Asymmetric Deformation of Bubble Shape – Cause or Effect of Vortex Shedding?

Wichterle, K.
2012

Dostupný z `http://www.nusl.cz/ntk/nusl-126645`

Asymmetric deformation of bubble shape – cause or effect of vortex shedding?

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Two perpendicular projections of rising bubbles were observed in countercurrent downstream diverging flow. Evidently, the bubbles did not enter the boundary layer at the channel wall and plug liquid flow assumption was acceptable in our experimental equipment. It proved that this experiment is adequate for simulation of bubble rise in quiescent liquid column. Recent data taken by high speed camera Olympus allowed a period 60 seconds to be recorded. Image analysis by tailor-made program provides time series of quantities related to the position, size, and shape of bubbles. Besides determination of the aspect ratio of equivalent oblate ellipsoid, deviation from this shape has been investigated in sense of the parameters shown in Fig.1. Autocorrelation of the data indicate that the bubble inclination, α, is harmonically oscillating with frequency 5-10 Hz, cross correlation shows that shift of the center of mass Δx as well as the horizontal velocity increase with increasing α, Δz increases with increasing $|\alpha|$, and there is not any significant phase shift in oscillation of these quantities. Bulky bottom side of bubbles is in accordance with the model of bubble oscillation induced by instability of equilibrium of gravity and surface tension forces. Dependence of the oscillation frequency on surface forces (Eötvös number) is evident, while viscosity does not play role. Therefore vortex shedding likes to be an effect of the oscillation and not its cause.

Introduction

Medium size bubbles rising in low-viscosity liquids are non- spherical bodies. Usually it is approximated by an oblate ellipsoid; nevertheless typical shape of a bubble is presented in Fig. 1.

Trajectory of larger bubbles rising in liquids is not a straight vertical line. It has apparently helical or zigzag pattern. Prosperetti (2004) noted that such behavior had been mentioned yet in the notebooks of Leonardo da Vinci (1515) and introduced the term „Leonardo's paradox".

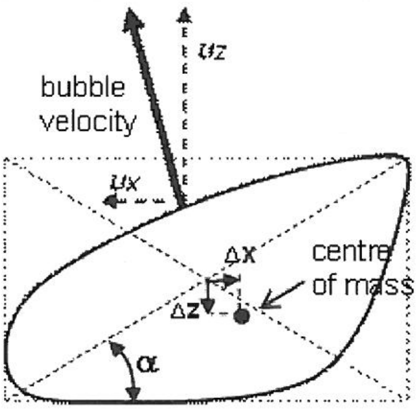

Fig. 1. Side projection of a medium-size bubble in low-viscosity liquid.

The shape of medium size bubbles is similar to an oblate ellipsoid. The body is wobbling and, unlike the motion of solid bodies in liquids, the bubble is usually oriented towards the direction of motion by its largest area. As the rising velocity of medium size bubbles in water is 0.2-0.3 m/s, the bubbles can be traced in laboratory vessels only for a short time period. Therefore, quantitative data related to the shape and size of rising bubbles is limited. Essential qualitative description of the bubble motion was pointed out by Saffman (1956). Pioneering experimental studies of small bubbles were done by Aybers and Tapucu (1969a,b), Mercier et al. (1973), for larger bubbles by Lindt (1972). Recently, a number of other investigators have applied various advanced visualization techniques for monitoring bubble motion, e.g. Duineveld (1996), Yoshida and Manasseh (1997), Fujiwara, Tokuhiro and Hishida (2000), Ellingsen and Risso (2001), de Vries (2001), de Vries, Biesheuvel and van Wijngaarden (2002), Mougin and Magnaudet (2002), Wu and Gharib (2002), Zhang, Eckert and Gerbeth (2005), Shew, Poncet and Pinton (2006).

In parallel, realistic hydrodynamics models including the case of deformable bubbles are solved by CFD methods e.g. Ryskin and Leal (1984), Bunner and Tryggvason (1999), Esmaeeli and Tryggvason (1999), Magnaudet and Eames (2000), Tomiyama et. al. (2002a,b), Koebe (2004). However, the computation required by these models is time consuming and only specific results are available, in certain cases still affected by initial conditions of the model.

Generally, it was assumed, that the oscillation results from vortex shedding. This paper is testing this hypothesis by experiments with liquids of different properties – in particular viscosity and surface tension.

Experimental

We have been recording two projections of bubbles rising in of different liquids by high-speed camera (150 frames/s). Our experimental equipment with counter-current downward diverging flow of liquid allows us to record and analyze the shape and movement of bubbles during considerable long time period. Frequency of bubble oscillation can be determined by autocorrelation analysis of the quantities varying in time series. Selected quantities were inclination angle, α, horizontal component u_X of velocity, and horizontal shift Δx of center of mass of the projected area. Meaning of them is apparent from Fig.1.

Example of the results is shown in Fig.2 for an air bubble of volume 200 mm^3 in water. All autocorrelation functions indicate evident repeatability of the bubble oscillation with unit frequency.

As shown in Fig. 3, the frequencies of oscillation somewhat depend on the size of bubbles.

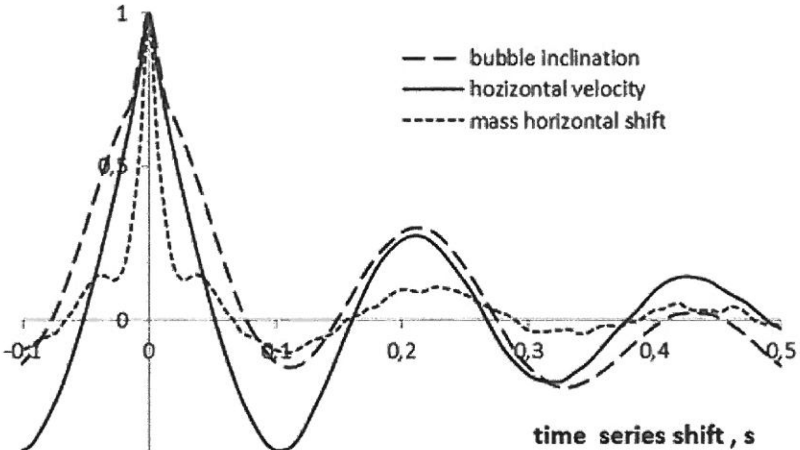

Fig 2. Autocorrelation functions of selected quantities.
Air bubble of volume 200 mm^3 in water

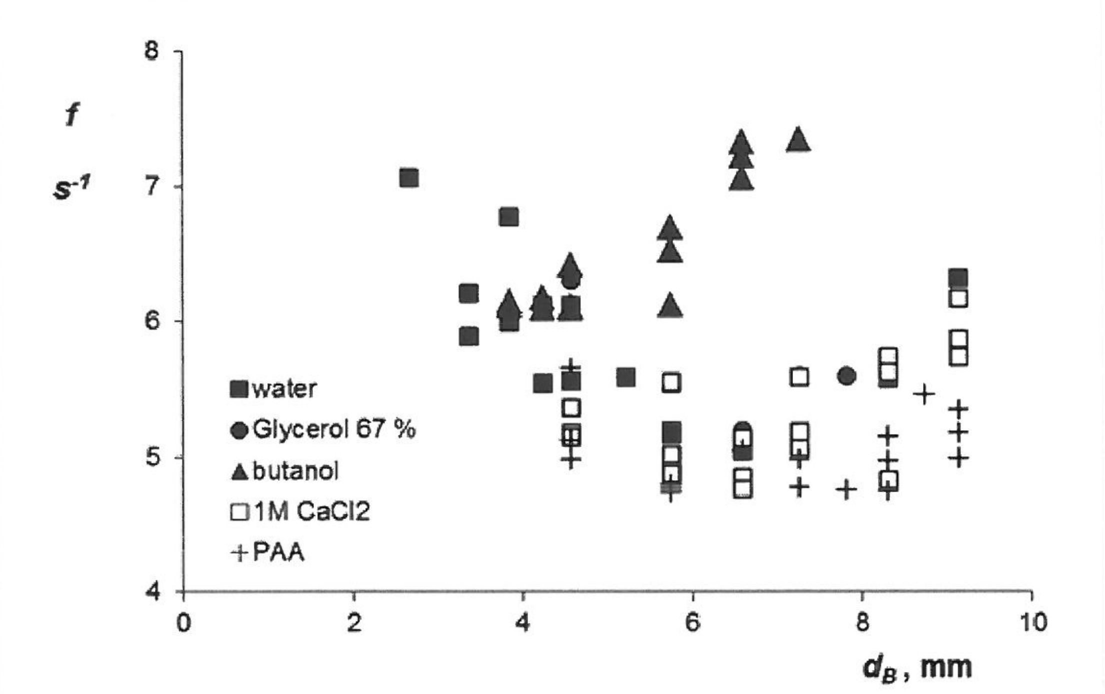

Fig 3. Frequency of bubble oscillations as a function of the bubble size

According to general assumption that the oscillation is controlled by vortex shedding, dimensionless Strouhal number

$$St \equiv \frac{f\, d_B}{u_Z} \tag{1}$$

should depend primarily on the Reynolds number

$$Re \equiv \frac{d_B\, u_Z\, \rho_L}{\mu_L} \tag{2}$$

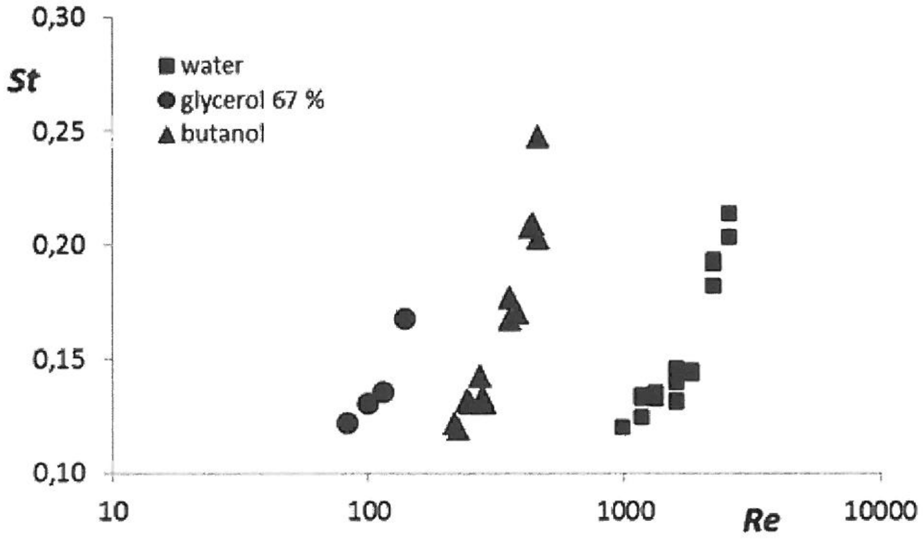

Fig 4. Strouhal number as a function of Reynolds number

However, as shown in Fig. 4, the function *St*(*Re*) does not lead to uniform representation of the frequency data neither for liquids of similar viscosity and different surface tension (water and butanol) nor for liquids of similar surface tension and different viscosity (water and glycerol solution).

Such result can be considered to be evidence that the frequency of bubble oscillations is not controlled by viscosity - inertia relations and therefore the vortex shedding does not play primarily role in the process.

Possible initiation of bubble oscillations

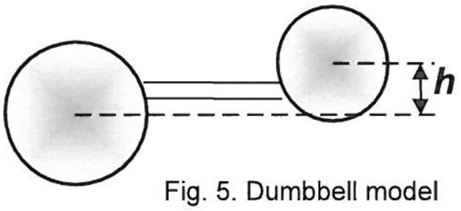

Fig. 5. Dumbbell model

When it is not viscosity, other option is to consider surface tension – inertia effect. Such idea can be explained by simple dumbbell model of oscillating spherical bubbles (Wichterle et al. 2012). Surface tension results in a couple of interconnected spherical bubbles (Fig.5) in different curvature of the spheres. Diameters d_1, d_2 should be

$$\rho_L\, g\, h = 4\,\sigma\left(\frac{1}{d_1} - \frac{1}{d_2}\right) \tag{3}$$

The upper bubble is smaller, and therefore its buoyancy force is smaller. Consequently, acceleration of the rising velocity is higher for the lower sphere. The rising acceleration d^2h/dt^2 is a function of rising velocity dh/dt and vertical distance h. For small h, the relation can be simplified to a linear differential equation

$$\frac{d^2h}{dt^2} + \frac{g}{C_M}\left[\frac{D\,h}{4\,L^2} + 2\frac{1}{U}\frac{dh}{dt}\right] = 0 \tag{4}$$

where D and U is mean diameter and mean rising velocity of the spherical bubbles, resp. Here, C_M is dimensionless coefficient of virtual mass, which is 0.5 for spheres; however it should be quite higher for the dumbbell. This differential equation is just the equation of harmonic oscillations under the condition

$$Eo > \frac{4\,g\,D}{C_M\,U^2} \tag{5}$$

where the Eötvös number is

$$Eo \equiv \frac{|\rho_L - \rho_G|\; g\, D^2}{\sigma} \tag{6}$$

Therefore, frequency of natural oscillation of the dumbbell is for larger values *Eo* equal to

$$f = \frac{\sqrt{Eo}}{4\pi}\sqrt{\frac{g}{C_M\,D}} \tag{7}$$

When a modified Strouhal number is introduced by normalization of bubble frequency by surface force effects:

$$St_\sigma \equiv f\left(\frac{\sigma}{|\rho_L - \rho_G|\, g^3}\right)^{\frac{1}{4}} \tag{8}$$

then we have

$$St_\sigma = \frac{Eo^{\frac{1}{4}}}{4\pi\sqrt{C_M}} \tag{9}$$

While C_M may probably depend also on the bubble shape, which is generally controlled by *Eo*, we can deduce from the dumbbell model that there may exist an universal correlation $St_\sigma(Eo)$. We have proved plausibility of this idea by our own data, as shown in Fig. 6. Comparison with the data of other authors is presented in Fig. 7.

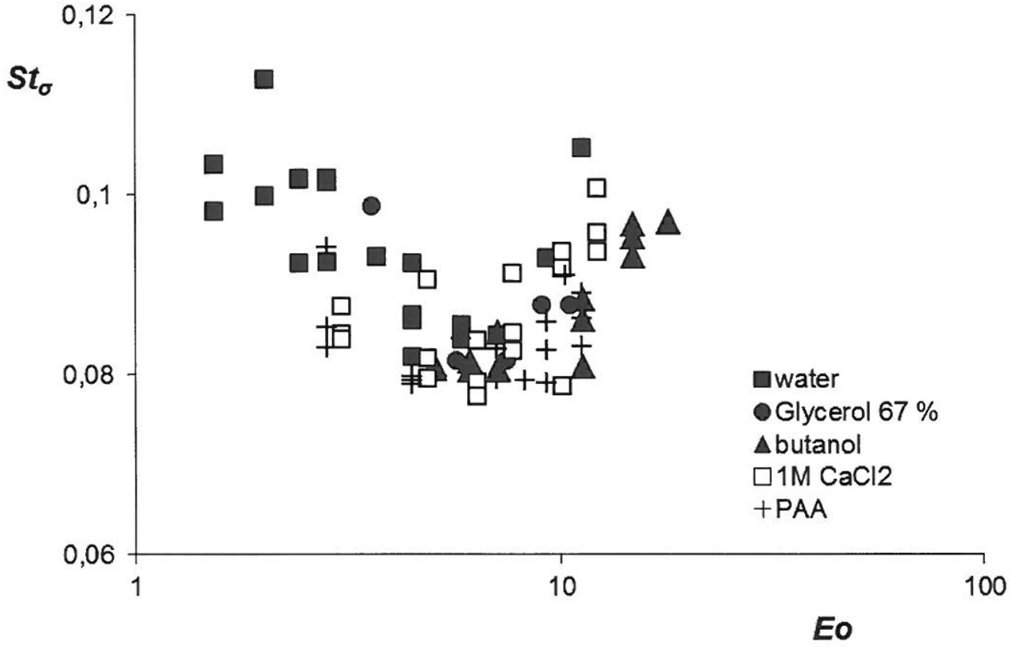

Fig 6. Modified Strouhal number as a function of Eötvös number.
Original data

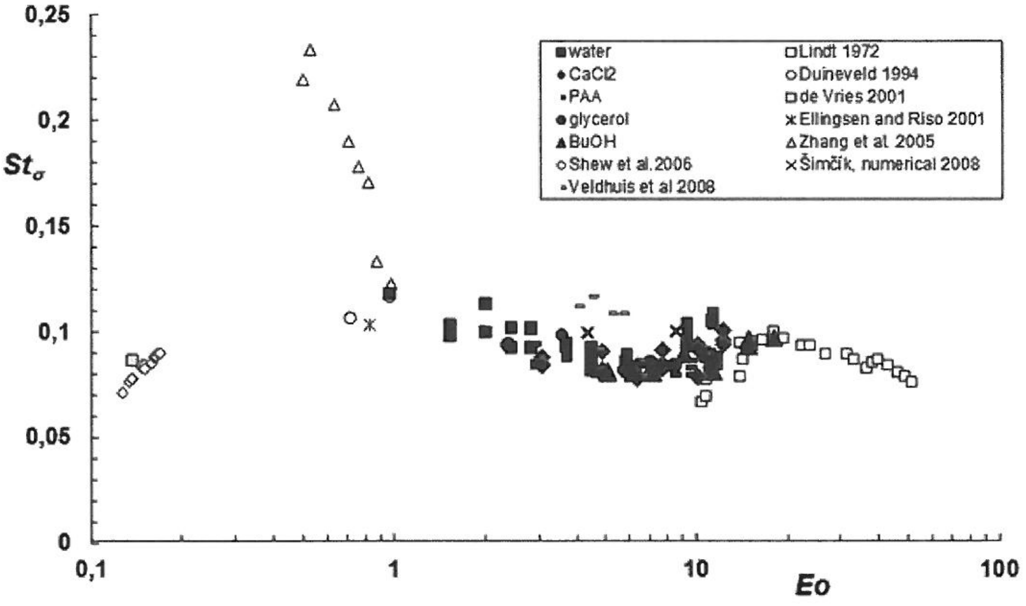

Fig 7. Modified Strouhal number as a function of Eötvös number
Comparison with literature data

More detailed characteristics of bubbles

Assumption of the shape oscillation approximated by the dumbbell model is in contradiction with the idea that medium size bubbles are essentially like oblate ellipsoids. Two perpendicular projections of bubbles recorded for quite a long time (60 s) by high speed camera (150 frames/s) allowed selecting the intervals when the bubble is observed just from the side. From lateral view (like the one in Fig. 1) we can calculate position of the center of mass. Values of relative shift $\Delta x/d_B$ and $\Delta z/d_B$ are plotted in Fig. 8.

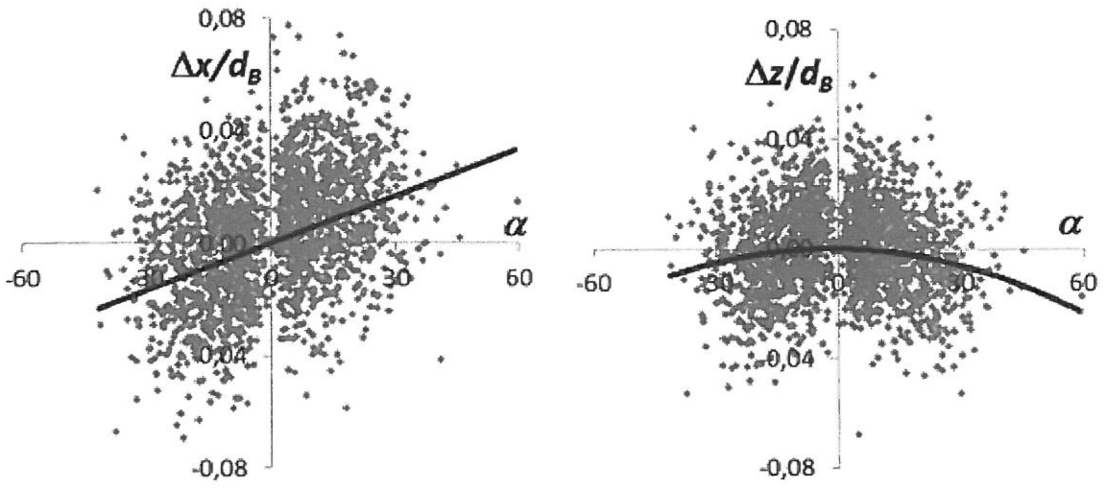

Fig. 8. Asymmetricity of bubbles – deviation od oblate ellipsoid shape as a function of incûination angle. Bubble 200 mm^3 in water

According to it, there are systematic deviations of the oblate ellipsoid shape, which depend on the bubble inclination. Apparently, the bottom side of bubble is always bulkier, in accordance with the assumptions of the dumbbell model.

Conclusions

α Experiments with rising bubbles indicate that there exists a definite frequency of variation of the bubble shape, position, and velocity.

α Experiments with liquids of various viscosity and surface tension proved that the vortex shedding alone do not control the bubble oscillation.

α Simple theoretical "dumbbell model" can explain potential effect of surface forces to the bubble shape and position. Related differential equations predict damped harmonic oscillation of definite natural frequency.

α Simple correlation of natural frequency of bubbles has been suggested, using the modified Strouhal number as a function of Eötvos number.

α This correlation proved to be plausible for correlation of both original and literature data within a wide range of variables.

α Detailed image analysis of bubble shape has shown that the shape of bubbles is slightly different from the anticipated oblate ellipsoid form. The differences are regular, their changes are in accordance with the dumbbell model, e.g. the lower part of bubbles is always bulkier.

α As mentioned, the dumbbell model alone predicts significantly damped oscillations. Steady oscillations are probably stimulated (in accordance to the generally accepted theory) by vortex shedding; nevertheless their frequencies are controlled exclusively by the surface forces.

Acknowledgements

Presented research has been supported by the grant No.104/07/1110 from the Grant Agency of the Czech Republic.

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