Quantitative Visualization of Microbubble Streams in Taylor Vortices

Tomoaki Watamura, Yuji Tasaka and Yuichi Murai

Graduate School of Engineering, Hokkaido University, Sapporo, Hokkaido, Japan

In this study, the motions and distributions of microbubbles in Taylor–Couette vortices were simultaneously measured by using an imaging approach. To obtain the velocity of microbubbles and the velocity distribution of the liquid phase, particle tracking velocimetry (PTV) adopting laser induced fluorescence (LIF) technique were employed by a single color-imaging video camera. This setup enabled us to distinguish tracer particles from microbubbles in captured images. The modifications in the waviness of Taylor vortices, enhancement of the basic wave and reduction of the modulation wave, are consistent with a recent study (Watamura et al., 2010). Further, the simultaneous measurements of velocity field and microbubble motions show a preferential distribution and organized ascending motion of the microbubbles in the wavy vortical structure of Taylor–Couette flows.

1. INTRODUCTION

Understanding behaviors of microbubbles in flow structures is important for applications of flows containing microbubbles. One of the interesting applications is the reduction of skin frictional drag acting on large vessels (1). Drag reduction technique using microbubbles of O(10 μm) diameter provides significant high efficiency. For instance, skin frictional drag reduction of O(10 %) can be achieved using tiny value of void fractions smaller than 0.1 % (2-5). Using a traversing Pitot tube, Serizawa et al. (6) measured the spatially and temporally averaged velocity profiles of a gas–liquid two-phase flow in a pipe; they showed that the transition of the pipe flow is suppressed by the addition of microbubbles. This phenomenon is explained as “re-laminarization”. Several previous studies of turbulent boundary layers containing microbubbles suggest that the interaction between distributions of microbubbles and turbulent coherent structures is an important factor in reducing the frictional drag (3-5). The observed phenomenon is described as “the accumulation of microbubbles in a critical zone” (3), or as “a complex and strongly nonhomogeneous concentration profiles” (4). In spite of these remarks, (i) motions, (ii) distributions, (iii) locations of microbubbles in the vortical structures, and (iv) local modifications in flow structures induced by bubble forcing have never been discussed because of the following issues: (a) difficulties in optical approaches to the measurements (also mentioned by Jacob et al., 2010), (b) needs for simultaneous velocity measurement schemes for both microbubbles and the surrounding liquid phase, which can provide spatial-temporal resolved data, and (c) difficulties in measurements of spatio-temporal development of the flow structures. Thus, the scopes of previous studies were limited to present the velocity statistics of liquid phase, namely, averages and correlations even in the latest publications (4,5).

To overcome the difficulties on measurement of spatio-temporal development of the flow structures,
Taylor–Couette flows (see Fig. 1) have been adopted as experimental platforms. Taylor–Couette flows can serve as model experiments for studying the effect of addition of bubbles on the coherent vortical structures of surrounding liquid phase. The major advantages of using Taylor–Couette flows for the evaluations are follows; (a) they are flows in closed systems, unlike the spatially developing flows in open systems, e.g. pipe flows, channel flows, and flows between parallel flat plates; (b) they have fluctuated vortical structures, i.e. wavy Taylor vortices; (c) their flow modes and transition are easily controlled; and (d) they enable us to compare the flow state to that in single phase flows based on the rich knowledge. Addition of bubbles for drag reduction has also examined by measuring the torque acting on the inner cylinder. For larger bubbles having diameter of $O(1 \text{ mm})$, the deformation of bubbles reduces the drag by 20% . However, for un-deformable bubbles having diameter of $O(100 \text{ \mu m})$, the bubbles accumulate in particular regions of the Taylor–Couette flow; at the center of the vortex (Taylor vortex) core or in the out-flow region near the inner cylinder (see Fig. 1 (b)). As the knowledge mentioned above, Taylor–Couette flows appear to be suitable systems for evaluating the influences of microbubbles.

We investigated the effects of additions of microbubbles with diameter of $O(10 \text{ \mu m})$ to a Taylor–Couette system; the flow transition was suppressed without any changing in the basal Taylor vortex structure, even with tiny void fractions of $O(0.01\%)$. According to the “Einstein’s formula”, increase of the effective viscosity due to the existence of microbubbles is negligible small. In this case, the effective viscosity is modified as $\mu = 1.0001 \mu_0$, where $\mu_0$ is the viscosity of the fluid for single phase fluid. Velocity measurements using ultrasonic velocity profiling (UVP) indicated that the suppression of the flow transition from wavy vortex flow (azimuthal waves superimpose on the Taylor vortices) to modulated wavy vortex flow (wave modulation appears on the azimuthal waves) is presumably caused by the preferential distribution of microbubbles in the Taylor vortices, which is generated by a two-way interaction between the microbubbles and the liquid phase flow. To clarify the distribution of microbubbles in the Taylor vortices, we applied particle tracking velocimetry (PTV) adopting laser induced fluorescence (LIF) to a Taylor–Couette flow containing microbubbles. Such experiments can simultaneously provide the local void fraction on a measurement plane with the velocity vectors for both liquid and gas phases.

This paper describes establishment of the measurement technique used for microbubbly flows, modifications in the flow pattern of the liquid phase, and the resulting organized distribution of microbubbles in oscillating wavy vortex structures. As mentioned above the Taylor–Couette system has been used for model experiments to represent influences of additions of bubbles on vortical structures. Knowledge obtained in this system, therefore, would advance our understanding of the influence of microbubbles on flows.

2. EXPERIMENTAL SETUP

The experiments were conducted in the vertical Taylor–Couette system shown in Fig. 1. The rotating inner cylinder with a radius ($R_i$) of 95 mm was made of black-painted CFRP, and the stationary outer cylinder with an inner radius ($R_o$) 105 mm was made of transparent Plexiglas to enable visualization of the flow generated between the concentric cylinders. The gap distance between the cylinders was $d (= R_o - R_i) = 10 \text{ mm}$. The height of the cylinders was $h = 200 \text{ mm}$. The radius ratio of the cylinders, $\eta (= R_i / R_o)$, and the aspect ratio of the fluid layer, $\Gamma (= h/d)$ were 0.905 and 20, respectively. The cylinders were placed in a transparent square water jacket for visualization. The Reynolds number of the flow system is defined by

$$Re = \frac{Ud}{\nu} = \frac{2\pi\Omega R_o (R_o - R_i)}{\nu},$$

where $U$, $\Omega$ and $\nu$ are the inner wall velocity, rotating frequency and kinematic viscosity of water used as
the test fluid. Reduced Reynolds number, $Re/Re_c$, is set in 8, where $Re_c$ is the critical Reynolds number for the onset of the primary instability, $Re_c = 134.5^{18}$. At this value of $Re/Re_c$, the flow mode is modulated wavy Taylor–Couette flow $^{13,14}$, which consists of two different traveling velocities of Taylor vortex with wavy patterns.

![Diagram of experimental setup](image)

**Fig. 1** Schema of (a) experimental setup of Taylor–Couette system and (b) Taylor vortices appearing in the fluid layer

Hydrogen bubbles with mean diameters of 60 μm (see Ref. 16) were generated by water electrolysis conducted from a platinum wire having a diameter of 100 μm. The wire was mounted at the bottom of the fluid layer, allowing the microbubbles to disperse into the fluid layer. The bulk void fraction, $\alpha$, was estimated from the electric current for the water electrolysis, and is given as

$$\alpha = \frac{Q}{\pi (R_e^2 - R_i^2) u_{term}}, \quad Q = \frac{1}{2} \frac{RT}{P} I,$$

where $Q, R, T, P, I$ and $u_{term}$ are gas flow rate, gas constant, temperature, atmospheric pressure, electric current and terminal velocity of a single bubble in a static fluid $^{19}$, respectively. The maximum value of $\alpha$ in the measurements was less than 0.012 %.

**3. MEASUREMENT TECHNIQUES**

PTV is adopted to simultaneously measure the velocity distributions of both liquid and gas phases. Generally, bubbles and tracer particles can be distinguished by the object area in the obtained images $^{20}$. Microbubbles, however, cannot be distinguished from tracer particles in the images, because the size difference between these two objects is negligible small. To distinguish the microbubbles from tracer particles, color-based PTV with LIF for bubbly flow $^{21}$ is extended to enable to use in microbubbly flows. Particles with a mean diameter of 15 μm containing laser induced fluorescent dye (specific gravity: 1.1, absorption wavelength: 550 nm, emission wavelength: 580 nm (see ref. 22)) are seeded as tracer particles. The test section of the $r-z$ plane is illuminated by a 2 mm thick, 2 W laser light sheet: the wavelength is 532 nm. As we can expect, tracer particles produce orange fluorescent light, and microbubbles provide green light scattered from the gas–liquid interface, when these are illuminated by the laser light. Images containing this color information of particles are recorded by a color-imaging high speed video-camera (Photron, Fastcam MAX 120 KC) having a spatial resolution of 40 μm/pixel.

Particles on each pixel in an image are identified by setting a threshold for “value” in the HSV color space $^{23,24}$, and searching eight surrounding pixels. Hue, $H \in [0, 360]$ degrees, saturation, $S \in [0, 1]$, and value, $V \in [0, 1]$, are defined as follows;
\[
H = \begin{cases} 
60 \times \frac{G - B}{\max(R, G, B) - \min(R, G, B)} & \text{(if } \max(R, G, B) = R) \\
60 \times \frac{B - R}{\max(R, G, B) - \min(R, G, B)} + 120 & \text{(if } \max(R, G, B) = G) \\
60 \times \frac{R - G}{\max(R, G, B) - \min(R, G, B)} + 240 & \text{(if } \max(R, G, B) = B) 
\end{cases} 
\]

\[
S = \frac{\max(R, G, B) - \min(R, G, B)}{\max(R, G, B)} ,
\]

\[
V = \max(R, G, B) .
\]

Values for \(H\) and \(S\) on each pixel with RGB color information are calculated. Then, the saturation-weighted averaged hue of a particle is calculated for a particle representing color. The positions of particles on the image plane are defined as the centers of the particle area. The resulting color image processing for calculating a particle color are shown in Fig. 2. The probability density function of the hue, which represents the color of all detected particles, is shown in Fig. 3. The two local maxima at 10 and 120 degrees represent red fluorescent light from tracer particles and green scattered light from gas–liquid interface of microbubbles, respectively. Colors representing tracer particles and bubbles in the images are distinguished using the criteria determined by a multilevel threshold method \(^{25}\) based on Otsu method \(^{26}\). This technique provides simultaneous PTV for both gas and liquid phases using a single camera instead of using two cameras with optical filters.

![Fig. 2 Principle and procedure of particle identification and color treatment; (a) original image, (b) image with thresholding, (c) identification of each particle, (d) hue distribution, (e) saturation distribution, (f) weighted color and (g) representative color of a particle](image)

![Fig. 3 Probability density function of the hue of a particle](image)
Velocity vectors for each phase are obtained by PTV. Grid point relocation of the liquid phase vectors is conducted. Then stream function, \( \psi \), is calculated to exhibit a successive Taylor vortex arrays in the axial direction as following equation,
\[
\psi = -\int ru_z dr.
\] (6)

The stream function displays the global Taylor vortex structure in the measurement plane, and the positions of the maxima and the minima in the stream function are identified as the vortex cores. The stream function is commonly used to visualize the Taylor vortex structures \(^{11,27}\), even for time-dependent flows \(^{11,27}\). Because individual bubbles can be identified, the number of bubbles in every image is countable in sequence. From the number density of bubbles, the time series of local void fractions can be measured; this measurement method simultaneously provides the velocity of both liquid and gas phases, and number density of microbubbles.

4. RESULTS AND DISCUSSIONS

4.1 TIME SERIES OF BUBBLE DISTRIBUTIONS

Fig. 4 shows time variations of (a) the series of vortex core positions which are defined as the maxima or the minima of the stream function, and (b) the number of bubbles detected in the \( r-z \) cross section from an image in a sequence. In Fig. 4 (a), the normalized vertical position \( z^* = (z - h/2) / d \) corresponds to the out-flow region of the Taylor vortex. In the figures, time, \( t \), in the figures is normalized by the rotational frequency of the inner cylinder, \( \Omega \). When the Taylor vortices are located at the crests of the axially oscillating azimuthal wave, the number of microbubbles increases. On the other hand, it decreases at the trough of the wave. This indicates that the bubbles make organized fluctuations of volume fraction, i.e. voidage wave, in the azimuthal direction. The cross-correlation between the ensemble-averaged position of the Taylor vortex cores and the number of bubbles is found to be 0.91. This indicates that the microbubbles prefer to exist at the crest of the azimuthal wave. Because of the preferential distribution and the motion of larger bubbles in the wavy oscillation of Taylor vortices, the flow mode is modified from "torus mode" to "spiral mode" when two pairs of Taylor vortices coalesce \(^9\). In contrast, our experiments at lower void fractions of microbubbles show that the axial wavelength and frequency of the basic wave remained constant with the addition of microbubbles.

![](image)

Fig. 4  (a) Vortex core position in normalized axial direction and (b) number of microbubbles in the time series

4.2 INSTANTANEOUS VELOCITY VECTOR FIELDS

Fig. 5 shows the instantaneous velocity vector distribution of the microbubbles, the instantaneous velocity vector field of the liquid phase, and the corresponding stream function distribution. The stream function distributions show the Taylor vortex pair at the crest and trough of the wave oscillation. At the crest, the microbubbles are accumulated in the axial flow, which connects two successive
counter-rotating Taylor vortices. This shows the meandering ascending motion of the microbubbles. On the other hand, the microbubbles do not show the same ascending pattern at the trough of the wave motion. To investigate the effect of the addition of microbubbles on the basic azimuthal wave and its modulation, time variations in the axial velocity component, $u_z$ at $(r-R)/d = 0.25$, are extracted from the velocity distributions obtained from PTV; these variations are analyzed using Fourier transform. In Fig. 6, gray symbols represent the variations in the peak values of power spectra with the void fraction $\alpha$, the peak values correspond to the basic wave frequency, $f_w$, and the modulation frequency, $f_m$. In the figure, the background component refers to the minimum power between $f_m$ and $f_w$ on the spectra. The power of the basic wave increases with increasing void fraction, while the power of the modulation wave decreases. These results indicate that the addition of microbubbles suppresses the flow transition from wavy vortex flow to modulated wavy vortex flow. This result is consistent with the previous result obtained from UVP (representing by black symbols in Fig. 6).

Fig. 5 (a) and (d) velocity vector field of liquid phase, (b) and (e) corresponding stream function, and (c) and (f) velocity vectors of bubbles, left and right panels indicate the results obtained at the crest and the trough of wavy motion, respectively.

Fig. 6 Power of velocity fluctuations corresponding to the basic and the modulation wave component versus void fraction. Black symbols indicate results from UVP (Ref. 16), and gray symbols indicate results from PTV. Circles represent basic wave power, and crosses represent modulation wave power, and squares represent background component.
4.3 DISCUSSIONS

We now address the interaction between the microbubbles and the coherent Taylor vortices. When the buoyant force acting on bubbles in a vertical Taylor–Couette system is greater than the inertia force of the fluid, the bubbles uniformly ascend without creating any distribution patterns and break Taylor vortex structures \(^{10,15}\). This state can be classified as a one-way interaction, which is the effect produced in liquid phase flows by the ascending bubbles. On the other hand, when the fluid inertia force is greater than buoyant force of the bubbles, the bubbles are captured in the cores of the Taylor vortex and are arranged along the azimuthal wave like strings \(^{10,12}\). Because the scales of the vortical structures are unaffected by the presence of bubbles, the bubbles behave as passive tracers. This flow state is classified as a one-way interaction; in the present case, this one-way interaction is the effect produced in the bubble distributions by the vortical structure. In this study, the distribution patterns and motions of the microbubbles seem to be organized by the wavy Taylor vortex structure. This suggests that the interaction between the vortical structures and the microbubbles is a one-way interaction from the vortical structures to the distribution of microbubbles. Nevertheless, the velocity fluctuation powers corresponding to the basic and modulation waves are modified by the addition of microbubbles (see Fig. 6): the interaction between the microbubbles and the vortex structure represents another one-way interaction, from the distribution of microbubbles to the vortical structure. These results from simultaneous PTV indicate the two-way interaction between the distribution of microbubbles and the vortical structures. This scenario appears to be similar to the case of resonance effects on waves due to external forcing.

In general, with increasing Reynolds number, the velocity fluctuation power corresponding to the basic wave decreases, while that corresponding to the modulation wave appears and increases. However, with the addition of microbubbles, the variation in the power of the basic wave increases beyond the maximum value in the single phase condition. The microbubbles accumulated on the crest of the azimuthal wave may induce the enhancement of the basic wave. This is apparently similar to resonance effects on waves due to external forcing. Unlike large bubbles, microbubbles do not significantly modify the flow structures because of their small slip velocity and diameter. The “small” but certain slip velocity organizes the microbubble motion into the spatially and temporally periodic flow structures. These organized microbubbles have the potential of adjusting the flow structures by the suppression of the flow transition, as explained in this study. We believe this phenomenon is the key factor to understanding the high sensitivity (or high efficiency) of microbubbles to the control of turbulent flows.

5. CONCLUSION

The two-way interaction between distributions of microbubbles and vortical structures, which suppose to bring the suppression of the flow transition in Taylor–Couette flows, was investigated experimentally. To measure the behaviors of both liquid phase and microbubbles in the axial-radial cross section of the Taylor–Couette flow, the measurements for microbubbly flow applying PTV together with LIF were conducted using a single color-imaging high-speed video camera. From saturation-weighted averaged-hue determinations, we were able to distinguish tracer particles and microbubbles using color information in images. From the time series of the axial positions of Taylor vortices and number of microbubbles in the measurement plane, we found that the microbubbles organize preferential distributions in the azimuthal direction. The number density of microbubbles increases at the crests of the azimuthal wave of axial oscillation, and decreases at the troughs. Furthermore, at the crests, microbubbles show preferential accumulation and ascending motion in the axial flow, which connects neighboring Taylor vortices. Temporal variations in the liquid phase velocity field also represented the enhancement of the basic azimuthal wave and suppression of the modulation wave, as mentioned in our previous study. These obtained results indicate that there is a selective two-way interaction between the flow structure and the existence of microbubbles. This mutual interaction provides the enhancement of
the basic azimuthal wave and suppresses its modulation waves, which is similar to the case of resonant effects on waves due to external forcing.

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