Frictional Drag reduction by wavy advection of deformable bubbles

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Abstract. Bubbles can reduce frictional drag in wall turbulence, and its effect is expected to use for ships and pipelines to save their power consumptions. A number of basic experiments have been carried out to date for finding out the best condition for enhancing the drag reduction. One issue that remains at present is the difference of the performance between steady and unsteady status in terms of bubble concentration. All the experiments in the past deal with the steady effect, i.e., the drag reduction is evaluated as a function of mean void fraction or given gas flow rate of continuous injection. Despite to this, the actual phenomena highly depend on local interaction between two phases upon unsteady manner. We focus on this point and elucidate the influence of time-fluctuating void fraction on the total response to the drag reduction. This view is in fact important to estimate the persistency of the bubble-based drag reduction in the flow direction since bubbles formulate wavy advection during their migration.

Our experiments are designed to measure the above-mentioned effect from laminar, transitional, and turbulent flows in a horizontal channel. For avoiding the contamination effect that worsens the reproducibility of the experiment, Silicone oil is used as carrier fluid. The oil also simulates the high Weber number bubble condition because of low surface tension. The unsteady interaction between the wavy advection of bubbles and the local skin friction, a synchronized system is constructed to connect the high-speed camera with the shear transducer, which can evaluate the interaction at 1000 fps. From the results, we confirm that the drag reduction is provided at Re>3000 in the turbulent flow regime, and also the total drag reduction is enhanced by the presence of the waves.

1. INTRODUCTION
Drag reduction is one of the most important fields of research in engineering since it directly contributes to energy saving in any facilities and devices. Use of bubbles is considered as feasible method recently because of several advantages in comparison with other methods. For instance, the engineers in shipbuilding are keen to apply this technique for the drag reduction of large ships. It is known that there are several important parameters that characterize the drag reduction by bubbles; void fraction, thickness of bubbly layer, and bubble size. In dimensionless expression, we need to investigate the dependency of Reynolds number, Weber number, and Froude number. On the mechanism of the drag reduction, which has been studied a lot to date, we need to conclude that it is not explained so simply. The drag reduction would be caused not only by the decreases in density and viscosity of mixture fluid but also by the dynamic two-phase interaction in the boundary layer. Even in laminar flow, the effective viscosity is significantly altered with deformation of bubbles which are
subjected to shear stress, as reported by Rust and Manga (2002). Namely, the shear response of bubbles, or Rheological properties of bubbles plays an important role in modifying the surrounding turbulent flow field. At high Reynolds number, the interaction process is further complex than that at the laminar flow. Kawamura (2005) performed a DNS study for investigating the bubble deformation in a turbulent flow and found out the role of the bubble deformation. A different type of DNS study by Lu et al. (2005) has shown that the bubble deformation is one of the next key factor that can promote the sensitivity of the drag reduction. On the other hand, microbubbles that resist against the shear stress around have different effect of the drag reduction. Xu et al. (2002), Ferrante and Elghobashi (2004) investigated this and clarify that the advection of microbubbles relative to the near wall structures shifts the position of the momentum exchanging eddies far from the wall.

The many reports mention that there is a condition for the amount of injecting bubble in order to provide the highest performance of the drag reduction. We assess this as gain factor of the drag reduction, which is the ratio of the power-saving realized by the drag reduction to the power required for bubble generation. Air-film method so-called can separate the liquid from the wall to totally cut out the shear stress. However, the gain factor of this method is close to unity; 1% of void fraction provides 1% of drag reduction. To maximize the gain factor, we need to use mm-order bubbles that are easily generated with a variety of techniques. Using such a normal size bubble can obtain the gain factor from 4 to 10 (Murai et al. (2007)). This amplification of the gain factor happens when adequate interaction is realized between two-phases in boundary layer. Kitagawa et al. (2005) investigated the interaction between bubbles and turbulent events on structures in Reynolds stress distributions, including bubble deformation. They concluded that ‘pseudo-turbulence’ caused by the slip of bubbles relative to the liquid modifies the structure and characteristics of real-turbulence. Winkel et al. (2004) studied influence of bubble size and behavior using seawater, surfactant and tap water as carrier fluids, and concluded that bubble behaviors such as deformation and slipping are strongly affected by contaminants in the water such as particulates and ionic impurities. Therefore, it is plausible that theoretical prediction is hardly possible for explaining the drag reduction. The present experiment uses silicone oil and it has three advantages: 1) the gas-liquid interface is not susceptible to contamination due to the non-polar liquid, 2) bubble deformation can be achieved even in low Reynolds number turbulent flow because of lower surface tension than tap water, and 3) wide range of the Reynolds number covering laminar flow to turbulent flow can be achieved due to the high viscosity of silicone oil.

In this paper, we describe measurement techniques to investigate the relationship between the local void fraction and the local wall shear stress, and then discuss how the drag reduction is realized in the case of wavy advection of bubbles. With the data obtained, we reduce the factor that amplifies the drag reduction performance by bubbles.

2. EXPERIMENTAL APPARATUS

A schematic diagram of the experimental apparatus is shown in Fig.1. The apparatus comprises a flow controller, rectifier controller, test section, and deaeration unit. Silicone oil and air are used as working fluids under laboratory temperature. The silicone oil was driven by a pump (Ebara Pump, 80VNP2.2) that is controlled by an inverter (Showa Instrument Information Co. Ltd., FT-03070). The test section is a horizontal rectangular channel made of transparent acrylic resin, 20 mm in height, 160 mm in width and 6000 mm in length.

The outline of a bubble injection device is drawn in Fig.2. Air bubbles are injected into the horizontal channel from the top surface through 140 capillary tubes whose inner diameter is 0.1 mm. Air is supplied by a compressor (Amadera pneumatics co., Handicon T05P5S17), and the flow rate is measured by an air flowmeter (Tokyo Keiso Co. Ltd., F04-108478). The bulk mean liquid velocity ranges from 0.2 to 2.0 m/s. The injector is located 875mm downstream from the end of the diverging-converging channel.

Bubbles are completely removed by the double chamber structure of the tank. The tank utilizes the
swirling effect in the inner chamber and buoyant separation effect in the outer chamber.

![Schematic diagram of the experimental facility.](image)

**Fig. 1** Schematic diagram of the experimental facility.

![Schematic of bubble injection device; air goes through array of capillary needles](image)

**Fig. 2** Schematic of bubble injection device; air goes through array of capillary needles

Table 1 shows the experimental conditions. The skin friction coefficient $C_f$ is defined by the following equation,

$$ C_f = \frac{2 \tau}{(1 - \alpha) \rho U^2}, \quad (1) $$

where $\tau$, $\alpha$, $U$ and $\rho$ are respectively the local wall shear stress measured by the shear transducer, the bulk mean void fraction, the bulk mean velocity in the channel and the mean density of two-phase flow. $\alpha$ and $U$ are given by,

$$ \alpha = \frac{Q_g}{Q_l + Q_g}, \quad (2) $$
where \( \dot{Q} \) is the volume flow rate, \( H (= 2h) \) is the channel height and \( B \) is the channel width. The subscripts \( g \) and \( l \) indicate the gas and liquid phases, respectively. The bulk mean velocity \( U' \) increases due to the volumetric increase in the flow as the air bubbles are injected into the channel. Therefore, to evaluate the skin friction coefficient in a two-phase flow, \( C_{f0} \) is modified by the following equation (Kodama et al. (2000)).

\[
C'_{f0} = C_{f0} \frac{\tau_{lU}}{\tau_{lU'}},
\]

where, \( \tau_{lU} \) is the wall-shear stress estimated by the Blasius formula, and the subscript 0 indicates the bubble-free condition. In this study, the skin friction ratio, i.e. the ratio of the skin friction coefficient with bubbles to that without bubbles, is employed to evaluate the modification of the drag.

The steady geometry of the bubbles is solely a function of Weber number, which is calculated by

\[
We = \frac{\mu Gd}{2\sigma},
\]

where \( d \) is the non-deformed bubble radius, \( G \) is the velocity gradient, \( \mu \) is the suspending fluid viscosity, and \( \sigma \) is the surface tension.

| Table 1 Experimental conditions |
|----------------------------------|
| **Main conditions**             |
| Channel size                     | 40 × 160 × 6000 [mm]          |
| Channel half height              | \( h \) 20 [mm]               |
| Bulk void fraction               | \( \alpha \) 0.0 … 2.5 [%]    |
| Mean bubble diameter             | \( D \) 0.7 [mm]              |
| Bulk liquid velocity             | \( U \) 0.6, 1.0, 1.5, 2.0, 2.5 [m/s] |
| Bulk Reynolds number             | \( Re = 2hU/\nu \) 1103 … 4425 [-] |
| Frictional Reynolds number       | \( Re\tau = hu\tau/\nu \) 70 … 140 [-] |
| Silicone oil                     | Density \( \rho \) 935 [kg/m³] |
| Kinematic viscosity              | \( \nu \) 1.07×10⁵ [m²/s]    |
| Temperature                      | \( t \) 20 [deg.C]            |
| Surface tension                  | \( \sigma \) 21×10⁻³ [N/m]   |
| **Camera conditions**            |
| Measurement point                | \( x/h \) 30, 90 [-]         |
| Frame rate                       | 1000 [fps]                   |
| Shutter speed                    | 1/2.0×10⁴ [s]                |
| Resolution                       | 1024×1024 [pixels]           |
| Sampling time                    | \( T \) 60 [s]               |

3. MEASUREMENT OF BUBBLY TURBULENT FLOW

3.1 Flow Visualization Technique
We carried out a synchronous technique to study the relationship between the bubble motion and wall friction. Images of bubbles are recorded by a high-speed digital video camera (Photron, Fastcam-Max). To obtain a backlight projection of the gas-liquid interface, a metal halide light (Photron, CVF-SL 150W) is used as the light source. The frame rate is 1000 fps and the shutter speed 1/20,000 s. The depth of field for the camera lens (Nikon, Micro-Nikkor105mm f/2.8) is 450 mm. A pulse generator synchronizes the trigger timings of the shear transducer and the high-speed camera. The calibration and image processing provide dimensionless values for the shear stress and bubble concentration, which are the friction coefficient and local projection of the void fraction. The measurement positions are $x/h = 30$ and 90, which correspond to 300 and 900 mm downstream of the air injection device, respectively. The measurement domain is $53.8 \times 53.8$ mm and the magnification factor is 0.0526 mm/pixel.

### 3.2 Direct Measurement of Wall Shear Stress
Measurement of the wall frictional drag is carried out as a direct measurement of the wall shear stress by a shear stress sensor (SSK Co. Ltd., S10W-4, capacity 3.9mN, temporal resolution 20Hz). Figure 3 shows the sensing part of the device, which is 10 mm in diameter. The flatness of sensitive area relative to the inner surface of the channel is carefully controlled using a lead plate. The shear stress signal is received and converted into electric signal by an analog amplifier (SSK Co. Ltd., M-1101). The measurement data is recorded by a PC as digital data via a data recorder (Keyence Co., NR-500).

**Fig. 3 Schematic of shear stress sensor mounted at the upper wall of the channel**

### 3.3 Construction of Synchronous Measurement System
Figure 4 is a schematic diagram of the synchronized measurement system. A pulse generator synchronizes the trigger timings of the camera and the data logger for the shear stress sensor. The image acquisition position is 80 mm downstream from the measurement position of the wall-shear stress because the devices cannot be physically located at the same position. Hence there is a time lag between the data obtained by each device. The time lag is removed using the local mean advection velocity of the bubble interface, which is measured by particle image velocimetry (PIV). The advection velocity has a relative velocity to the mean liquid velocity in the channel. In the case of high void fraction, the bubbles become separated air films and move faster than the liquid. In the case of low void fraction, small bubbles appear and move slightly slower than the liquid because of the additional friction induced. The mean bubble diameter is 0.99 mm from the image analysis. The Weber number, which is the ratio of the shear stress to the surface tension, is 0.07 to 0.2.
4. RESULTS AND DISCUSSION

4.1 Flow Pattern of Bubbles

In this experiment, we carried out particle tracking velocimetry (PTV). The center of gravity for individual bubble is extracted by image processing via edge detection, binarization, thinning and labelling. We obtained the velocity vectors using PTV (four-time steps PTV). Figure 5 shows a snapshot of bubbly flow with a velocity of 0.5 m/s and void fraction of 2.0 %. The injected bubbles extensively distribute in the spanwise direction and cluster in the streamwise direction. As a result, the bubble distribution becomes a stripe pattern for all conditions.

Figure 6 shows the original images of bubbles. The shape of a bubble is spherical in laminar flow as shown in Fig. 6 (a). The bubble size irregularly expands in the streamwise direction with high Reynolds number. The expanded bubbles regain their sphere, and some bubbles break up.

Fig. 5 Snapshot of bubbles that cover with channel wall (U = 0.5 m/s, α = 2.0 %).
Figure 8 shows the skin friction ratio as a function of void fraction. When the liquid velocity $U$ is slow, the ratio takes a larger value than unity but should be smaller than two. This ratio corresponds generally to the ratio of turbulent friction to laminar friction as shown before. However, its value decreases as the void fraction increases. On the other hand, the skin friction ratio takes a value smaller than unity when both the liquid velocity and the void fraction are high. In the case of the liquid velocity being equal to or larger than 2.0 m/s ($Re=3734$ to 3811), a frictional reduction of 9 % is obtained in the maximum case. This tells us the bubbles play a role in reducing the friction in such a low Reynolds number region.

![Fig. 6](image)

**Fig. 6** Snapshot of bubbles near the upper wall ($x/h = 90$)

![Fig. 8](image)

**Fig. 8** Local skin friction ratio vs. bulk void fraction at a) $x/h=30$ and b) $x/h=90$. 

Figure 9 shows a sample of real data for the shear stress in the bubbly flow under these conditions. The fluctuation is significant relative to the average value. The relationship between the fluctuation frequency of the shear stress and fluctuation frequencies of the bubbles is of importance. Figure 10 shows the spectrum of real data. This fluctuation frequency of the shear stress is dependent on three factors of length. Frequencies in the range $5 \times 10^7 < f < 1 \times 10^2$ are dependent on the liquid velocity divided by the half width of the channel, those in the range $1 \times 10^2 < f < 2 \times 10^2$ are dependent on the bubble-bubble averaging spacing, and those in the range $2 \times 10^2 < f < 3 \times 10^2$ are dependent on the bubble size. In the latter case, the response to bubble size is high due to the size ranging from 1 to 5 mm. Although this relationship does not have a specific point, this frequency region is of interest in that it is the region of interference between frictional drag and bubble-bubble average spacing.

### 4.3 Equivalent Bubble Diameter

Figure 11 shows the probability density distribution of the bubble diameter in the drag reduction condition at $x/h = 30$. The bubble diameter is an equivalent diameter extracted from the number of pixels in image processing. The mean bubble diameter is 988 μm and the standard deviation is 410 μm. The bubbles, which have larger Weber number than one, drastically deform in the turbulent flow. The range of the deformed bubble is between spherical microbubble and fragmental bubble.
4.4 Velocity of Bubbles

Figure 12 shows the bubble velocity vectors obtained using PTV. Figure 13 shows the velocity distribution of bubbles. The mean velocity of bubbles is 1.6 m/s. In this experiment, bubbles of diameters smaller than 100 μm (3 pixels) are ignored. Figure 13 shows the probability density distribution of the streamwise velocity of bubble at $x/h=30$. The results of this experiment show the individual bubble velocity remains constant, regardless of bubble size.

![Velocity vectors of bubble centroids](image1)

![Frequency of bubble velocity in the streamwise direction](image2)
Figure 14(a) shows an original image of the synchronized measurement experiment at $x/h=30$. We measured the projection void fraction from the binary image (Fig. 14(c)). Figure 15 shows the power spectrum of the skin friction (a) and void fraction (b).

![Fig. 14 Image analysis of the backlit projection of bubbles: (a) original image, (b) thinning image, (c) binary image to measure projection void fraction](image)

![Fig. 15 Power spectrum vs. frequency of (a) shear stress and (b) void fraction](image)

### 4.5 Correlation of Bubble and Shear Stress

Figure 16 shows the waveforms of the shear stress and projection void fraction using the synchronized measurement system. The upper picture is the corresponding bubble image at the same sampling period. The mean void fraction, Reynolds number, and Weber number are $\alpha=2.0\%$, $Re=U_h/\nu=1800$, and $We=2\rho U_h/\sigma=1870$, respectively. The skin friction in the graph is normalized by that of the single-phase condition. The waveform of the skin friction (solid curve) fluctuates with large amplitude as the local projection void fraction (dotted curve) varies in time. The ratio of the fluctuation amplitude is roughly the same for both quantities; however, there is a certain phase shift between them. That is, the moment of highest void fraction does not match that of the largest drag reduction.
Figure 16 shows a two-dimensional trajectory of the two quantities. The trajectory is generally correlative relationship when the bubbles directly reduce a skin frictional drag. This is a historical effect of the bubbles on the skin friction, and furthermore the skin friction decreases greatly as bubbles begin to leave. This trend indicates the turbulent boundary layer is gradually altered in the streamwise direction by bubbles. Such a transient behavior was analyzed numerically by Xu et al. (2002) and Ferrante and Elghobashi (2004). A problem in numerical studies before this alteration was known was that the time-average skin friction hardly decreased as the time elapsed. Drag reduction occurred only in the initial stage of bubble-liquid interaction. However, the present experimental result has newly shown that the time average does decrease when the local/instantaneous value has a large fluctuation accompanying a phase shift.

Figure 18 shows the relationship between the time-averaged drag and instantaneous drag. The level of reduction estimated by this factor is something like the gain in drag reduction. The gain factor of the skin friction reduction per void fraction is calculated. The gain factor considered here is defined by the following equation, which indicates the magnitude of the drag reduction effect per void fraction.

$$
\bar{G} = \frac{1}{\alpha} \left( 1 - \frac{C_f}{C_{f0}} \right) = \frac{1}{\alpha} \left( \frac{\Delta \tau}{\tau_0} \right).
$$

(5.6)

When drag reduction occurs, the gain factor takes a positive value. If the factor is greater than unity, it means the drag reduction being amplified and enhanced by the bubbles more than the density effect. On the other hand, the instantaneous gain factor considered here is defined by the following equation, which indicates the magnitude of the instant drag reduction effect per instant void fraction.

$$
G' = \frac{1}{\alpha'} \left( \frac{\Delta \tau'}{\tau_0} \right).
$$

(5.7)

Here, we define the instantaneous drag reduction ($\Delta \tau'$) and instantaneous void fraction ($\alpha'$) in terms of the maximum $\Delta \tau_{\text{max}}$ and $\alpha_{\text{max}}$ values. The time average value is obtained as 1.8, but the instantaneous
maximum value is obtained as 3.2. As a result, the effect of the drag reduction is higher than the time-averaged drag when we focus on instantaneous behavior.

Fig. 17  Trajectory of two quantities: the drag reduction and the projection void fraction

Fig. 18 Instantaneous gain factor vs. time lag between the peak of the ratio of drag reduction and the peak of void fraction

5. CONCLUSIONS
Bubble-induced drag modification is experimentally investigated using a horizontal channel. We use silicone oil as the carrier fluid since it enables us to stabilize the interfacial properties, to adjust low Reynolds number flow, and to control the condition of high capillary number. From the channel flow experiments, the following results are obtained.

- The injection of bubbles increases the friction coefficient by less than 50% in the case of laminar channel flows. In the transition region from laminar to turbulent flows, the friction coefficient increases up to two fold because bubbles activate the turbulent flow transition. The increase in the ratio of the friction coefficient matches that of the ratio of turbulent to laminar friction coefficients.

- After the transition to turbulent flow, the increased ratio of the skin frictional coefficient is reduced gradually by an increase in the void fraction. For the case when the flow is originally turbulent, the mixing of bubbles produces a certain drag reduction.

- The present experimental result has shown that the time average of the friction decreases when the local/instantaneous value has a large fluctuation. This indicates that the local drag reduction is promoted by unsteady interaction between two phases rather than the steady effect of the drag reduction. The wavy advection of the bubbles in our experiment is naturally created along the long spatial development of the two-phase boundary layer. Artificial supply of the wave, or intermittent injection of bubbles might cause a further enhancement of the total mean drag reduction (which is reported in another paper in this conference by H. Park et al).

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