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VOF simulation on a large bubble in a linear shear flow

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1. Introduction

Instability of flow around a body moving in a fluid can induce lift force acting on the body. One example of this phenomena is a bubble rising. Lift acting on a bubble effects on a void fraction distribution of a bubbly flow, which can be related to two phase flow in a nuclear reactor, bubble column reactor, and a flow around a ship. Therefore, a lot of studies have been conducted on a lift acting on a bubble. However, it is hard to predict the lift theoretically, due to the nonlinearity of the flow around a bubble. This leads researchers to use experimental or numerical methods.

Study of Tomiyama et al.(2002) is the most well-known experimental results on a bubble rising in a linear shear flow. They used water-glycerin mixture as a liquid and rotating belt to make linear shear flow, and measured lift coefficients. As a main scale, they proposed a modified Eötvös number $Eo_H = \frac{\rho g d_H}{\sigma}$, where ρ is density of liquid, g is acceleration of gravity, σ is surface tension of a bubble interface, d_H is major axis of an ellipsoidal bubble. They observed that sign of lift coefficients are plus for small bubble, and minus for large bubble, with transition criteria of $Eo_H \sim 6$. Such experiment which uses rotating belt is extended by Dijkhuizen et al.(2010). Recently Yang et al.(2013) and Li et al.(2016) reported about lift force acting on a bubble in high Eo ($10 < Eo < 70$) which based on an equivalent diameter d and high Reynolds number $Re = \frac{\rho v d}{\mu}$ (estimation of present author is $1000 < Re < 20000$.), where v is relative velocity between bubble and liquid flow, μ is dynamic viscosity of the liquid.

Currently, numerical data for a bubble rising in a linear shear flow in high *Re* condition is very rare. Main reason might be due to too heavy computational cost. In this study volume of fluid (VOF) method is used to study single bubble rising in a high *Re* linear shear flow. Actually, due to not enough spatial resolution near bubble interface, spurious current is made and there may be some error in results of this study. Nevertheless, overall trend of previous experiments (Yang et al.(2013), Li et al.(2016)) can be reproduced.

2. Methods

In order to consider high *Re* condition, air-water bubbles are treated with $d=1.25, 5, 10, 15, 20mm$. ($\rho=958.3\ kg/m^3$, $\mu=2.84\times10^{-4}\ Pa\cdot s$, $\sigma=\sigma_w=0.059N/m$) In the case of $d=15, 20mm$, bubbles are broken, and this result is contradict with Li et al.(2016)'s experiment. The reason of the contradiction may be due to the limitation of numerical approach of this study (ex. Mesh refinement, initial condition, solver, etc.). To obtain results of $Re>10000$, ideal fluid which have surface tension $4\ \sigma_w$ is used for $d=15, 20mm$ cases.

Geometry of a liquid has a shape of box with 10d width (x), 20d height (y), and 3d thickness (z). Due to computational costs, only central region ($2.5d<x<7.5d$) have refined mesh (cells per diameter=20). Upper surface is designated as inlet with $U_x=U_z=0$, $U_y=-x\ m/s$, i.e. shear ratio of the base flow is $-1s^{-1}$. $x=0$ is set to static wall, and $x=15d$ is set to $U_y=-15d\ m/s$. Symmetry conditions are given at $z=0$ and $z=3d$.

2.1 VOF calculation

Fluent 15.0 is used as a solver. PISO algorithm is used for pressure-velocity coupling. Constant time step *2~50* micro second is used. Initial shape of bubble is set to spherical for $d=1.25mm$, and set to ellipsoid with aspect ratio 2 for larger bubbles.

Bubbles of $d=1.25, 5, 10mm$ are calculated with laminar model. In that case, explicit VOF method is used. 3rd order MUSCL as a spatial derivative and first order implicit method as a temporal derivative are used.

Meanwhile large eddy simulation(LES-WALE) method is used as a turbulence model for bubbles of $d\geq 10mm$. Implicit VOF method is used with compressing algorithm for interface interpolation. Bounded central differencing as a spatial derivative and bounded second order implicit method as a temporal derivative are used.

2.2 Data analysis

After the calculation, a trajectory of a bubble is reconstructed and fitted by a straight line. For comparison with computed result of vertical movement and well known previous data, correlation of Fan&Tsuchiya(1990) on terminal velocity of air bubbles in liquids is used.

$$v_{rel}\left(\frac{\rho}{\sigma g}\right)^{1/4} = \left[\left(\frac{Mo^{-1/4}Eo}{K_b}\right)^{-n} + \left(\frac{2c}{\sqrt{Eo}} + \frac{\sqrt{Eo}}{2}\right)^{-n/2}\right]^{-1/n} \quad (1)$$

where $n=1.6$ for pure liquid, $K_b=14.7$ for aqueous solution, $c=1.2$ for mono component liquid.

For analysis of lateral movement of a bubble, a lift coefficient is calculated. At first, quasi-steady lift is defined as following equation.

$$\overrightarrow{F_L} = -C_L \rho_l V\left(\overrightarrow{v_g} - \overrightarrow{v_l}\right)\times\left(\nabla\times\overrightarrow{v_l}\right) \quad (2)$$

where V is volume of a bubble. This lift is balanced by x directional component of buoyancy. Because density ratio between air and water is far from 1, the lift coefficient is simplified as follows,

$$C_L \cong \frac{g}{w}\frac{\left|\overrightarrow{v_g} - \overrightarrow{v_l}\right|_x}{\left|\overrightarrow{v_g} - \overrightarrow{v_l}\right|^2} \quad (3)$$

For comparison, following two experimental correlation are used. Tomiyama et al.(2002) proposed a following function of Eo_H.

$$C_L = \begin{cases} \min\left[0.288\tanh(0.121Re), f(Eo_H)\right] & Eo_H < 4 \\ f(Eo_H) & 4 < Eo_H < 10 \end{cases} \quad (4)$$

$$f(Eo_H) = 0.00105Eo_H^3 - 0.0159Eo_H^2 - 0.0204Eo_H + 0.474$$

Later, Dijkhuizen et al.(2010) produced a following correlation.

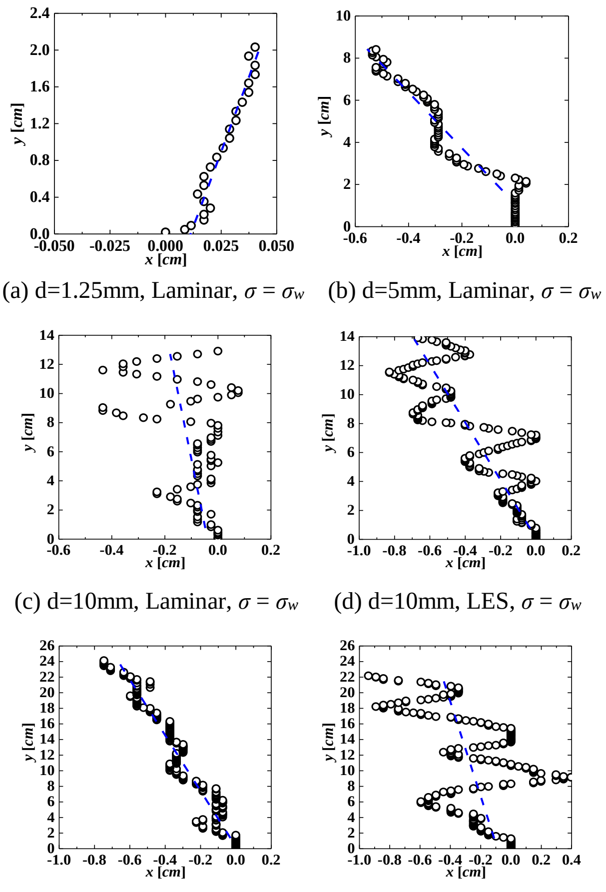
$$C_L = \min\left(\sqrt{\left(\frac{6J(Re,Sr)}{\pi^2\sqrt{ReSr}}\right)^2 + \left(\frac{1}{2}\frac{Re+16}{Re+29}\right)^2}, 0.002Eo_H^2 - 0.11Eo_H + 0.5\right) \quad (5)$$

3. Results and Discussions

Trajectories of a bubble is presented at fig.1. Only $d=1.25mm$ case shows bubble movement to moving wall, i.e. $C_L>0$, and a relatively straight trajectory. From the comparison between (c) and (d) of fig.1, larger shift can be observed from analysis result of LES. In the case of (d) and (e), amplitude of zigzag path of (e) is decreased and it may be due to decrease of Eo.

Because all the cases shows some un-periodical characteristics, there is a difficulty of determination of fitting region. Here, all the positions from initial position to final position are included to obtain the fitting curve. Larger height of analysis domain will be recommended for further study.

Vertical component of relative velocity of a bubble is shown in fig.2. Comparing with correlation of Fan&Tsuchiya(1990), over prediction is observed. In the case of $d=10mm$, turbulence modelling does not generate much difference.



(a) d=1.25mm, Laminar, $\sigma = \sigma_w$ (b) d=5mm, Laminar, $\sigma = \sigma_w$

(c) d=10mm, Laminar, $\sigma = \sigma_w$ (d) d=10mm, LES, $\sigma = \sigma_w$

(e) d=15mm, LES, $\sigma = 4\sigma_w$ (f) d=20mm, LES, $\sigma = 4\sigma_w$

Fig. 1. Trajectories of a bubble rising in a downward linear shear flow.

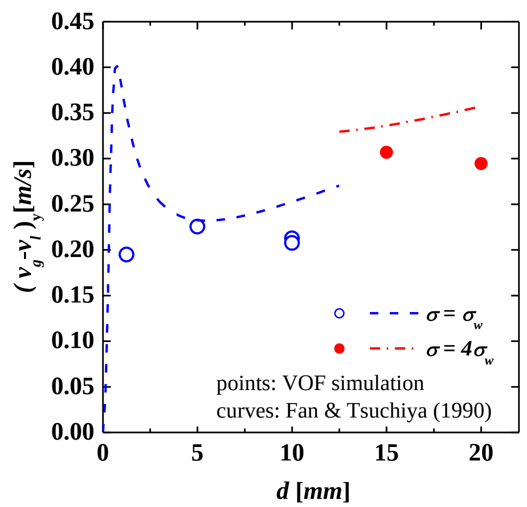
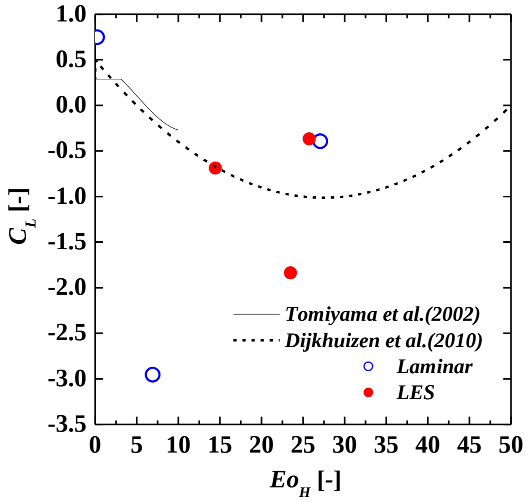
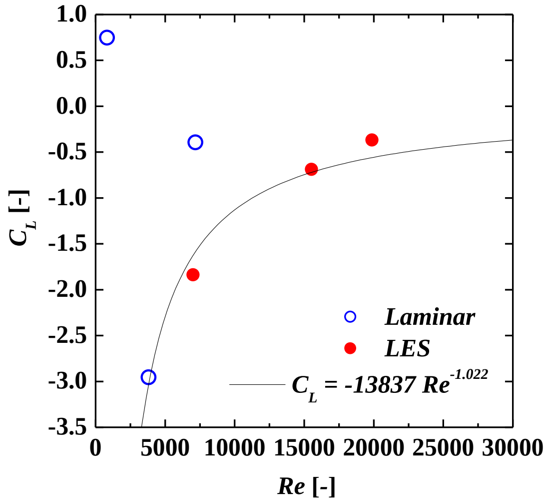


Fig. 2. Vertical relative velocity of a bubble



(a)



(b)

Fig. 3. Lift coefficients of a bubble rising in a downward linear shear flow.

Fig.3 shows lift coefficients following Eo_H and *Re*. In the case of Fig.3(a), it is hard to determine a trends of data. However, in the case of Fig.3(b) with an exception of a data about *d=10mm* from a laminar model, C_L are almost proportional to the inverse of *Re* and it seems that asymptotic value of C_L for infinitely large *Re* is between 0 and -0.5.

3. Conclusion

VOF simulations are conducted for investigation of lift acting on single bubble rising in a high *Re* linear shear flow. In spite of small amount of data and numerical error about spurious current near bubble interface, some insights can be obtained.

First, a turbulence model generates large difference on C_L of large *Re* bubble. Second, for lift acting on a large *Re* bubble in a linear shear flow, *Re* is better scale than Eo_H and C_L is proportional to inverse of *Re*. Despite of some quantitative difference between results of experiment(Yang et al.(2013), Li et al.(2016)) and present numerical study, all results shows $-7<C_L<0$ for large *Re* bubbles.

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