SCHLIEREN 3D VISUALIZATION OF THE SHAPE AND WAKE OF SINGLE ZIGZAGGING / SPIRRLLING BUBBLES FREELY RISING IN A QUIESCENT FLUID

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ABSTRACT

The flow in the wake of single air bubbles freely rising in water is visualized experimentally using the schlieren technique in combination with video recording. The experiments focus on ellipsoidal bubbles of diameter in the range of about 2.0 – 2.4 mm, which show spiralling or zigzagging motion during their rise in water. Bubble shape and wake structure were simultaneously recorded from two orthogonal directions.

1 INTRODUCTION

An important number of experiments have shown that millimetric bubbles rising in low viscosity liquids do not generally follow a straight trajectory [1-3]. In the regime where bubbles exhibit approximately oblate spheroidal shapes, they have either zigzagging or spiralling trajectories. Different methods of investigation are available to give experimental support to the understanding and numerical modelling of the behaviour of single bubbles. In this work, we used as experimental tool the slightly invasive, but very versatile and sensitive schlieren technique [4] with the aim to simultaneously visualize, in a three dimensional way, the shape, path and wake of a freely rising air bubble in clean water. The purpose of this study was to get more knowledge on the type of motions observed for bubbles with unstable paths.

2 EXPERIMENTAL METHOD

2.1 Test section

Experiments were performed in a quartz-walled water tank, with single bubbles of synthetic air released from the tank bottom into quiescent distilled water. The water channel facility and a part of the optical set-up are shown in Fig. 1. The bottom liquid layer in the water tank consisted of NaCl solution with a typical height above the bubble generator of 5 to 10 bubble diameters. During the initial phase of bubble rise, salted fluid was trapped into the wake and acted as a flow marker after the bubble left the bottom layer and entered the region with distilled water. The lifetime of the wake behind the bubble was preliminarily investigated in order to fulfil the requirement of single rising gas bubbles in quiescent liquid, ensuring that bubble-and-wake behaviour is not affected by the preceding bubbles [5].

2.2 Visualization technique

Schlieren technique is visualizing the refractive index gradients. The salted water, dragged in the wake of the bubble, may be observed. As the refractive index of air and water are different, the method captures the bubble shape simultaneously. In Fig. 2 a schematic overview of the optical setup, described in a previous paper [6], is shown. Bubble-and-wake representations were recorded by two synchronized CCD cameras and evaluated field-by-field. A trigger signal for the frame grabbing procedure was generated by a circuitry detecting the change in the picture content produced by a rising bubble.
Fig. 1 - Test section

Fig. 2 - Schematic overview of the schlieren setup

A two-way schlieren setup of this kind has been seldom attempted, as it did not seem appropriate for most applications. A similar setup was previously used for the study of rising bubbles by employing temperature gradient as flow marker [7].

3 RESULTS AND DISCUSSION

The problem of path instability of a rising bubble was recently modelled [8]. A one-to-one correspondence between the wake structure and the nature of the path has been established.

The proposed physical scenario for explaining the evolution of the whole system is described below. For small enough aspect ratios, a moderate amount of vorticity is generated on the bubble surface and is evacuated downstream under the form of an axisymmetric wake (combined action of viscous diffusion and axisymmetric transport). Beyond a certain critical aspect ratio, as an important amount of vorticity is generated at the bubble surface, the mentioned mechanism is not efficient enough. Therefore the axisymmetric wake becomes unstable and splits into a double-threaded open wake (Fig. 3).

In the zigzagging stage (Fig. 3b and 3b'), the vorticity contained in the two counter-rotating vortices changes sign twice during a period of the path, crossing zero when the curvature of the path vanishes. The double-threaded structure vanishes twice during a period of the motion and therefore the amount of vorticity shed downstream is still limited by this fact.

In the spiralling stage the two threads tend to wrap up around one another, they vanish at no moment and the vorticity contained in each of them keeps a constant sign all along the trajectory. For an observer moving with the bubble, the wake is seen as two streamwise vortex filaments which are wound in a helical path and are twisted around each other within one revolution of the bubble [3]. The spiral path is a more stable configuration (vorticity can be evacuated with great efficiency).

Experimental results showing these types of wake structure have been previously reported [7].

The present experimental visualizations are in accordance with the above-described model. In the present work the path of a rising bubble in distilled water was correlated with the wake behind the bubble: for a rectilinear path the wake consisted of a single-threaded wake, while a double-threaded wake was observed after a path instability set in, for both zigzagging and spiralling bubbles. Differences exist between the wake of a spiralling bubble and the wake of a zigzagging bubble and they are illustrated by this experimental study.

The visualizations were carried out for bubbles with a shape of oblate spheroids, with equivalent diameters ($d_{eq}$) in the range of 2.0 - 2.4 mm. The equivalent diameter is defined as $d_{eq} = \frac{2(ab)^{3/2}}{b}$ and the
aspect ratio is given by $\chi = b / a$, for the bubble whose major and minor axes have lengths $b$ and $a$, respectively. The equivalent diameter and aspect ratio have been determined from the images of the projections of the bubble as shown later.

### 3.1 Zigzagging bubble

After a path instability sets in, the bubble movement can be either a zigzag or a spiral. Two views are needed to identify spiralling or zigzagging as, even for a perfect zigzag, the motion might often look like a spiral.

![successive schlieren images of the wake of three bubbles](image)

**Fig. 4.** - Successive schlieren images of the wake of three bubbles (a, b, c) in zigzagging motion. Each pair of images contains the two orthogonal views (xz and yz, respectively).

The wakes of zigzagging bubbles are shown in Fig. 4; they present very interesting phenomena. Just behind the bubble, a double-threaded wake (two counter-rotating vortex filaments) is visible in the two orthogonal views, but the wake is unstable on a short time-scale (at a distance of few bubble diameters). It has been reported [7] that these patterns, observed in the wake several bubble diameters behind the bubble, are the result of the instability of the double-threaded wake: for the bubbles in the present regime of
interest, the instability of the double threaded wake is very similar to Crow instability [9], which, in general, is associated with the instability of the trailing vortices behind airplanes.

In Fig. 4a the two perpendicular views of a zigzagging bubble whose motion is in a single plane (two dimensional) can be seen. By coincidence, the plane shown on the right side of Fig. 4a (yz plane) coincides with one of the projection planes in this experiment. The path in the right view (yz) looks like a straight vertical line and that in the left view (xz) as a part of a sinusoid, clearly showing the zigzagging motion in a plane.

There exists a contradiction in the published experimental results concerning the zigzagging bubbles. Some authors [1, 3] observed vortex shedding at the maximum amplitude of the zigzag and they related this to the mechanism for maintaining the zigzag motion. In other experiments [7], on the other hand, a stable double-threaded wake was observed at this point. The wake visualization of the zigzagging bubbles in the present experiments showed a behaviour, which is in agreement with the latter observation: a stable double-threaded wake at the moment of the maximum amplitude of the zigzag (Fig. 5). The left views (xz) in Fig. 5 only show a single thread due to the projection: one thread blocks the view of the other one.

![Fig. 5 - Stable double-threaded wake at the moment of the maximum zigzag amplitude for three bubbles (a, b, c) (schlieren images containing two orthogonal views: xz and yz, respectively)](image)

The wake of zigzagging bubbles consists of a double-threaded wake as long as the curvature is non zero. When the curvature becomes zero the vortex filaments reconnect and successively a double-threaded wake consisting of two counter-rotating vortex filaments of opposite sign is formed [7].

In addition to the zigzag motion, the bubble tilts in the plane in which it moves. In order to interpret the bubble contours, the fact that the images represent projections of the oblate bubble, which changes its orientation to the vertical during its motion, has to be taken into account. Large deformation (10-15%) in the aspect ratio between the two projections for zigzagging bubbles could be noted (Figs. 4, 5).

### 3.2 Spiralling bubble

Contrary to zigzagging bubbles, the wake of spiralling bubbles consists of a double-threaded wake at all times. Thus, the wake of a spiralling bubble is continuous and consists of a pair of attached streamwise vortices which move with the bubble.

The present visualizations show a double-threaded wake for every spiralling bubble (Fig. 6). Both clockwise and counter-clockwise helical paths have been observed.

Although even for the perfectly spiralling bubble the wake becomes unstable a long time after the bubble has left the frame of view, this wake is considered stable. When spiralling bubbles are small or close to perfectly spiralling this is a stable wake. For large bubbles this wake is unstable close to the bubble (tendency towards zigzag).

In the spiralling stage the two threads tend to wrap up around one another and the vorticity contained in each of them keeps a constant sign all along the trajectory. For a spiralling bubble the orientation of the filaments is not changing relative to the orientation of the bubble. The bubble orientation changes in such a way that the minor axis is directed along the path.
In work on bubbles it is reported by various authors [1, 2] that the shape of the bubble can be described as an ellipsoid, however with the velocity vector directed along the minor axis. The present visualization experiments demonstrate the same orientation of the minor axis of the bubble.

The variation of the aspect ratio observed in the two orthogonal projections is considerably lower for the spiralling bubbles (1-3%) in comparison with the zigzagging bubbles (10-15%). Due to the continuous and steady wake, the spiralling bubble unlike the zigzagging bubble, does not experience shape oscillations but maintains the same shape over time [3, 7].

Due to a misalignment of the two orthogonal projections, the height of the bubble differs in the two views in Fig. 6a, which might appear as if the two views were not recorded simultaneously. In the subsequent processing the misalignment was compensated for by using the recording of the reference system (employed also for size calibration purposes).

In general, zigzagging and spiralling bubbles present similar wakes close to the bubble, but these wakes show great differences in their subsequent behaviour. The wake of zigzagging bubbles is unstable on a short time-scale, whereas the instability of the wake of a spiralling bubble sets in much later. The instability in the wake can be explained by the tendency of the counter-rotating vortex filaments to become unstable. For a zigzagging bubble the initial perturbation (the reconnection of the vortex filaments) is larger than in case of a spiralling bubble with a regular wake. Therefore the instability develops much quicker and is already visible close to the bubble.

**Fig. 6** - Wake stability of the double-threaded wake of two bubbles (a, b) in spiralling motion (successive schlieren images containing two orthogonal views: xz and yz, respectively)

Similar to the case of zigzagging bubbles (Fig. 5), it can be noted that the wake is positioned asymmetrically behind the bubble (Fig. 7), the vortices being clearly displaced out of the centre of the bubble, which is moving in a direction counter to the induced flow field.

**Fig. 7** - Asymmetrical attachment of the vortices of the wake of two bubbles (a and b) in spiralling motion (schlieren images containing two orthogonal views: xz and yz, respectively).

(a) \( d_{eq} = 1.60 \text{ mm}; \chi_{xz} = 1.66; \chi_{yz} = 1.68 \)

(b) \( d_{eq} = 1.65 \text{ mm}; \chi_{xz} = 1.74; \chi_{yz} = 1.74 \)

(a) \( d_{eq} = 1.64 \text{ mm}; \chi_{xz} = 1.78; \chi_{yz} = 1.73 \)

(b) \( d_{eq} = 1.65 \text{ mm}; \chi_{xz} = 1.79; \chi_{yz} = 1.74 \)
4 CONCLUDING REMARKS AND SUGGESTIONS FOR FUTURE WORK

A bubble-and-wake visualisation method has been developed based on the schlieren technique. The visualization confirmed that, for free rising bubbles, a double-threaded wake exists when the curvature of the path is non-zero: the wake of either spiralling and zigzagging bubbles consists of two counter-rotating vortex filaments. For both zigzagging and spiralling bubbles, the pair of streamwise vortices are attached at the bubble base, the attachment point of the vortex pair being displaced asymmetrically to one side of the bubble. Differences between the two motion types have been observed in the aspect of the wake far behind the bubbles; they can be explained by an instability of the system of the two counter-rotating vortex filaments [7]. As the initial disturbance of the wake for a zigzagging bubble is larger than for a perfectly spiralling bubble, this instability is observed closer to the bubble.

Further work is planned to gain detailed experimental data on bubble dynamics by simultaneous recording of two perpendicular views of bubble-and-wake and the top-view of bubble path in a set-up that uses a high-speed camera. There are several aspects that are still to be clarified:
- It has been reported [10] that in the inviscid spiralling of bubbles, in which both linear and angular impulse are conserved, it is essential that there exists a drift angle between the velocity vector of the bubble and the minor axis of the ellipsoid, which is a good approximation of the instantaneous shape of the bubble. In the present visualizations, no drift angle has been observed, the rise velocity vector was directed along the minor axis of the bubble. Further detailed experiments studying the shape and orientation of the bubble are therefore necessary.
- Published modelling results [7] predict a horizontal displacement of the mean position with respect to the release point of both zigzagging and spiralling bubbles. Experiments to verify this assumption are also intended.

REFERENCES