier series were used. Since we consider that the bubble's movement reaches to the terminal velocity at the test section, the vertical movement was fitted linearly with least square method. Therefore 3D trajectory of a bubble could be reconstructed as shown in Fig. 2. The rising velocity U_b of the present data shows a good agreement with the Mendelson's model[2]. Used liquid is cold filtered water.

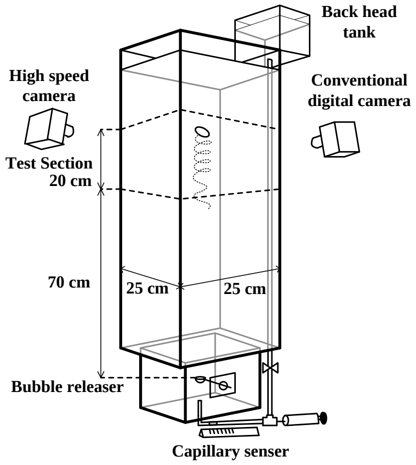

Fig. 1. Schematic of the experimental apparatus

2.2 Determination of Kinematical & Dynamical Characteristics of the Spiral Motion

First, we obtain radius R_w and angular velocity Ω of spiral motions for reconsidering the Saffman's formula[1]. From the power spectrum of x position, frequency which has largest energy was considered as rotation frequency in x direction f_x, and the energy was considered as R_{wx}. The determination of f_y, R_{wy} is similarly obtained. With following root mean square calculation as equation (1), R_w and Ω were determined.

$$R_w = \sqrt{(R_x^2 + R_y^2)/2}\ ,\ \Omega = 2\pi\sqrt{(f_x^2 + f_y^2)/2} \tag{1}$$

Secondly, the lift force F_L was determined by equation (2), the simplified set of the generalized Kirchhoff equations,

$$\begin{aligned} F_D &= -F_B\cos\theta \\ F_{L2} &= -F_B\sin\theta + \rho_f V(C_{M2}a_2 + C_{M1}(d\theta/dt)U_b) \\ F_{L3} &= \rho_f V(C_{M3}a_3 - C_{M1}(d\phi/dt)\sin\theta U_b) \end{aligned} \tag{2}$$

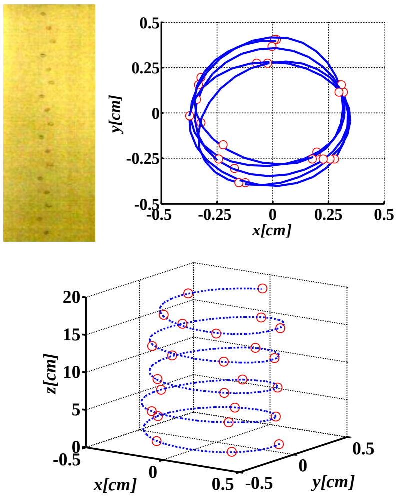

Fig. 2. Typical path of spiral motion (d_{eq} = 3*mm*)

It is similar to the form suggested by Shew et al.[3]. We followed their method about fixed shape assumption, definition of coordinate system, and calculation of $d\phi/dt$ and θ. The angle between direction of bubble's velocity and its minor axis was assumed to be zero[4].

3. Results and Discussion

3.1 Kinematical Result with Saffman's prediction

Saffman[1] developed the ratio of the angular velocity to the rising bubble velocity as follows,

$$\frac{\Omega R_w}{U_b} = \frac{X\theta}{KZ} \qquad (3)$$

This formula was reconsidered with calculation of its right hand side. θ was assumed to be 30°. K is the correction value for separation flow. The dimensionless number Sp which is defined as $Sp = \Omega R_w/U_b$ was calculated from the experimental data and compared with the above theoretical prediction. In Fig. 3, equation (3) shows similar tendency with the present data. However, there were very large difference in Sp, and theory could not predict that the spiral motion can be made for the bubble larger than $d_{eq} \approx 7mm$.

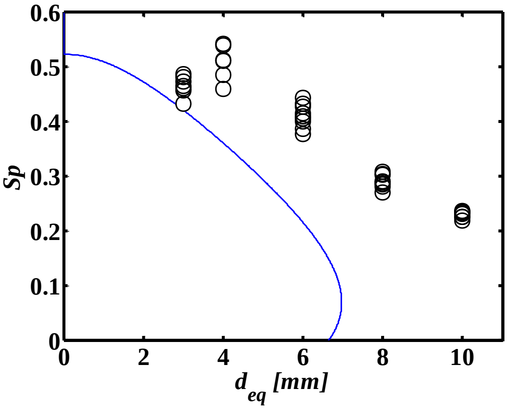

Fig. 3. Comparison Sp of the present experiment (circle) with the predicted Sp from equation (3) (solid line; K=1.75 (Saffman's recommend))

3.2 Wake induced Loads of the Spiral Motion

We calculated the drag coefficient C_D and the lift coefficient C_L defined as follows,

$$(F_D, F_L) = 0.5(C_D, C_L)\rho_f U_b^2 \pi (d_{eq}/2)^2 \qquad (4)$$

Fig. 4 shows experimental results of C_D and C_L. For $d_{eq} \leq 4mm$ region, determined drag coefficients were just fitted to the prediction of the Tomiyama et al.[5], and also the tendencies for the overall interval were reasonable.

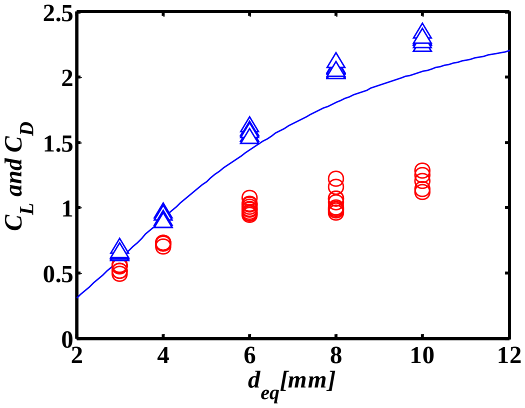

Fig. 4. C_D (triangle), C_L (circle) and C_D correlation of Tomiyama et al.[5] (solid line)

In the case of C_L, it increased from near 0.5 like as C_D while d_{eq} is small. But when d_{eq} = 6~10mm, present data show a gentle slope.

4. Conclusion

We investigated about dynamics and kinematics of large bubbles in water. Saffman's formula could not provide complete spiral characteristics, but it could represent same tendency with the experimental data in the way of decreasing Sp with increasing d_{eq}. Wake induced lift force of a free rising large bubble was obtained with fixed shape assumption. It seems that recent progress of understanding about the wake instability behind an axisymmetrical body can be helpful to explain the calculated C_L.

ACKNOWLEDGEMENT

The present work is supported by the Korea Science and Engineering Foundation (KOSEF) grant funded by Ministry of Education Science and Technology (MEST).

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