Wake Structure of Circular Cylinder in Microbubble Mixture

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Abstract. Injecting microbubbles near wall can reduce the frictional drag. While it has been confirmed by a variety of experiments to date, the fluid dynamics mechanism of drag reduction has not been comprehensively understood so far. We measure the wake structure of a circular cylinder in microbubble mixture to figure out the characteristic of the interaction between microbubbles and liquid flow accompanying high turbulence. The flow field is restricted to be two-dimensional by confining the bubbly two-phase flow into a thin horizontal channel of 2 mm in height. Microbubbles around 100 μm in diameter are generated with water electrolysis at far upstream the measurement section. Experiment is conducted at Reynolds number higher than $10^4$ to clarify the role of microbubbles in highly turbulent situation. We use solid particles as the PTV-tracer in the single-phase flow and assume that microbubbles trace the liquid flow in the microbubble mixture. We measure the turbulent intensity and Reynolds shear stress distribution from the PTV data and demonstrate that microbubbles significantly suppress the turbulence. In addition, the Karman vortex shedding frequency, which is measured from the unsteady stream function, increases when microbubbles are mixed.

1. INTRODUCTION

Microbubble has attracted attention as the way to reduce the skin friction in recent years. It has been confirmed that injecting microbubbles near wall can reduce a skin friction since the first report published by McCormic and Bhattacharyya (1973). This method is expected to apply to the ship and the pipeline. A lot of laboratory experiments have been carried out to investigate the drag reduction effect. Madavan et al. (1984) achieved as much as 80% decrease in the frictional drag using a water channel. Guin et al. (1996) reported that the drag reduction ratio correlates with the void fraction near wall. However the mechanism of microbubble drag reduction has not been fully understood so far. At least the mechanism is not explained universally for a variety of flow configuration, but it should be classified into several regimes. Major parameters to classify it are the Reynolds number, Weber number, and void fraction. Increasing the effective viscosity which associates with the reduction of Reynolds stress is one of the principal candidates to explain the drag reduction mechanisms. However, the drag reduction effect of the previous experiments cannot be explained only by the increment in the effective viscosity. Nowadays the suppression of the turbulent flow has become a focus of the microbubble drag reduction. It means that the microbubbles relax the flow fluctuation only in small scale but do not affect the global property of flow. This is why the microbubbles sensitively alter the turbulent flow.

The turbulent flow in the boundary layer generates a large frictional drag. Kato et al. (1999) investigated the turbulent intensity in the buffer and inner turbulent regions using laser Doppler velocimeter (LDV) and indicated that microbubbles decrease the turbulent intensity when the skin friction decreases. Ferrante and Elghobashi (2004) performed a direct numerical simulation (DNS) of a
spatially developing turbulent boundary layer laden with microbubbles and explained that the
displacement of streamwise vortices away from the wall induces a drag reduction. In the case of
turbulent boundary layer, the role of microbubbles changes gradually in the direction of the flow since
the void profile in the wall-perpendicular direction changes as well. Furthermore, a wavy fluctuation
in void fraction occurs in the flow direction because of the bubble-bubble interaction. Such a system is
inconvenient for the fundamental study in which the role of microbubbles is investigated.

Matsumoto et al. (1988) numerically calculated the bubbly two-phase flow around a blade. They
reported the characteristic of bubbly blade about the pressure, Mach number and the void fraction
distribution. Also, Hulin et al. (1984) reported the local void fraction and the vortex shedding
frequency behind obstacles with a trapezoidal cross-section in gas-liquid flows and confirmed that
Strouhal number has a local maximum value at a certain void fraction. In this paper, the characteristic
of microbubble in highly turbulent condition is investigated by measuring the wake structure of a
circular cylinder. The cylinder wake structure of single-phase flow has been investigated in great
detail over the past century. Roshko (1954) indicated the cylinder wake structure between $Re=50$ and
$Re=4000$ in the single-phase flow. The cylinder wake has the various vortices shedding depending on
Reynolds number, and it strongly depends on the spatial development of boundary layer on the
cylinder surface from the front stagnation point to the separation point. Therefore, the detection of the
role of the microbubbles can be more widely realized with the use of the multiple phenomena
happened to the flow around the cylinder. Sugiyama et al. (2001) performed a numerical simulation of
two-phase wake flows around a cylinder and confirmed a same relationship between a void fraction
and Strouhal number as results obtained by Hulin (1984). In past studies millimetre-sized bubbles
have been used for investigation of two-phase wake flow around a cylinder. In the present study
through the visualization and the image processing, including particle tracking velocimetry (PTV), the
wake dynamic that associates with microbubbles is deduced from the results. We carry out the
experiment at high Reynolds numbers to see the interaction between microbubbles and the turbulent
structure. In particular, we are going to discuss the reason why a small amount of microbubbles could
dramatically alter the flow field that is subjected to hard turbulence in the order of $10^4$ in Reynolds
number.

2. EXPERIMENTAL METHOD

Figure 1 shows the schematic diagram of experimental apparatus which we used in this experiment.
The horizontal channel is made of transparent acrylic resin. We used a thin channel of which the
height was restricted to be 2 mm for keeping two-dimensional bubbly flow. The width of channel is 80
mm and the entire length is 1000 mm. The working fluid is the water. The test section is 400 mm away
from the hydrogen bubble generator. The mean liquid velocity is 2.1 m/s. Figure 2 shows the
schematic diagram of the test section. The circular cylinder is made of transparent acrylic resin. The
cylinder diameter is 20 mm and the height is 2 mm. The metal halide light is placed under the channel.
The backlight image was obtained by the high speed video camera from above. Figure 3 shows the
hydrogen bubble generator. Microbubbles are generated by the water electrolysis. The nickel is used
both the anode and the cathode of electrolysis. The size of the nickel is 45 x 5 mm. The interval
distance between two nickel electrodes is 2 mm. Figure 4 shows the probability density function of the
bubble diameter in this experiment. Bubble diameter is between 90 μm and 430 μm. The mean
microbubble diameter is 110 μm. A lot of microbubbles are distributed between 90 μm and 120 μm,
provided that the microbubbles less than 90 μm could not be recognized by the image analysis because
of the spatial resolution as well as the noises involved. The void fraction, i.e. the volume fraction of
microbubbles in mixture fluid is controlled to be 0.03 %. This is exactly controlled by the electric
current which is consumed for the electrolysis. The experiment was conducted under the condition
with microbubbles and with solid particles, respectively. The solid particles are used for measuring the
single-phase flow as the tracer particles. The solid particle diameter is 90 μm and the density is 1.01
g/cm³. Details of experimental condition are as summarized in Table 1.
Fig. 1  Schematic diagram of experimental apparatus: 1. Pump, 2. Flowmeter, 3. Horizontal channel, 4. Hydrogen bubble generator, 5. Test section, 6. Removal tank

Fig. 2  Schematic diagram of test section: 1. Circular cylinder, 2. High speed video camera system, 3. Metal halide light

Fig. 3  Hydrogen bubble generator using water electrolysis
3. RESULTS AND DISCUSSION

3.1 Turbulent structure behind circular cylinder

Inoue et al. (1986) investigated the characteristics of two-phase flow around a cylinder using bubbles of which diameter are about 4 mm. They reported that the bubble number density fluctuates because of the Karman vortex shedding from a cylinder. Figure 5 shows trajectories of solid particles and microbubbles around the circular cylinder. The main flow direction is from left to right. In present study the fluctuation of the bubble number density can’t be seen from the results. Both solid particles and microbubbles have a recirculation region behind the circular cylinder. We can see the small fluctuation of bubbles’ behaviour in the recirculation region. The fluid inertia is dominant there because of the change in local flow direction. The difference in density between the microbubble and the solid particle is significantly affected. Therefore, microbubbles have a fluctuated behaviour there. However, in large structure of which order is about same as a cylinder diameter, microbubbles have trajectories such as following the liquid. The difference of the flow between two types of the dispersion is picked up from the results as bellow.

Figure 6 shows the time-averaged velocity field of solid particles and microbubbles around the circular cylinder. We calculated the velocity of microbubbles and solid particles by PTV and rearranged the velocity field using a spatio-temporal Laplace equation (Ido and Murai, 2006). The period of the analysis is about 0.5 second (1498 frames). The streamwise velocity increases near $x/D=0$, and this includes extra acceleration due to the blockage effect, i.e. the circular cylinder occupies one-quarter of the channel width. According to the results, it is clear that the velocity of microbubbles is smaller than solid particles. Murai et al. (2006) reported that a bubble in shear layer
close to a wall has a streamwise velocity slightly slower than the liquid velocity. They measured this backward slip velocity to be about 10 to 20% of the local mean liquid velocity. In the present experiment, the velocity of microbubbles decreases by about 14% compared to the velocity of solid particles, i.e. liquid velocity. The reason of the decrease is explained by three factors. One is that the microbubbles are biased near the wall due to lift force, resulting in slower velocity near the wall. The negative slip in the shear flow induces lift force toward the wall, and this migration of bubbles provides negative slip again. Second is that the motion of microbubbles are strongly affected by the turbulence in liquid to have slow-downed velocity in mean value. For instance, the mean streamwise velocity of microbubble advection is significantly reduced when the microbubbles are accumulated into cores of streamwise vortex (Oishi et al, 2007, Suzuki et al, 2008). Third, we need to address that microbubbles in water-H2 gas combination have negative electric charge on individual bubble surface. This may provide a repulsion force to make bubbles scatter around and resists against flow deformation. Although the electric charge is not measured explicitly in this study, it is known to be around 10 mV. Spinning of microbubbles around particular axis generates Lorentz force as well, which has a potential to actively modify the turbulent eddies in the flow. However, we conclude that such an electro-magnetic effect of the bubble interface is not significant in the present flow condition. We have tried to put a strong magnet of 2 Tesla on the channel to see the difference of the microbubble behaviour, but nothing has been recognized about the magnetic effect. In fact the order estimation of Coulomb and Lorentz forces tells us that these forces are less than 10^-6 times as the buoyant force of bubbles. The difference of the bubble velocity caused by these electro-magnetic forces cannot be sensed and almost ignorable. Consequently, the major reason of the slow velocity for microbubbles should be explained by the fluid dynamics interaction between two phases.

(a) Solid particle

(b) Microbubble

Fig. 5 Trajectories of particles and microbubbles around circular cylinder
Figure 6 shows the time-averaged distribution of two-dimensional divergence of the velocity vector field for the two types of dispersions. The divergence indicates the discrepancy of the dispersion motion from the liquid flow field that satisfies the two-dimensional continuity equation in single-phase flow. Both solid particles and microbubbles have a large magnitude in divergence value near the surface of the cylinder while these two have the near zero value in the wake region. Hence, the microbubbles track the liquid flow uniformly as same as solid particles even if the microbubbles has the backward slip velocity. On the other hand, microbubbles have negative divergence on the front side of the cylinder as shown by the blue arch in the figure. This means that the microbubbles are accumulated into the upstream stagnation point, and also into the boundary layer of the cylinder. As the result, two-phase interaction gets active on the way to progress of the boundary layer around the front half of cylinder. The opposite side of the cylinder has a positive value in divergence, implying that the microbubbles are repulsed from the boundary layer. The position of the change in sign of the divergence is located around 90 degree from the front stagnation point. Since this position and the separation point of the flow are close to each other, it is presumed that the wake structure is strongly affected by the presence of bubbles. It is worth noting that large bubbles would have the similar distribution of the divergence, however, the affected area gets too wide to concentrate the two-phase
interaction into the boundary layer. Namely, only microbubbles can alter the flow via their focused action onto the boundary layer.

Figure 8 shows the turbulent intensity distribution, which is normalized by the kinetic energy of inflow. Comparing the two cases, two differences can be pointed out as follows. One is seen near the boundary layer of the cylinder before the separation point. For microbubble flow, the turbulent intensity ceases totally in the front stagnation region. This means that the transition from laminar to turbulent boundary layer is delayed with presence of bubbles, and hence the laminar boundary layer is maintained long there. This effect of microbubbles is also known in pipe flows. The turbulent flow transition of a pipe flow is significantly delayed by inclusion of microbubbles. Namely, the present experiment also supports the idea that the microbubbles contribute to the laminarization of flow. Injection of large bubbles must induce pseudo-turbulence where slip velocity gets large. Hence, the quite turbulence in the region near the front stagnation point in this experiment proves the feature of microbubbles action to fluid. Another difference recognized between the two results is the turbulent intensity near the reattachment region; x/D~1.5. In the case of solid particles, the turbulent intensity gets large there because of turbulent Karman vortex shedding. Injection of microbubbles suppresses the intensity there to be around half of the original condition. We think that this suppression is caused by the alternation of the boundary layer on the cylinder surface, but not by the local interaction between two phases around the reattachment region.

The relationship between the downstream turbulent intensity and the boundary layer structure on the cylinder surface can be found by analyzing the Reynolds shear stress distribution. Figure 9 shows the stress distribution for the two cases. Here the stress is defined simply by the correlation of u’ and v’, which are the velocity component in the streamwise and the perpendicular directions (but not the velocity component relative to the curved surface of the cylinder). The comparison of these two immediately finds out that the Reynolds shear stress is drastically reduced in the wake region by mixing microbubbles. This indicates that microbubbles relax the motion of turbulent eddies that convey the momentum. This is consistent to the turbulent intensity measured. Moreover, it is very important to mention that the Reynolds shear stress changes its sign near the upstream surface of the cylinder when microbubbles are injected. The negative Reynolds shear stress means inverse transfer of the momentum from slower to faster fluid. This cannot happen in ordinary turbulent shear flow, but it happens to the microbubble mixture as measured here. The mechanism of the inverse transfer of the momentum may be associated with divergence of the flow velocity in the region close to the upstream cylinder surface (see Fig. 7 (b)). Since the local flow diverges there, the thickness of the boundary layer expands more rapidly than the ordinary development rate of the thickness.
3.2. Frequency of Karman vortex shedding

Figure 10 shows the time series distributions of the instantaneous stream function. The stream function is calculated by integrating the velocity distribution. With this expression, it is confirmed that Karman vortex shedding occurs both for the particles and the microbubbles. The flow patterns are similar to each other, however, we can find that the thickness of the boundary layer around the cylinder is obviously large in the case of microbubble flow (see the thickness of green region around the cylinder). In addition, the thickness in the case of microbubble flow expands at around 45 degree from the front stagnation point. This is explained by the divergence effect of the microbubble motion.

Figure 11 shows the power spectra of the flow field obtained by fast Fourier transform. Here target quantity of the spectrum analysis is chosen to be stream function in the wake region because the stream function is insensitive to measurement noise. Also, the employment of the stream function leads to easier detection of organized structure in large scale such as oscillatory wake or Karman vortex. Four points of investigation are set behind the cylinder as shown in the figure 11. From the results, it is again confirmed that the amplitude of the flow fluctuation decreases when microbubbles are injected. There are two peaks in the power spectra both in the solid particle and the microbubble. The flow with solid particles has peak values at 32 Hz and at 38 Hz. The flow with microbubbles has peaks at 35 Hz and at 41 Hz. It is generally well known that Strouhal number defined by Eq. (1) takes the value around 0.21 at Re_{D}>10^3 in the case of circular cylinder.

\[ \text{St} = \frac{fD}{U} \]  

Under the value of the Strouhal number at 0.21, Karman vortex shedding frequency should be about 33 Hz in the case of single-phase flow (here, we use the averaged streamwise velocity at \( x/D=0 \) as \( U \) in the equation). This frequency is close to the first peak frequency detected in the present experiment for the solid particles. Therefore, we can assume that the first peak in the power spectra indicates the Karman vortex shedding frequency. The second peak in each spectrum takes place as the result of modulation which is originated from slow oscillation at 6 Hz (thus, the second frequency is given by adding 6 Hz to the first frequency). The slow oscillation comes up due to the blockage effect, i.e., due to the difference from the cylinder in infinite space. Therefore we focus only on the first peak to discuss the effect of microbubbles.
In the case of microbubble flow, this first peak frequency increases by 9% compared to the single-phase flow. Reynolds number of the present measurement is 46000. It is known that Strouhal number decreases with increase in Reynolds number in turbulent flow at $2000 < Re < 2 \times 10^5$. The effective Reynolds number decreases due to the increment in effective viscosity and the decrement in fluid density in two-phase flow. That can explain the change in frequency of microbubble flow. However, the present void fraction is 0.03% and the effective Reynolds number little changed. The change in frequency can’t simply associates with change in Reynolds number in present measurement. The change in Strouhal number by mixing millimetre-sized bubbles can be seen in past studies (Sugiyama et al. 2001, Yokosawa et al. 1986). The present void fraction is quite different from the past one. The change in frequency in the present experiment may be the unique phenomenon of microbubble flow.
On the condition of large concentration of microbubbles, the surface tension works like an elasticity in the liquid phase between microbubbles. This effect may influence with the change in frequency between the solid particle and the microbubble. Yokosawa et al. (1986) reported that the vortex shedding frequency of bubble crowd under the low void fraction was equal to that of the single-phase flow within a few percent errors. We need to collect more data including the effect of fraction of microbubble in the liquid to discuss this matter. The turbulent flow assumption of the relationship between Strouhal number and Reynolds number yields to the following aspect. In single-phase flow, the vortex shedding frequency in turbulent condition decreases with the increase in Reynolds number due to delayed separation for the turbulent momentum transfer. Hence, the increment in the frequency implies the separation occurring early. Microbubbles, therefore, suppress the turbulent momentum transfer to result in early separation of the boundary layer.

4. CONCLUDING REMARKS

PTV is applied to the measurement of a wake flow field caused by a circular cylinder. By comparing the velocity vector fields in two cases; with solid particle and with microbubble, we recognize several significant changes of the turbulent flow structure influenced by microbubble. From the turbulent intensity and the Reynolds shear stress, it is confirmed that the microbubbles suppress the
flow fluctuation. The Karman vortex shedding frequency, which is obtained from the stream function of the wake flow field, increases with mixing of microbubbles. This is explained by two factors caused by microbubbles. One is divergence effect near the front stagnation region, which makes boundary layer expand along the surface of the cylinder. This effect provides negative Reynolds shear stress to keep the laminar boundary layer long. Another is the microbubble effect for hastening the flow separation. This is originated from suppression of the turbulent momentum transfer before the separation point.

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NOMENCLATURE

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\begin{align*}
\text{u} & \quad \text{velocity vector} \quad [\text{m/s}] \\
\text{u} & \quad \text{streamwise velocity} \quad [\text{m/s}] \\
\text{v} & \quad \text{spanwise velocity} \quad [\text{m/s}] \\
\text{U} & \quad \text{bulk mean velocity} \quad [\text{m/s}] \\
\text{D} & \quad \text{cylinder diameter} \quad [\text{m}] \\
\psi & \quad \text{stream function} \quad [\text{m}^2/\text{s}] \\
\nu & \quad \text{kinematic viscosity} \quad [\text{m}^2/\text{s}]
\end{align*}
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