Bubble behavior in a vertical Taylor-Couette flow

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Abstract. Bubble distributions organized in a vertical Taylor-Couette flow are experimentally investigated. Modification of shear stress due to bubbles is measured with a torque sensor installed on the rotating inner cylinder. The wall shear stress decreases as bubbles are injected in all the tested range of Re from 600 to 4500. The drag reduction ratio per void fraction measured in the present experiment, which indicates net gain of the drag reduction, has been evaluated. The gain was more than unity for Re < 2000 while it descends negative for Re > 4000. The maximum gain achieved was around 10 at Re = 600, at which point the bubbles dispersed widely on the inner cylinder surface and effectively restrict momentum exchange of fluid between the two walls. The expansion of Taylor vortices in the vertical direction by the presence of bubbles was confirmed by flow visualization including particle tracking velocimetry. Such bubble behaviours interacting with Taylor vortices are discussed in detail in this paper.

1. Introduction
Taylor-Couette flow is a typical research target for investigating the fluid mechanics of shear flows and involves a number of nonlinear phenomena as this conference deals with them. The flow regime map of the Taylor-Couette flow is classified by a function of two Reynolds numbers, i.e. Reᵢ for the inner rotor and Reₒ for the outer rotor as summarized by Andereck et al [1]. The map was established in the past except in a very high Reynolds number region at which a huge experimental facility is required to be tested. Recently some new trials are being carried out to modify or alter the existing flow structure using a third parameter for the flow. Use of the third parameter can be a hint to know the mechanism of nonlinear energy transfer [2][3] and controllability of the flow structure, such as by additional disturbance / oscillation of the cylinder in an arbitrary direction, and eccentric displacement of the rotating axis.

Our study aims to know the possible effects of shear stress modification in the Taylor-Couette flow by mixing a small amount of gas bubbles. This study was initially planned in relation to a state-of-the-art technique called microbubble drag reduction for a wall boundary layer [4]. The technique is recently of much interest since it can actually reduce the shear stress, and is expected to be put into practical use e.g. for large ships [5]. It was experimentally confirmed at several institutes to date that the microbubbles produced 80% drag reduction in optimized cases [6][7]. However, the mechanism of
the reduction itself is still unclear even though a great number of investigations have been performed in the last two decades. This is because the experiment for the turbulent wall boundary layer involves difficulties in the measurement of local time-dependent two-phase flow as well as in the bubble injection method. Furthermore, the drag reduction by bubbles is at present considered to be a limited phenomenon effective only for a relatively short distance from the bubble injection point [8]. We also think that there is a problem in the definition of the drag reduction, that is, the drag reduction appears only where the mean flow of the carrier phase alters near the bubble injection point. Due to these problems, we come to a point to modify the research strategy and to return to the origin to investigate the essential phenomena in shear flows containing bubbles.

Adopting the Taylor-Couette flow as the target flow field of carrier phase, several advantages can be utilized regarding the study of microbubble drag reduction as follows. 1) The knowledge of the flow structure at single-phase condition is already accumulated in the past so that the difference produced by bubbles might be seen easily. 2) The persistence of the drag reduction does not need to be treated since the flow is periodic in the azimuthal direction. This condition also gives an idea that, if the drag were confirmed to decrease, it would imply that the bubbles could reduce the drag indefinitely. 3) Upon decreasing the Reynolds number, the possibility of shear stress reduction in a laminar state can be studied as well. For instance, the effective viscosity of bubbly liquid (Einstein 1904 and further explained by Batchelor 1967), which decreases with bubble deformation (Rust and Manga 2002), can be validated. 4) Upon increasing the Reynolds number up to a turbulent flow, the relationship between the shear stress modification and the flow structure can be elucidated in detail.

Atkhen et al [9] reported the bubble distribution pattern in a vertical Taylor-Couette flow system accompanying axial downward liquid flow and revealed the relationship between the axial Reynolds number and the bubble phase velocity in highly turbulent flow conditions. Djeridi et al [10] showed the bubble distribution pattern both in air bubbles and cavitation bubbles, and found that the bubbles’ wavy distribution in the azimuthal direction depended on the properties of the gas phase. Berg et al [11] measured bubble-induced drag modification in highly turbulent Taylor-Couette flows at Re>10^5, and confirmed a drag reduction of 20%. They also ascertained that a drag reduction was not obtained in the case of solid particle mixture.

In our research, the relationship between the void fraction profile of non-condensable gas bubbles and the shear stress is investigated based on optical measurement to determine the bubbles’ role in the flow modification of the Taylor-Couette flow. In this paper, we describe about the experimental method, the visualization result of bubble behavior, the shear stress modification by bubbles, and the flow alternation of Taylor vortices in the gap.

2. Experimental method
Figure 1 shows a schematic diagram of the experimental set-up. The inner cylinder is 120mm in the outer diameter, and made of a resin painted black to aid flow visualization. The outer cylinder is 144mm in the inner diameter with a thickness of around 6mm, and made of transparent acrylic resin. The gap is 12mm so that the radius ratio of the Taylor-Couette system is 0.833. The effective height of the gap filled with liquid is 240mm while the height of the inner cylinder is 400mm. The liquid is open to the atmosphere to release bubbles on the free surface. The aspect ratio of the gap is 20.

A stepper motor whose rotational speed can be varied from 40 to 300 rpm is mounted on the shaft connected to the inner cylinder. A torque meter is installed on the shaft and measures the torque acting on the inner cylinder. The maximum measurable torque is 0.05 Nm. The relative error of the torque measurement is estimated as plus or minus 1%.

The outer cylinder is submerged in a transparent oil jacket to reduce the effect of light refraction. With a slight eccentric displacement of the coaxial cylinders, a considerable oscillation of the free surface could emerge inside the gap, resulting in irregular behavior of the torque. Therefore, the concentricity of the two cylinders is carefully tuned by monitoring the behavior of the free surface. A steady gradient of the free surface caused by the inclined shaft is also removed.
Silicone oil of kinematic viscosity 5cSt and density 915 kg/m³ is used as working fluid because of its stable properties, especially regarding contamination. The surface tension is 19.7x10⁻³ N/m, which is around one forth as that of water. Laboratory air is mixed into the liquid by a bubble generator located below the test section. The bubble generator is made of a porous material. The bubbly liquid made by the bubble generator is slowly transported to the test section by a positive displacement pump until uniform bubble number density is given in the test section before starting the measurement. As the measurement is started, the circulation of the flow is stopped but the bubble generator works to keep the bubble distribution uniform.

The void fraction inside the gap is not controlled but the gas flow rate is measured by a gas flowmeter. The average void fraction $\alpha$ in the test section is estimated by:

$$\alpha = \frac{Q_g}{\pi (R_2^2 - R_1^2) U_g},$$

where $Q_g$ is the gas flow rate, $R_1$ and $R_2$ are the radii of the inner and the outer cylinders. The average bubble rise velocity $U_g$ is measured by particle tracking velocimetry (PTV) applied for bubble-images. Individual bubble velocity vectors are obtained using PTV, and their vertical component is averaged during 0.3s. The uncertainty of the mean bubble rise velocity is estimated as 0.16mm/s according to image resolution, and that of gas flow rate is 0.005 in relative error. Therefore, the measurement uncertainty of the average void fraction is 10⁻⁴.

It is confirmed that the bubbles do not remain on the top free surface as foam (e.g. of beer) but leave the surface. In the case of water-air two-phase flow, once a small amount of surfactant is mixed inside such a rotating system, a great deal of foam appears resulting a drastic amplification of the torque as well as damping of vortices in the vicinity of the surface. Using silicone oil can avoid such a phenomenon because of the inert interface for the surfactant and the contamination.

The bubble distribution is illuminated with a metal halide light projected from the side in the case of whole field visualization.

![Experimental set-up of vertical Taylor-Couette flow system](image)

**Figure 1.** Experimental set-up of vertical Taylor-Couette flow system

### 3. Experimental conditions

The flow regime map of Taylor-Couette flow in the case of single-phase flow is shown in figure 2, which is adapted from the article [1]. The Reynolds number is defined by:
\[
\text{Re} = \frac{(R_2 - R_1)U}{\nu} = \frac{R_1(R_2 - R_i)\omega}{\nu},
\]

(2)

here, \(U\), \(\omega\) and \(\nu\) are the inner wall velocity, angular velocity and kinematic viscosity of the liquid. Since only the inner cylinder rotates while the outer cylinder is fixed, therefore, the observable flow regimes at \(\text{Re}<4000\) are circular Couette flow, Taylor vortex flow, wavy vortex flow, modulated waves, and turbulent Taylor vortex flow. There are four critical Reynolds numbers during these flow transitions (which are known to be dependent on the radius ratio). Increasing the void fraction will modify the transition Reynolds number between two states, and may alter even the flow structure itself. Simultaneously, the effective viscosity –so called, can slightly increase in the case of bubbles’ presence. However, the concept of the effective viscosity is only available in laminar flows but its behavior is unknown in the case of the transition region and turbulent flow conditions. Actually the bubble and the liquid have different velocity inside the bubbly Taylor-Couette flow, we do not introduce the idea of the effective viscosity here. Nevertheless, the maximum effective viscosity in the present tested range is estimated as around 5% larger than the pure liquid viscosity. The measurement uncertainty for \(\text{Re}\) is 5%, estimated by the temperature-dependent kinematic viscosity. It is worth noting that the effective viscosity as function of void fraction [12][13] is not considered in the definition of equation (2).

**Figure 2.** Flow regime of single- and two-phase Taylor-Couette flow

**Table 1.** Experimental conditions

| Parameter                      | \(R_1\) | \(R_2\) | \(R_o/R_i\) | \(L/d\) | \(\rho_l\) | \(\nu\) | \(\sigma\) | \(d_g\) | \(Q\)                | \(Re\) | \(Ta\) | \(Fr\) | \(We\) | \(Ca\) | \(We_t\) |
|-------------------------------|---------|---------|-------------|---------|-----------|---------|-----------|--------|---------------------|--------|-------|-------|-------|-------|--------|
| Inner cylinder radius         | 60mm    | 72mm    | 0.833       | 20 \((d=R_2-R_1)=12\text{mm}, L=240\text{mm}\) | 915kg/m³ (at 298K) | 5x10⁻⁶ m²/s (at 298K) | 19.7x10⁻³ N/m | 0.5 - 0.6mm | 0, 0.67 to 1.67x10⁻⁶ m³/s | 600 to 4500 | 7.28x10⁴ to 4.09x10⁶ | 0.33 to 2.46 | below 0.60 | below 0.01 | below 0.14 |
Detailed experimental conditions are listed in Table 1. The wall velocity of the inner cylinder ranges from 0.13 to 1.88 m/s. The maximum friction velocity is $3.96 \times 10^{-2}$ m/s. Dimensionless parameters in the table are defined as below. Capillary number, which indicates bubble’s deformability under a shear stress, was less than 0.01 in the present flow; therefore bubbles are almost spherical all through the experiments.

$$Ta = \frac{\omega^2}{v^2} \left( \frac{R_2 + R_i}{2} \right)(R_2 - R_i)^3, \quad (Ta \text{ is the ratio of centrifugal force to viscosity}) \quad (3)$$

$$Fr = U \left( gR_i \right)^{1/2} = \omega \left( \frac{R_i}{g} \right)^{1/2}, \quad (Fr \text{ is the ratio of inertia to gravity}) \quad (4)$$

$$We = \frac{\rho U g^2 (2R_i)}{\sigma}, \quad (We \text{ is the ratio of inertia to surface tension}) \quad (5)$$

$$Ca = \frac{\mu R_i}{\sigma} \left( \frac{\omega}{R_i / R_i - 1} \right), \quad (Ca \text{ is the ratio of viscous shear force to surface tension}) \quad (6)$$

$$We_\tau = \frac{\rho \left( 2R_i \right)}{\sigma} \left( \frac{2R_i \omega}{R_i / R_i - 1} \right)^2. \quad (We_\tau \text{ is the ratio of inertial shear force to surface tension}) \quad (7)$$

Figure 3 shows a histogram of bubble diameter denoted by probability density function. The bubble diameter is measured by image analysis for a series of locally photographed pictures. The histogram is slightly shifted to smaller bubble size as Reynolds number increases and the peak bubble diameter decreases significantly. However mean bubble diameter is approximately 0.6 mm in all cases. Namely,
the discussion hereafter can be made without considering the bubble-size as experimental parameter. These profiles were not altered significantly by the changes of gas flow rate equivalent to up to 5% in void fraction.

4. Bubble distribution patterns

Figure 4 shows examples of pictures of instantaneous bubble distribution in developed states. The white dots are the bubbles scattering the light. With the results of the bubble distributions, the following points can be made.

The bubbles distribute uniformly in the case of low rotational speed. This is because the bubble rise velocity is faster than the wall velocity of the cylinder. At $Re=600$, the Taylor vortices should be already appearing in the liquid. However, the bubbles do not organize into any clear structure for too low a velocity within each Taylor vortex. The bubbles in this case approach to the surface of the inner cylinder until $Re$ of 1000. This is explained by the centripetal force acting on the bubbles in the rotational system. Owing to the high concentration of the bubbles near the surface of the inner cylinder, all the bubbles rotate with around 80% of the velocity of the inner cylinder in the case of $Re<1000$. This means that the bubbles migrate much faster in the azimuthal direction than typical liquid velocity of the organized flow structure in the gap such as in a Taylor vortex or wavy vortex.

Upon increasing the rotational speed up to $Re=1800$, a clear organized structure of the bubble distribution takes place. That is, many bubbles accumulate into a single spiral path. It is known that spiral Taylor vortex appears in the single-phase flow if the outer cylinder is independently rotated in the inverse direction to the inner one. In the two-phase flow experiment, a spiral structure in the bubbles appears without rotating the outer cylinder. The similarity between these flows is difficult to explain but at least it seems clear that the bubbles should distribute so as to allow continuous bubble rising at the developed state.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{bubble_distributions}
\caption{Side views of bubble distributions organized in Taylor-Couette Flow at various values of $Re$}
\end{figure}
Figure 5. Bubble distribution diagram showing dependence of bubble distribution on $Re$ and $Q$.

Figure 6. Blow-up images of bubble’s spiral cloud
Figure 5 shows a classification of bubble distribution patterns observed in the Taylor-Couette flow, which is obtained under conditions of small gas flow rate; \( Q < 30 \text{ml/min} \). The bubbles at low Reynolds numbers distribute almost uniformly. The bubbles start to organize at certain Reynolds number around \( \text{Re}=1200 \). After the bubbles show an organized cloud, there are two major patterns of the organization. One is a spiral structure and the other a non-spiral pattern. As the gas flow rate increases, the spiral structure dominates. The spiral structure involves a phase velocity in the vertical direction. The non-spiral structure, i.e. an ordinary ring array structure, emerges as the gas flow rate is reduced. The bubble distribution pattern in the region near the transition lines between the spiral and the ring structures has a hysteresis effect of the experimentation, and switches irregularly from one state to the other over a long period. Moreover, the bubble distribution pattern for both cases can be divided into two types in terms of their radial distribution. At low Reynolds number (less than around 3000), the bubble cloud is located in the vicinity of the inner cylinder surface (Type A). In high Reynolds number, the bubble cloud shifts toward the central region of the gap (Type B). Eventually, we confirmed five bubble distribution patterns in the present vertical Taylor-Couette flow system, including the uniform distribution.

Figure 6 shows a blow-up image of bubble distribution in the gap at two Reynolds numbers. The white bands are the location of bubble clusters moving on a spiral path. The slope of the band corresponds to the downward phase velocity of spiral path. Here the phase velocity means the advection velocity of banded void fraction profiles, but does not mean the Lagrangian bubble cloud velocity or individual bubble velocity. It is defined for the Eulerian migration of the organized bubble distribution. The sign of the phase velocity implies the direction of the global rotation of organized structures, and it begins from almost zero at \( \text{Re}=1000 \) but becomes negative as Reynolds number increases. In addition, there are fluctuating components found in the path as seen in the images. One possible reason for this is an existence of a modulated wave mode of Taylor-Couette flow at this range of Reynolds number, but the mechanism correlating to the bubble behavior is unclear at this stage of the study. Comparing the results for the two Reynolds numbers, the spiral path is more stabilized at \( \text{Re}=3600 \), implying that bubbles diffuse actively within the turbulence produced in the liquid. Also, the pitch, which is the spacing of two neighbouring paths in the vertical direction, becomes larger.

**Figure 7. Phase velocity of bubble’s spiral cloud**

Figure 7 shows phase velocity of the bubble distribution in the spiral cloud state as a function of \( \text{Re} \). The phase velocity is defined as the parallel advection velocity of the bubble profile in the vertical direction. The phase velocity is measured by auto correlation for the brightness information of the
image. The orientation of the phase’s advection was vertically downward in all the tested range in Reynolds number and gas flow rates. This means that the spiral structure itself rotates in the turning direction of the outer cylinder. The absolute phase velocity is very slow and less than 1 mm/s at low Reynolds number and is linearly amplified as Reynolds number increases. The ratio of the phase velocity to the absolute azimuthal velocity of the outer cylinder is 1.07% in the maximum case. This corresponds to one turn of the spiral structure per 100 revolution of the cylinder. The reason for the existence of the downward phase velocity is explained by relative velocity between bubbles and liquid in the direction of the spiral path. That is, the bubbles in the cloud have advancing velocity (in other words; drift velocity or slip velocity) relative to the liquid due to their component of buoyancy. This also suggests that the bubble’s slip velocity ratio to the liquid along the spiral trajectory is also around 1%. The phase velocity slightly increases with the increment of gas flow rate because of promotion of the slip velocity between two phases.

Figure 8. Local bubble distribution in the gap

Figure 9. Radial bubble profiles inside the Gap

Figure 8 shows instantaneous bubble distributions in the gap, obtained by a backlight illumination. Solid dark spots in each picture are the bubbles suspended in the gap. At Re=600, the bubbles freely rise uniformly along the inner cylinder surface. Taylor vortex should exist already at this Reynolds number but no bubbles are reacted. At Re=1700, bubbles accumulate into a particular area in the vicinity of the inner cylinder. At 2000<Re<4000, bubbles are once released from the inner cylinder and draw a circulating trajectory around Taylor vortex core (at this stage Taylor vortex itself is not
shown but it is shown later). Further increasing Reynolds number; the area of the bubble presence expands wide due to turbulence effect.

Figure 9 shows bubble distribution in the radial direction inside the gap, averaged in time for a sufficiently long sampling time. This is measured by image analysis for the brightness information scattered from individual bubbles. The results indicate that the bubble’s profile in the gap is highly dependent on Reynolds number. At Re=600, the bubbles accumulate in the vicinity of wall surface of the inner cylinder due to centripetal force, provided that there is a bubble-free layer near the wall. Increasing the Reynolds number makes the profile wider in the gap for the interaction with Taylor vortex as well as its turbulence effect.

5. Frictional drag modification

Figure 10 shows the measurement results of friction coefficient, which is defined by:

$$C_f = \frac{\tau_w}{\rho U_j^2/2} = \frac{2\tau_w}{\rho_j (R_o \omega)^2}. \quad (8)$$

Here $\tau_w$ is the wall shear stress, i.e. skin friction of the inner cylinder measured by the torque sensor. The results show that the present measurement data exist between two theoretical curves obtained by Bilgen and Boulos [14]. The top curve is for the turbulent Taylor vortex regime while the bottom is for the circular Couette flow regime [15]. The experimental result in single-phase test agrees well with the theoretical value of turbulent Taylor vortex for Re>1500. The inclusion of bubbles makes the friction coefficient smaller than that of single-phase flow but cannot reduce it beyond the curve of Couette flow regime. This implies that the bubbles reduce Taylor vortex.

![Figure 10](image)

**Figure 10.** Friction coefficient of the inner cylinder, measured as a function of Re. Continuous lines represent theoretical values for single-phase laminar/turbulent Taylor-Couette flow.

Figure 11 shows friction reduction ratio as a function of Re number. The friction reduction ratio is defined by:

$$\eta = \frac{C_{f0} - C_f}{C_{f0}} = 1 - \frac{C_f}{C_{f0}} \quad (9)$$

The data show that the friction reduction ratio reaches 36% in the best case of the present experiment. However, $\eta$ decreases with an increase of Re, and becomes almost zero at Re=4000. At present we do
not understand well the reason why drag increase happens at $Re > 4000$ but one possible reason may be an accumulation of bubbles into Taylor vortex cores, by which each Taylor vortex is not damped but is rather stabilized. In addition, the turbulent intensity of the Taylor vortices might increase due to pseudo turbulence produced by bubbles, resulting in drag increase at high $Re$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure11.png}
\caption{Friction reduction ratio $\eta$ as function of $Re$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure12.png}
\caption{Measured sensitivity of drag reduction (gain factor) as a function of inverse Froude number $1/Fr$.}
\end{figure}

Figure 12 shows sensitivity of drag reduction, which is defined by:

$$S = \frac{\eta}{\alpha} = \frac{1}{\alpha} \left( 1 - \frac{C_f}{C_{f0}} \right),$$

as a function of inverse Froude number $1/Fr$. This quantity is also known as the gain factor of the bubble-based drag reduction. For example, when 1% of skin frictional drag reduction is obtained by
1% of void fraction in the gap, the sensitivity is obtained as unity. As seen in figure 12, the sensitivity is amplified up to around 10 in the best case, at which only a 1% supply of void fraction provides 10% of drag reduction. This tells us that the skin frictional drag reduction obtained here is not caused by a simple mechanism such as reduction of the average mass density, but apparently indicates the alteration of flow structure by bubbles. In addition, this sensitivity in the Taylor-Couette flow system indicates the fact that a significant drag reduction for quasi-steady flow is possible.

6. Transition of Taylor vortex structure

Figures 13 shows examples of the instantaneous structures of Taylor vortices visualized by the light sheet illumination method. This visualization was carried out under different conditions from the previous case, i.e. the mean bubble diameter was 2.0mm. Two cases of Reynolds numbers are investigated. One is the case of dispersed bubbly flow regime at $Re=900$. The other is the case of flow transition regime at $Re=1800$. The pictures show the pathline images of small tracer particles seeded in the liquid phase and those of bubbles scattering light on their surfaces. Large bright objects in each image are the bubbles suspended in the gap. The pathline images are made of temporal overlapping of brightness during around 40 frames (500fps for $Re=900$, and 1000fps for $Re=1800$). In each figures, the ratio of the Taylor vortex wavelength to the gap; $\lambda/d$ is shown, which is measured manually from the images. The following points are recognized with these visualization results.

![Image of pathline images](image)

**Figure 13.** Modification of Taylor vortex structure by introduction of bubbles at two different values of Re (In this experiment mean bubble diameter was 2.0mm)

Each Taylor vortex has a regular alignment in the gap in the case of single-phase flow. Its wavelength matches well with the many earlier reports. At $Re=900$, the Taylor vortex structure emerges also in the two-phase flow condition. However the wavelength is elongated compared to the single-phase flow. The elongation ratio estimated with the visualization is seen to be around 30%. There are several potential reasons for the elongation. One is the buoyancy effect, i.e. the bubbles distribute more near the inner cylinder surface. For instance, the clockwise vortex in the figure is accelerated while the counter-clockwise vortex is damped. The other candidates, such as the increment of effective viscosity and the reduction of the in-cell mass density, could be minor contribution to the
elongation. This point is the most important part of our study and we need to ascertain the physical process in detail as the next step of the study. Anyway, as the wavenumber of the Taylor vortex decreases, the momentum exchange is relaxed resulting in the reduction of the shear stress.

At $Re=1800$, the bubbles also concentrate near the surface of the inner cylinder. However, almost all the bubbles distribute in the stagnation region where the liquid leaves the inner wall for the outer wall. This region is stable for the bubbles since the bubble rise velocity and the downward liquid velocity is balanced there. There are only a few bubbles starting to leave the stagnation region in the radial direction and reaches the core part of the Taylor vortex due to the centripetal force within the vortex. In addition, the structure of the Taylor vortex just above the bubble stagnation region is highly distorted. This is because it has a counter-clockwise motion so that a great momentum exchange between the vortex and the buoyant bubbles takes place. The momentum transfer between the inner and the outer cylinder is reduced as the counter-clockwise vortex is distorted. The wavelength of the Taylor vortex is enlarged by around 12% at $Re=1800$. The elongation ratio is smaller than the case of $Re=900$, resulting in weaker drag reduction. On the other hand, the bubbles accumulated in the stagnation region drastically reduce the effective area of the viscous shear force. We think that the combined effect of both phenomena may result in such a significant drag reduction.

7. Summary
The distribution and the motion of bubbles suspended in a vertical Taylor-Couette flow were investigated experimentally. This paper has presented the bubble distribution characteristics interacting with Taylor vortices, and some measurements of skin frictional drag reduction. The range of experimental conditions was $600<Re<4500$ at the radius ratio of 0.833. Silicone oil and air were used to ensure stable properties for the bubble interface. Mean bubble diameter was 0.6mm. The following points were noted during this study.

The initially uniform bubble distribution became organized into a spiral structure at $Re>1100$, and had a complex time-dependent behavior including modulated waves. The reduction ratio of the shear stress was up to 36% in the best case, and the sensitivity of the shear stress reduction due to introduction of bubbles took the largest value of around 10 at $1/Fr=3.0$. The bubbles accumulated in the vicinity of the inner cylinder surface at low Reynolds number but were dispersed widely in the turbulent Taylor vortex regime. The structure of Taylor vortices was altered by the presence of bubbles, including an elongation of the vortex arrangement, and this correlates with the modification of skin frictional drag.

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