Turbulent Shear Control with Oscillatory Bubble Injection

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Abstract. It is known that injecting bubbles into shear flow can reduce the frictional drag. This method has advantages in comparison to others in simplicity of installation and also in environment. The amount of drag reduction by bubbles depends on the void fraction provided in the boundary layer. It means, however, that certain power must be consumed to generate bubbles in water, worsening the total power-saving performance. We propose oscillatory bubble injection technique to improve the performance in this study. In order to prove this idea of new type of drag reduction, velocity vector field and shear stress profile in a horizontal channel flow are measured by ultrasonic velocity profiler (UVP) and shear stress transducer, respectively. We measure the gas-liquid interface from the UVP signal, as well. This compound measurement with different principles leads to deeper understanding of bubble-originated drag reduction phenomena, in particular for unsteady process of boundary layer alternation. At these experiments, the results have demonstrated that the intermittency promotes the drag reduction more than normal continuous injection for the same void fraction supplied.

1. INTRODUCTION
Frictional drag occupies 80 % of all drag and hence it affects significantly the fuel consumption rate of large ships like a tanker and a container carrier. McCormick (1973) found that the skin friction on the submerged body was reduced by injecting microbubbles around it. Madavan (1984) reported the efficiency of the microbubble drag reduction reaches as much as 80 %. After these reports, a number of researchers confirmed that this effect is feasible for practical use via various types of experiments. In comparison to other methodology for drag reduction, the use of bubbles has advantage in the both of simplicity and pollution free. By the latest experiments applied to a real ship, the net power efficiency of the ship was improved actually about 2 % (Kodama et al., 2006). However, this value is the result of subtraction of 5 % for generating bubbles, from the power-saving realized by drag reduction, 7 %. It obviously tells us that the power for generating bubbles worsens the net power-saving ratio, and we need to introduce a new designing concept to improve the net performance.

Reviewing a great deal of technical reports to date, how bubbles provide the frictional drag reduction can be classified into two types. One is quasi-steady effect that is characterized by change in fluid properties such as in average density and effective molecular/eddy viscosity (Murai et al., 2008). Another is unsteady effect in macroscopic sense, which takes place when two-phase boundary layer develops in streamwise direction before reaching fully developed state. The latter phenomenon is already deduced in several reports that deal with numerical simulations of bubbly shear flow. That is, the drag reduction occurs effectively when two phases exchanges their momentum before reaching the equilibrium state (Murai et al., 2006). On the other hand, experimental people quite often experience that local void fraction fluctuates naturally in time during drag-reducing situation. Even in such a case,
they still evaluate the sensitivity of the drag reduction as only a function of time-average void fraction or mean gas flow rate whereas the physical mechanism is not explained by steady flow configuration.

Considering this background, we have investigated the effect of fluctuation in bubble flow rate. For this topic, we showed the waveform of local skin friction for a naturally provided fluctuation in void fraction in the previous report (Oishi et al., 2006). At that time, we mentioned the interesting behaviour of local gain factor, which was raised by amplifying the fluctuation in the local void fraction. This effect is obtained because the local drag reduction is non proportional to the local void fraction but is promoted exponentially. That is, a wavy supply of void fraction enhances the drag reduction more than constant one for the same gas flow rate. This can be called “non-linear effect” to the void fraction. On the other hand, we measured the liquid flow field around a single bubble with PTV in order to find out the effective region of the bubble in the streamwise direction (Murai et al., 2007). With this measurement, we concluded that the local skin friction was affected longer than the size of bubble, indicating the local unsteady effect of bubble-originated drag reduction. This effect can be called as “phase-lag effect” which also amplifies the drag reduction. As one of the method to combine these two effects; the non-linear effect and the phase-lag effect, we propose a new type of drag reduction by bubbles, that is, oscillatory bubble injection. This method utilizes the artificially provided oscillation in gas flow rate, but not the naturally provided voidage waves. In comparison to bubble injection at constant gas flow rate, i.e. continuous bubble injection, both the two effects are utilized in the case of oscillatory bubble injection, and thereby the net performance should be improved. In the present study, three types of bubble injection methods are designed and compared with changing the injection frequency.

2. EXPERIMENTAL METHODS

2.1 Experimental Setup

The schematic diagram of the experimental facility is shown in Figure 1. The test section is a horizontal rectangular channel made of transparent acrylic resin and is 40 mm in height \( H = 2h \), 160 mm in width \( W \) and 6000 mm in length, respectively. Silicone oil is used to avoid the contamination effect on bubble interface, whose property is listed in Table 1. The silicon oil circulates in the channel, and the bubbles are mixed by capillary needle type of bubble injector. The bubbles are eliminated in the downstream region, by swirling the fluid in a bubble removable tank before returning to the inlet of the channel.

![Fig. 1 Schematic diagram of experimental facility](image-url)
Table 1. Characteristics of silicone oil (KF96-10cs)

| Property                  | Value                  |
|---------------------------|------------------------|
| Temperature (T)           | 28 °C                  |
| Density ($\rho$)          | 932 Kg/m$^3$           |
| Kinematic viscosity ($\nu$)| $7.7 \times 10^{-6}$ m$^2$/s |
| Surface tension ($\gamma$)| $19.9 \times 10^{-3}$ N/m |
| Sound velocity ($a_0$)    | 970 m/s                |

Figure 2 and Figure 3 shows the detail schematic diagram of test section and the experimental system for control of bubble injection and simultaneous measurements. A bubble injector and a shear transducer are mounted on the upper wall of the channel at $x/H = 43.75$ and $x/H = 65$ from the channel inlet, respectively. The injector is connected with an electromagnetic valve so that the arbitrary fluctuation in gas flow rate is realized with a function generator. For measuring the internal flow structure with UVP, two ultrasound transducers are set on the bottom wall of the channel at $x/H = 68.75$ at different angles, ±8 degree. Two ultrasound absorber boards are mounted on the upper wall and the bottom wall of the channel near the measurement line of UVP. It absorbs ultrasound and prevents multi-reflected echo of ultrasound beam. Another function generator synchronizes two UVPs and a data logger. These measurement machines start to record the different data simultaneously, which are velocity, echo, shear stress and valve operation.

![Schematic diagram of test section](image1)

Fig. 2 Measurement instruments in test section of channel

![Experimental system diagram](image2)

Fig. 3 Experimental system for control of bubble injection and simultaneous measurements
Figure 4 shows the definition of valve control parameters. The measurement conditions are shown in Table 2 and Table 3. The variable parameters in this experiment are, mean void fraction ($\alpha'$, Eq.(1); $Q_g$ and $Q_l$ are flow rates of gas and liquid phase), time of bubble injection pulse ($t_{in}$), and valve frequency ($f$). Local void fraction ($\alpha$, Eq.(2)) is $1.5 \times 10^{-2}$ and $Re$ number defined by Eq.(3) is fixed at 2200. Here we treat ($U$) and ($\rho$) as invariable parameters because of sufficiently small value in bulk void fraction.

\[
\alpha' = \frac{f \cdot t_{in} \cdot Q_g}{Q_l + f \cdot t_{in} \cdot Q_g}
\]  \hspace{1cm} (1)

\[
\alpha = \frac{Q_g}{Q_l + Q_g}
\]  \hspace{1cm} (2)

\[
Re = \frac{U_h}{\nu}
\]  \hspace{1cm} (3)

![Fig. 4 Definition of valve operation for realizing intermittent injection](image)

### Table 2. Measurement conditions

| Parameter                        | Value       |
|----------------------------------|-------------|
| Basic frequency of UVP           | 4 MHz       |
| Particle density                 | 930 Kg/m³   |
| Particle diameter                | 180 µm      |
| Time resolution                  | 10 ms       |
| Velocity resolution              | 17 mm/s     |
| Distance resolution              | 0.5 mm      |
| Shear stress resolution          | 0.05 Pa      |

### Table 3. Experimental conditions

| Parameter                        | Value       |
|----------------------------------|-------------|
| Reynolds number ($Re$)           | 2200        |
| Local void fraction ($\alpha$)   | $1.5 \times 10^{-2}$ |
| Mean void fraction ($\alpha'$)   | $0 - 1.5 \times 10^{-2}$ |
| Injection frequency ($f$)        | 0.2 – 0.5 Hz |
| Injection time ($t_{in}$)        | 0.5 -1.5 s  |
| Bubble diameter                  | 5-50 mm     |

#### 2.2 Detection of Gas-Liquid Interface

Presence of bubbles in the channel flow can be detected from the echo signal of the pulsed ultrasound. Murakawa (2008) used two types ultrasound transducers, 2 MHz and 8 MHz, to distinguish bubbles and solid particles suspended in liquid. Such a combination of different ultrasonic waves provides additional information of fluid flow in particular for multiphase fluids. In the case that the bubble size is sufficiently larger than the basic wavelength of ultrasound, just monitoring
the echo intensity of monotonic ultrasound gives us the interfacial information of bubbles. Hence, we use a single ultrasound transducer for detecting of the gas-liquid interface in this study.

Figure 5 shows the echo amplitude of single-phase flow and two-phase flow obtained by the current set of UVP. The green region in the figure indicates that the ultrasound transducer receives adequate echo intensity for tracer particles seeded in the flow. As seen in the red bottom layer in each figure, the transducer cannot receive significant echo near the bottom wall, \(0 \leq y/h \leq 0.15\), because of near field characteristics of ultrasound pulse close to the head of the transducer. This problem, however, does not affect the detection of bubbles since bubbles exist in the upper half of the channel. In single-phase flow, it is possible to find the upper wall with the echo information by finding the maximum intensity at that place, \(y/h = 1.0\). There is a single peak of the echo found in the vertical direction of the channel.
since ultrasound-absorbing boards are inserted. Without these boards, secondary peak takes place within the channel height due to multiple reflection of the pulse between the two parallel walls of the channel. In the case of two-phase flow, ultrasound pulse reflects on the gas-liquid interface, like a mirror, so the echo at the interface has the value higher or lower than that in surrounding region. The local high value in the echo intensity means that the ultrasound pulse reflects normal to the interface and returns straight to the transducer. The local low value comes up for oblique reflection of the pulse at the interface, with which the pulse does not return to the transducer. For these reasons, the outline of the bubble is identified as shown in Fig. 5(b), in which the interface is detected as a thin colourful layer in the channel.

Once the pulse reflects on the interface, it does not reach the upper wall to get the information deeper than the position of the interface. Although this is a demerit of the present technique, this full reflection of the pulse at the interface prevents from multiple reflection between the interface and the upper wall. Therefore, the position of the interface is uniquely captured. Figure 5 shows the gas-liquid interface measured by the present signal processing.

2.3 Two-Dimensional Velocity Vector Field

Utilizing two UVP systems with different measurement angles, velocity vector information can be obtained. For example, the same technique was reported by Taishi (2002). Figure 7 shows the relationship between the velocity components measured by UVPs and velocity vector of flow. In our system, two ultrasound transducers having same angle with opposite direction, \( \theta = \pm 8^\circ \), are used to get the velocity vector. The velocity vector \((u, v)\) is then calculated by Eq. (4), where \( \xi \) is the velocity component along the ultrasound beam direction and \((u, v)\) are the streamwise and the vertical velocity components of flow. Here, \( u_1 \) and \( u_2 \) are the velocity components which two UVP systems output as streamwise velocity.

\[
\mathbf{u} = (u, v) = \left( \frac{\xi_1 - \xi_2}{2 \sin \theta}, \frac{\xi_1 + \xi_2}{2 \cos \theta} \right) = \left( \frac{u_1 - u_2}{2}, \frac{u_1 + u_2}{2} \tan \theta \right) \tag{4}
\]

Fig. 7  Relationship among measured velocities and flow velocity vector

Figure 8 represents a sample of the velocity vector field inside the channel that contains bubbles, provided that the number of vectors measured is five times as that shown in the figure. Integrating the
vector information in time, we can evaluate the turbulent shear characteristics of the flow and the role of bubbles, which will be mentioned later.

![Velocity vector field of liquid in the channel](image)

(Gray region stands for gas bubble which is also detected by ultrasound pulse.)

3. RESULTS AND DISCUSSIONS

3.1 Bubble Shape by Oscillatory Injection

Figure 9(a) is a sample of the bubble shape measured by the echo information, which is averaged by phase of the valve operation (see (b)). At all the conditions, the time lag between the valve operation and the bubble measured is constantly obtained at given flow rate of liquid. The drifting speed of the bubble in the streamwise direction takes constant value, which is calculated by the time lag and the distance between the injector and the ultrasound transducer.

![Bubble shape measured by ultrasonic echo information](image)

(a) Bubble shape measured by ultrasonic echo information

![Valve operation for injecting bubbles intermittently](image)

(b) Valve operation for injecting bubbles intermittently

Figure 10 shows the measured relation between the injection time (the period of open status of the valve) and the passing time (the period of bubbles detected). As the linear trend seen in the result, the passing time or the length of individual bubble can be regularly controlled by the injection time as we designed so. When the valve operation has the highest frequency and the longest injection time, $f = 0.5$ Hz, $t_{in} = 1.5$ s, the bubbles are continuously injected since the passing time is longer than period of the bubble injection. It is noted that the individual bubble shape changes randomly within a certain range of the fluctuation because Weber number of the bubble is high enough to allow the turbulent
The deformation of the interface. We are going to take phase-statistic values to focus on the effect of the oscillatory bubble injection rather than investigating the local behaviour close to the interface.

![Fig. 10 Relation between the passing time and the injection time](image)

### 3.2 Shear Stress on Upper Wall

The time-averaged shear stress at the upper wall is shown in Figure 11. The ordinate is normalized by the shear stress of the single-phase condition. With the data, we can confirm that the shear stress of oscillatory bubble injection provides the value smaller than that of continuous injection at the same void fraction. Namely, the drag reduction is promoted by injecting bubbles in the flow intermittently. The dotted lines in the graph are linearly fitted trends of the data for the two different types of the bubble injection. In the case of continuous injection, the drag is rather increasing by injecting bubbles at low void fraction. To obtain the drag reduction, the continuous injection requires to inject bubbles more than 0.5% in void fraction. To the contrary, the oscillatory injection immediately provides drag reduction at zero-limit of void fraction. Furthermore, the drag reduction by the oscillatory injection always has higher performance than that of continuous injection at the range tested.

![Fig. 11 Ratio of shear stress at the upper wall for two different bubble injections](image)
A gain factor of skin friction reduction is calculated from the measured wall shear stresses, and its trend against mean void fraction is shown in Figure 12. The gain factor is defined by

\[
G = \frac{1}{\alpha} \left( 1 - \frac{\tau}{\tau_0} \right),
\]

where \( \alpha \) is the mean void fraction inside the channel, \( \tau \) and \( \tau_0 \) are the wall shear stress of two-phase and single-phase conditions, respectively. The gain factor, hence, indicates the magnitude of the drag effect per unit void fraction. This is to say, the sensitivity of drag reduction by bubbles. The gain factor takes a positive value when the drag reduction realizes. The gain factor at unity \((G = 1)\) means that 1% of void fraction provides 1% of drag reduction. As seen in the results, the gain factor for the continuous injection reaches around 15 at enough void fraction supplied in the flow. This means that 1% of drag reduction realizes 15% of drag reduction. However, this high performance is not kept for low void fraction, by decreasing the gain rapidly to negative. The oscillatory injection overcomes this problem. The gain factor of the oscillatory injection is kept around 20 in considerably wide range of void fraction, \( \alpha > 0.2 \times 10^{-2} \).

In order to discuss how the drag reduction is effectively enhanced by the oscillatory bubble injection, the waveform of the local skin friction around a single bubble is investigated. Fig. 13 shows the conditional averaged waveform of the shear stress at the upper wall; each the dashed line represent the average of the shear stress in the single-phase flow and continuous injection and the gray area represents the area existing bubble. The time lag between the waveform and the bubble area is corrected with the drifting speed of bubble. According to the results, before the bubble passes the position of the shear transducer, the shear stress is a little increased (see the left hand side of each bubble in the figure). This is explained by two-phase interaction in bubble-front region. When it enters the bubble existing area, the stress is decreased rapidly in a short time. The drag reduction achieves at the twice of the continuous injection. After that, the drag reduction is kept to be the same as the continuous injection when a long bubble is passing. Namely, the large drag reduction occurring in the first short period of bubble-entrance provides the improvement of the mean drag reduction in the case of oscillatory injection. In the later half of the bubble, the local shear stress restores smoothly to get the value of single-phase flow. This region has less drag reduction in comparison to the continuous
injection, however, the volume of the gas is a little as well (see the shape of the bubble in Fig. 9). Thereby, the gain factor is not worsened by the phenomenon occurring in the later half of the bubble. From the compassion among these three cases, it is clear that the bubble with a shorter period (or a shorter length) enhances the drag reduction per the same volume fraction. It is worth noting that further shortening the bubble length will lead to the drag reduction performance lower. Our group investigated on the dependence on bubble length in the past and concluded that there was an optimum bubble size to maximize the drag reduction (Murai et al., 2007). This is so because small bubbles, which are comparable to the boundary layer thickness, will activate the momentum transfer, resulting in increment of drag. Therefore, the improved effect by the oscillatory bubble injection would be unavailable for the bubble injection at too high frequency, which exceeds the speed of bubble divided by the boundary layer thickness.

![Waveforms of skin friction caused by intermittent bubble injection](image)

**Fig. 13** Waveforms of skin friction caused by intermittent bubble injection
3.3 Reynolds Shear Stress

In order to deepen the understanding on the effect of the oscillatory bubble injection, Reynolds shear stress is assessed from the UVP data.

Figure 14 shows the time averaged Reynolds shear stress for five different flow conditions. The results indicate that the flow is affected by bubbles at the upper half of the channel while the profiles are kept the same as that of single phase flow in the lower half, $y/h < 0$. Here we note that the Reynolds shear stress is not perfectly measured by two synchronized UVPs because of the limited spatial resolution of UVP. That is, the turbulence having the scale smaller than the resolution is uncounted in the data. Therefore, the measured value gets always smaller than the true one. However, we can still evaluate the measured value in relative sense since the energy cascade is known to occur obeying the universal law. The present results have shown that the Reynolds shear stress is reduced largest by the continuous injection, but smallest by the oscillatory injection at the shortest injection period. Since the Reynolds shear stress is defined only inside the liquid phase, this trend does not immediately correspond to the drag reduction performance obtained. Moreover, the time-averaged Reynolds shear stress cannot validly express the unsteady effect of the drag reduction, which is the key phenomenon of the oscillatory bubble injection.

![Fig. 14 Reynolds shear stress profiles for different bubble injections ($f = 0.33$ Hz)](image)

Figure 15 shows the local Reynolds shear stress distribution around the bubble. This figure represents the moving-averaged Reynolds shear stress for a single shot of bubble, which is non-dimensionalized by friction velocity ($u_\tau$). Since UVP cannot measure the velocity above the bubble interface, no information is obtained there. Such a region is also painted black. The time series of the Reynolds shear stress includes the one created by the original shear-induced turbulence in liquid flow. The result clearly shows that the local shear stress is reduced in the vicinity of bubble interface. This matches the general knowledge, i.e. the gas-liquid interface hardly keeps turbulence as well as the shear stress. In addition, the Reynolds shear stress in the upper half of the channel is broken to be wavy distribution beneath the bubble. This is a response of shear turbulence against suddenly unloaded stress at the upper wall. Hence it is explained that the effect of the oscillatory bubble injection is created with this unsteady response of liquid flow, which occurs periodically with passing of bubbles.
4. CONCLUSIONS

The effect of oscillatory bubble injection in frictional drag reduction is investigated experimentally, using a controlled bubble injection system. Information of liquid-area and the gas-liquid interface are successfully obtained from the echo amplitude of ultrasound. Hence, simultaneous measurement for the velocity and the phase distributions is realized by signal processing of ultrasound pulse. In addition, the wall shear stress and the Reynolds shear stress distributions are also successfully measured by compounding the two ultrasonic transducers and one shear transducer under synchronized control. With the present measurement, it is confirmed that the oscillatory bubble injection enhances the drag reduction significantly, and can save the power to generate bubble or can raise the gain factor of drag reduction. This improvement is realized by unsteady response of the shear flow against bubbles that pass intermittently. This effect is totally different from the one caused by the conventional continuous bubble injection. The oscillatory bubble injection amplifies the mean drag reduction by the repeated effect of unsteady drag reduction.

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