Microscopic Mechanisms for Skin Friction Reduction by Microbubbles

by

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Abstract

In order to clarify the skin friction reduction mechanism by microbubbles, both experiment and numerical simulation of turbulent channel flow with bubbles were carried out in the same parameter range, and were compared. In the experiment, silicone oil ten times more viscous than water has been used, in order to lower the Reynolds number to that of numerical simulation. The surface tension of the Silicone oil is 1/3 of that of water. In the numerical simulation, two numerical methods have been used. One is the Force Coupling Method (FCM), in which bubbles are assumed to be rigid and the influence of bubbles to the flow is simulated by body forces. The other is the Front-Tracking Method (FTM), in which fluid phase and gas phase are solved simultaneously and bubble shape is allowed to deform by being expressed with polynomials.

In the experiment the Reynolds number ($Re$) is 2,777 to 4,500, and the Weber number ($We$) is 200. The experimental values of local skin friction shows that the flow is semi-laminar at $Re=2,777$ in the non-bubble condition, and that, by injecting bubbles, the skin friction increases to the turbulent flow value, which means that bubble injection stimulates the flow and turns it to fully turbulent. At $Re=3,734 (3,811)$ the flow is already fully turbulent in the non-bubble condition, and therefore adding bubbles has little influence on the flow, resulting in little change in the skin friction. At even higher Reynolds number of nearly 4,500, adding bubbles decreases skin friction slightly.

The Reynolds number of the numerical simulation using FTM is 3,000. The time history of skin friction shows that at the wall where bubbles are clustered by buoyancy local skin friction tends to show slight decrease by adding deformable bubbles ($We=100$). However, by adding less deformable bubbles ($We=50$) local skin friction slightly increases. Computation at $We=200$ has blown up. The local skin friction in the FCM computation at $Re=4,000$ shows 2.3% increase by adding (rigid) bubbles. Therefore it may be stated that, at $Re=3,000$, addition of deformable bubbles tends to decrease skin friction, while addition of less deformable bubbles, or rigid bubbles, tends to increase skin friction.

In order to carry out numerical simulation of turbulent shear flow with bubbles at higher Reynolds number, the simulation of the homogeneous turbulent shear flow (HTSF) with deformable bubbles has been carried out. The result shows that large turbulent Reynolds number, smaller shear Reynolds number and large Weber number have positive influence on the microbubble drag reduction. The increase of the turbulent Reynolds number of HTSF corresponds to the increase of the Reynolds number of the turbulent channel flow (TCF), and therefore the result agrees with the experimental result that added bubbles decrease skin friction at higher Reynolds number but not at lower Reynolds number. The Weber number dependence of the HTSF result can be compared directly with that of TCF. Thus the result confirms that bubble deformation acts to decrease skin friction.

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1. Introduction

Microbubbles, i.e. small air bubbles, injected into the turbulent boundary layer developing along a solid surface moving in water, have significant skin friction reduction effect with no harm to the environment, and are regarded as a promising drag reduction device for ships. For example, in 2001 there was a full-scale microbubble experiment using a training ship of length \( L_{pp} \approx 120 \) m running at 14 knots, a typical cruising speed of a large tanker, in which the drag of the ship reduced by as much as 5%. Although the drag reduction effect of microbubbles generated using existing techniques is large enough to be applied to slowly moving ships such as tankers, it is always desirable to have larger drag reduction per unit volume of injected air. In order to do so, it is first of all necessary to know the mechanism how skin friction decreases with bubble injection.

The skin friction reduction mechanism of microbubbles is not yet fully understood. One of the main reasons for the difficulty in clarifying the mechanism is the lack of confidence in direct numerical simulation (DNS) for this type of flow. At the time this project started in 2002, there was hardly any DNS result in which the skin friction reduction by microbubbles was successfully simulated, but in almost all the numerical simulations microbubbles increased skin friction. For example, see Kawamura and Kodama (2001 & 2002) and Sugiyama et al. (2002).

The only exception was that by Xu et al. (2002), in which they simulated the microbubble drag reduction using the Force Coupling Method (FCM). However, later, the accuracy of the result was found to be ambiguous, because Sugiyama et al. (2004) showed that, by increasing the accuracy of the computation by including not only the force monopole term, which was the case with Xu et al. (2002), but also the force dipole term, the simulation predicts skin friction increase.

In Kawamura and Kodama (2001 & 2002) the Front-Tracking (F-T) formulation generalized by Unverdi and Tryggvason (1992) was employed in order to resolve both liquid and gas phases with flexible bubble shapes. This computation was perhaps the most accurate for microbubble flows at that time, but, still, the skin friction reduction by microbubbles could not be simulated, and the skin friction increased with increasing void fraction.

The failure of DNS in simulating skin friction reduction by microbubbles posed serious questions to the validity of DNS for microbubble flows. This put a serious handicap to the study on the skin friction reduction mechanism, because DNS has successfully given numerous valuable information, which cannot be obtained experimentally, on complex flows such as turbulence.

Therefore we, the present investigators, proposed this research project to find out the reason for the discrepancy between experiment and numerical simulation, hoping to regain the validity of DNS. There are several conditions that are different between those of experiment and DNS. One is the bubble dispersion effect. In the experiment, bubbles that are injected from the wall are initially concentrated near the wall and are gradually dispersed away from the wall due to turbulence as they go downstream. This transient state was simulated by Sugiyama et al. (2003) using the Eulerian-Lagrangian (EL) method, and the skin friction reduction was obtained in the transient region.

Another different condition is the range of the Reynolds number. Although the channel flow is fully developed and turbulent in both experiment and DNS, the friction Reynolds number \( Re_\tau \) of DNS is \( O(10^2) \), one or two orders of magnitude smaller than that of experiment. We suspected that this was the main cause of the discrepancy and, since carrying out DNS at the same friction Reynolds number as that of experiment is impossible because of today's computer power, we decided to carry out experiment at the same friction Reynolds number as that of DNS, so that direct comparison of DNS and experiment becomes possible.

The second chapter describes the experimental work, in which silicone oil of 10 cSt viscosity, ten times more viscous than water, was used as fluid media. Water was also used in some experiments. The third chapter describes the DNS work, in which the flow conditions were made the same as those of the experiment as much as possible. The forth chapter describes numerical simulation of homogeneous shear flow with deformable bubbles. The Reynolds number and Weber number dependence of the bubble effect on the flow away from the wall is further studied. The fifth chapter describes discussions and conclusions.
2. Experimental Study of Microbubble Channel Flow

2.1 Outline of the study

The main purpose of the experimental study is to clarify the low Reynolds number behavior of bubbly channel flow. For that purpose, silicone oil was chosen as fluid media. Its physical property is shown in Table 2.1.

That is, the Silicone oil used in the experiment has approximately the same density as water, it is ten times more viscous than water, and it has surface tension less than 1/3 of water. Using this silicone oil, we can lower the Reynolds number to approximately 1/10 of that of water at the same flow speed. The smaller surface tension causes some difficulty in bubble generation, as described in later sections. Use of Silicone oil for low Reynolds number conditions provides a number of merits as follows: 1) Interfacial property of bubble surface is stable in comparison with water flow. Contamination effect is so negligible that the comparison with DNS can be discussed exactly. 2) The channel height is kept large at such a low Reynolds number condition because of high viscosity of oil used. This makes optical measurement easier, and the ratio of bubble diameter to channel height is adjustable to DNS as well. In addition to experiments using Silicone oil, normal experiments using water were also conducted for comparison.

The experimental devices constructed are as shown in Fig.2.1. For comparison with DNS’s conditions, four kinds of horizontal straight channels have been made. A-Channel exists at Fukui University, and B-Channel at Hokkaido University. To vary the bubble diameter widely, i.e. 0.02 to 5.00 in the value of d/H, four types of bubble generation systems (porous plate method, capillary tube method, water electrolysis method, and laser-boring method) are employed. A1-Channel and B1-Channel were used in the water flow experiment, in which high Reynolds number channel flows (Re_H=5,000 to 20,000) are measured. The results using the B1 channel are omitted in this report. A2-Channel and B2-Channel, were used in the silicone oil flow experiment, in which low Reynolds number channel flows (Re_H=500 to 5000) are measured. The dimensions of the test section of each channel are shown in Table 2.2. Since the results using the B1-Channel are irrelevant to the present study, its dimensions are not shown in the table.

Fig.2.2 shows photographs of A-Channel and B-Channel.

---

### Table 2.1 Comparison of physical properties of silicone oil and water (at 20 deg. C)

<table>
<thead>
<tr>
<th>Property</th>
<th>Silicone oil</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>density ρ (kg/m²)</td>
<td>935</td>
<td>998</td>
</tr>
<tr>
<td>viscosity μ (kg/m.s)</td>
<td>10.38×10⁻³</td>
<td>1.002×10⁻³</td>
</tr>
<tr>
<td>kinematic viscosity ν (m²/s)</td>
<td>11.10×10⁻⁶</td>
<td>1.004×10⁻⁶</td>
</tr>
<tr>
<td>surface tension σ (N/m)</td>
<td>0.0201</td>
<td>0.07275</td>
</tr>
</tbody>
</table>

### Table 2.2 Dimensions of channel test sections

<table>
<thead>
<tr>
<th>Channel</th>
<th>Fluid media</th>
<th>height H(mm)</th>
<th>half height h(mm)</th>
<th>width (mm)</th>
<th>length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>water</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>6,000</td>
</tr>
<tr>
<td>A2</td>
<td>silicone oil</td>
<td>10</td>
<td>5</td>
<td>100</td>
<td>6,000</td>
</tr>
<tr>
<td>B1</td>
<td>water</td>
<td>40</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B2</td>
<td>silicone oil</td>
<td>20</td>
<td>10</td>
<td>160</td>
<td>6,000</td>
</tr>
</tbody>
</table>
2.2 Water channel flow

2.2.1 Synchronized measurement of wall shear stress and large bubble behavior

(1) Purpose of study

The microbubble method, i.e. in which small bubbles are injected into the turbulent boundary layer, reduces the skin friction significantly. Takahashi et al. (2003) carried out experiments in the microbubble method using a long flat plate ship, and showed the drag reduction up to 22%. It is considered that the mechanism of this method is relevant to several factors, such as reduction of mean local density and effective viscosity or translational motions of bubbles and bubble deformation interacting with coherent structure of turbulence; however, the mechanism has not been clarified comprehensively. On the other hand, the air film method, i.e. in which relatively large bubbles are injected at the bottom of ships and they migrate over the surface, is also recognized as an effective drag reduction method. Katsui et al. (2003) carried out an experiment of the air film method using a tanker-form model ship. They showed that the skin friction drag reduction worked proportional to the
area of air film. It implies that the drag reduction of the air film method is caused by preventing direct contact of the ship body with water. Both of the studies were carried out separately, and therefore the performance in the intermediate condition between microbubble and air film, i.e. a wide range of conditions of bubble diameter relative to the thickness of the boundary layer, has not been investigated explicitly. Moreover, owing to frequent coalescence and fragmentation of bubbles, the bubble diameter gradually changes and converges to an equilibrium size further downstream of the bubble injector. Therefore, it is important to study in such cases, in which the persistency of drag reduction effect will be discussed as well. In this part of study, direct measurement of time averaged skin friction is made in a horizontal channel in a boundary region between the microbubble and air film conditions for bubbles. In addition, the temporal relationship between local skin friction and bubble interfacial structure is investigated via the synchronized measurement, which will be described later in the section.

(2) Experimental method

The A1 channel is used in the experiment. A snapshot of the experimental apparatus is as shown in Fig.2.2. The test section is a horizontal rectangular channel made of transparent acrylic resin and is 10 mm in height, 100 mm in width and 6000 mm in length, respectively. Measurement windows locate in the upper wall of the channel at the interval of 250 mm in the streamwise direction. Tap water and room air are used for two phases at laboratory temperature (10 to 20 deg C). Air bubbles are injected into the horizontal channel through the air injection device, as shown in Fig.2.3. This device has a porous plate made of alumina with the nominal pore diameter of approximate 60 μm. The injection area is 14 x 48 mm². The bubbles are generated with compressed air supplied from outside the channel. The water circulates in the channel, and the bubbles are eliminated in the downstream region, by swirling the fluid in a bubble removable tank.

Fig.2.3 Experimental channel and air injection device (A1-channel)

The local wall-shear stress on the upper wall of the channel is measured by a shear transducer (SSK, S10W-01), which has the sensing part of 10 mm in diameter and the maximum load of 1 N, corresponding to 12.5 Pa of shear stress. A schematic diagram of the shear transducer is shown in Fig. 2.4(a) (b). In order to obtain the local wall-shear stress, the data are recorded to a PC through an amplifier and a data logger. The measurement of the shear stress is performed at \(x/h = 50, 200\) and 800, which correspond to 250, 1000 and 4000 mm downstream of the air injection device.
The detail of the experimental conditions is listed in Table 2.3. The photography of interfacial structure of bubbles is recorded using a high-speed digital video camera (Photron, Fastcam-Max), on which a tele-centric lens is mounted. The back light projection is adopted by a metal halide lamp. The frame rate is 500 fps and the shutter speed is 1/150000 s. The image of gas-liquid interface can be obtained clearly by this illumination method. The images taken via the camera are recorded as digital raw data in a PC. The field of view is approximately 17.5 x 17.5 mm and the magnification factor is 0.00172 mm/pixel. Fig.2.4(c) shows a schematic diagram of the synchronized measurement system. A pulse generator synchronizes the trigger timings of the camera and the data logger. The image acquisition position is 55 mm downstream the measurement position of wall-shear stress, because they cannot be located at the same position. Hence there is a time lag between the data obtained by each device. The time lag is removed in the process of data correction using the mean velocity of gas-liquid interface, which is measured by particle image velocimetry (PIV).

Fig. 2.5 shows the result of wall shear stress obtained by the shear transducer in the case of single-phase water channel flow. The ordinate and abscissa stand for the local shear stress and bulk mean velocity in the channel, respectively. In this figure, there is a slight difference between the experimental and theoretical values. This discrepancy comes from a very small error for the flatness of the sensing area to the channel wall, and it is in the order of 10 micron estimated by a boundary layer theory. However the overall tendency in the both data takes similar, and there is only a relative error to Blasius’s formula around –10% in the range tested, i.e. no significant random error. In practice, the ratio of two wall shear stresses for single- and bubbly flow cases can be evaluated with this method.

<table>
<thead>
<tr>
<th>Table 2.3 Experimental conditions for water channel flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk mean velocity, $U$</td>
</tr>
<tr>
<td>Mean void fraction, $\alpha$</td>
</tr>
<tr>
<td>$Re = UH/\nu$, $H = 2h$</td>
</tr>
<tr>
<td>$Re_f = U_f h/\nu$</td>
</tr>
<tr>
<td>$Fr_r = U_r (gh)^{1/2}$</td>
</tr>
<tr>
<td>$We = \rho U^2 h/\sigma$</td>
</tr>
<tr>
<td>Temperature of water</td>
</tr>
<tr>
<td>Density of water, $\rho$</td>
</tr>
<tr>
<td>Kinematic viscosity, $\nu$</td>
</tr>
<tr>
<td>Shear transducer</td>
</tr>
<tr>
<td>Sampling rate</td>
</tr>
<tr>
<td>Sampling time</td>
</tr>
</tbody>
</table>

Fig.2.5 Wall shear stress without bubbles
(3) Experimental results

Fig. 2.6 shows the result of skin friction on the upper wall at \( x/h = 50, 200 \) and \( 800 \), i.e. \( x = 250, 1000 \) and \( 4000 \) mm downstream of the air injection device. The vertical axis shows skin friction coefficient ratio \( \frac{C_f}{C_{f0}} \), whose each component is defined as

\[
C_{f0} \equiv \frac{\tau_w}{\frac{1}{2} \rho_w U^2} \tag{2.1}
\]

\[
C_f \equiv \frac{\tau_w}{\frac{1}{2} (1 - \alpha) \rho_w U'^2} \tag{2.2}
\]

\[
U \equiv \frac{Q_w}{A_c} ; \text{ bulk flow speed in the non-bubble condition}
\]

\[
U' \equiv \frac{Q_w + Q_a}{A_c} ; \text{ bulk flow speed in the bubble condition, taking into account the air flow rate}
\]

\[
\rho_w ; \text{ water density}
\]

\[
Q_w ; \text{ water flow rate, which takes the same value in the non-bubble and bubble conditions}
\]

\[
Q_a ; \text{ air flow rate}
\]

\[
A_c ; \text{ channel sectional area}
\]

That is, corrections due to speed increase and density decrease are applied. It results that

\[
\frac{C_f}{C_{f0}} = \frac{1}{1 - \alpha} \left( \frac{U}{U'} \right) \frac{\tau_w}{\tau_{w0}} \tag{2.3}
\]

In the case of \( x/h = 50 \) (see Fig. 2.6(a)), the skin friction ratio increases with increasing void fraction up to around 10 %. And then it begins to decrease at the higher void fraction. The skin friction ratio is lower than unity as the void fraction is given higher than 15 %. That is, the drag reduction occurs. The maximum drag reduction observed in the present experiment is approximately 40 % in all the conditions. It is also seen that the variation of the data owing to the speed of flow is obvious at the lower void fraction in the channel, and the skin friction ratio increases as the flow velocity decreases. To the contrary the deviation vanishes as the void fraction is given higher than 20 %. By paying attention to the difference in measurement points, the skin friction ratio always lower than unity for the case of \( x/h = 200 \) and \( 800 \) (see Figs. 2.6 (b) and (c)). And the skin friction decreases approximately linearly for the high void fraction. This fact implies that there is a transient effect of two-phase boundary layer developing in the streamwise direction on the wall shear stress. The distance of transient effect depends on the speed of channel flow. On the other hand, the two-phase boundary attains to an equilibrium state in the downstream region, which is nearly independent on the speed of flow. When the void fraction is higher than 20 %, it is confirmed that the skin friction ratio approaches a certain value in any flow velocities and measurement positions.

![Fig.2.6 Friction coefficient ratio at three locations as function of void fraction](image)

The gain factor of skin friction reduction to void fraction is shown in Fig. 2.7(a). The gain factor indicates the magnitude of the drag reduction effect per void fraction. In this figure, it is observed that the gain increases with increasing void-fraction in all the conditions tested, and reaches up to approximately 1.6 when the void fraction is higher than 20 %. In this experiment, the range of the gain is scattered from -3.0 to 1.6, and its absolute value exceeds unity. That means the drag modification
caused in this channel is not originated by simple mechanism such as a mean density decrease. Thus, bubbles in the case of low void fraction and low flow speed generate additional skin friction more than its volume fraction, and bubbles in a high void fraction reduce the friction more than its volume fraction. This tells us that a structural alternation happens inside the boundary layer as bubbles are mixed. Fig.2.7(b) shows the relationship between mean bubble diameter and bulk mean void fraction. In this figure, it is confirmed that the bubble diameter becomes larger with increasing bulk mean void fraction and distance from the bubble injection device.

Fig.2.7 Gain of drag modification and bubble diameter as function of void fraction

Fig. 2.8(a)(b) shows the temporal correlation of the skin friction ratio to the local projection void fraction $\beta$ for 1.0 m/s of the bulk mean velocity and 20% of bulk mean void fraction in channel, where the measurement positions are $x/h=50$ and 200 downstream of the air injection device. In those cases, approximately 30% of the drag reduction is obtained as the time averaged value. Fig. 2.8(c) explains the local projection void fraction $\beta$, which is defined as the ratio of the white area i.e. the projected bubble area, in the right half of Fig.2.8(c).

In Fig. 2.8(a)(b), the ordinate stand for the ratio of wall-shear stress (denoted by the heavy line) and the local projection void fraction (denoted by the thin line), respectively, and the abscissa stands for the time. When the projection void fraction is unity, it is that only air bubbles cover over the sensing part of the shear transducer. On the contrary, when the void fraction becomes 0, it indicates that only liquid exists at the sensing part. The images on the upper part are the time expansion image taken via the synchronized measurement. Fig. 2.8(d) shows an element of time expansion image. The direction of the flow is from right to left in the time expansion images. In total, it is clear that there is a negative correlation between the local skin friction and the local void fraction. And it can be seen that the local skin friction decreases especially in the rear part of large bubbles, and increases after the bubbles pass through the measurement part. When the size of bubbles becomes larger (in other words, $\beta$ takes unity for a long time), the skin friction decreases continuously for a long time. While the $\beta$ takes 0, the ratio of wall-shear stress is the same as the case of single-phase water flow. These results are observed typically in the case of downstream positions because the bubbles become larger and migrate periodically on the downstream position than on the upstream one. Here, we discuss the local skin friction profile along each bubble by analysing the data set of the synchronized measurement.
Fig. 2.8 Synchronized measurement of local skin friction and local projection void fraction

Fig. 2.9(a) shows the relationship between the local skin friction and dimensionless bubble coordinate in the streamwise direction, where the streamwise bubble length ranges from 20 to 70 mm. Here, the dimensionless bubble coordinate is defined as the ratio of the distance from the front of bubbles (t) to the total length of a single bubble (T). The dimensionless bubble coordinate of unity corresponds to the rear edge of bubbles. With this figure, it is found that the skin friction increases in the front part but decreases at the middle part, and then takes the minimum value at the rear part of the bubbles. The deviation of the skin friction from unity is larger in the latter half of the bubble more than in the former half, being providing drag reduction in total. These tendencies are confirmed similarly for bubbles of different size.

Fig. 2.9(b) shows the relationship between the mean skin friction inside single bubble and the streamwise bubble length. Fig. 2.9(c) shows the relationship between the bubble length and the least friction in a single bubble. The ordinate in these two figures is normalized by the single-phase wall-shear stress. In these figures, drag reduction always occurs during the bubble passage through the measurement point. Also, the skin friction decreases with increasing bubble length. In Fig. 2.9(c), when the bubble length takes a higher value than 50 mm (5H or 10h), the skin friction takes nearly 0 during the passage of the bubble. This is a sort of locally segmented air film, which has a shear-free structure inside itself. The critical bubble length at which the shear-free structure takes place (50mm in this study) might be a new target of the investigation.

Fig. 2.9 Ensemble statistics of skin friction for individual bubble
Summarizing the measurement results, the following points have been made clear.

(i) The skin friction ratio initially increases with increasing void fraction, and then begins to decrease at the higher void fraction. In this process, the gain factor (drag modification ratio to void fraction) is more than unity in the absolute value, implying sensitive control of the skin friction by bubbles.

(ii) There is a clear negative correlation between the local skin friction and the local void fraction. Especially, the friction decreases drastically in the rear part of individual bubble.

(iii) The mean skin friction takes a maximum value in the case of bubbles around 10mm (1.0H) injected. The smaller and the larger size than it enhances drag reduction.

(iv) The local average skin friction inside individual bubble decreases with increase of bubble’s streamwise length. In the case of bubbles larger than 50mm (a critical size, d/H=5), the local skin friction becomes zero.

2.2.2 Velocity measurement using Particle Tracking Velocimetry

(1) Purpose of study
Most of former experimental studies were implemented to evaluate Reynolds stress profile only in liquid phase, and did not consider explicitly the turbulent shear stress as two-phase flow, which is a function of local bubble motion as reported by Kataoka and Serizawa (1989, 1990). In this part of study, the momentum conservation equation of gas-liquid two-phase flow is used to acquire the componential turbulent shear stress as two-phase flow from experimental data obtained by Particle Tracking Velocimetry (PTV).

(2) Experimental method
A schematic diagram of the experimental apparatus is shown in Fig. 2.10(a). The configuration of the channel is the same as the one mentioned in Section 2.2.1, i.e. the A1 channel was used. The measurement location for PTV is at 250mm from the bubble injector device. The image acquisition of the two-phase flow is carried out using a high-speed digital video camera (Photron, Fastcam-Max-120KC, 512x512pixels) with a tele-centric lens (Computar, TEC-55). Fig. 2.10(b) shows the flow visualization system for PTV measurement. The tracer particles with 40 micrometer in average diameter are seeded to visualize the liquid phase flow. A metal halide light is used for illuminating the particles from the backside of the camera. In the present study, the backlight projection is implemented in the spanwise direction and the focal plane is adjusted on the central plane of the channel. The narrow depth of field is utilized to perform two-dimensional measurement of the flow. The frame rate is 4000fps and the shutter speed is 1/15000s. The image of gas-liquid interface is clearly obtained as well via this illumination method. The images taken by the camera are recorded as digital raw image data in a PC. The field of view is approximately 12x12mm and the magnification factor is 0.00225mm/pixel.

(a) Experimental channel for PTV
(b) Measurement section

Fig.2.10. Experimental set-up for particle tracking velocimetry
Fig. 2.11(a) shows a sample of the original image obtained by the above-mentioned photographing method. The size of the photograph is 12mm horizontally and 10mm vertically, equalling the channel height. Both blunt particles and clearly focused particles exist in the image for the intentionally narrowed depth of field. The degree of the focusing of lens can be evaluated by converting the image to spatial frequency spectrum. Focused particles have a high frequency band while defocused particles have a relatively low frequency band in the spectrum-base image. Thus, the focused particles can be extracted using a high-pass filter for the image as shown in Fig. 2.11(b). In contrast, blunt defocused bubbles and unclear particles existing outside the depth of field are removed with the high-pass filtering. Very small dark spots in the figure are the tracer particles. Individual bubble motion is measured by calculating the centroid of each bubble after image processing consisting of binarization and median filtering as shown in Fig.2.11(c). Local projection void fraction $\beta$ is measured using another set of bubble images as shown in Fig.2.11(d), in which those bubbles contacting the top wall, being removed in Fig.2.11(c), are maintained.

![Original image](image1)

![High-pass filtered image](image2)

![Separated bubbles](image3)

**(d) Separated bubbles (for projection void fraction $\beta$)**

Fig. 2.11 Bubble and particle images for particle tracking velocimetry ($x/h=50$, $U=2.0m/s$, $\alpha=0.08\%$)

(3) Experimental results

Fig. 2.12(a) shows the mean void fraction profile across the channel height. The domain size defined here is $0.11mm \times 0.11mm$. In this figure, $y/h=0$ is the upper wall and $y/h=2.0$ the lower wall. The local void fraction takes the highest value at $y/h=0.2$, while it is nearly 0 in the lower half region of the channel.

Fig. 2.12(b) shows the mean velocity profiles of liquid and bubbles in the top half coordinate of the channel, which is normalized by $u_{max}$. Here, $u_{max}$ is the maximum velocity of liquid phase at the center of the channel. The liquid phase velocity follows the $1/7$th power law approximately at $x/h=50$ from the bubble injector device. The bubble velocity profile has a slightly slower velocity than the liquid-phase. Integration of the projected void fraction across the channel by assuming uniform spanwise distribution gives bulk void fraction $1.92\%$, which is 24 times the actual bulk void fraction $\alpha=0.08\%$.

Fig. 2.12(c) shows the histogram of bubble diameter obtained by image processing. The mean bubble diameter is 0.7mm.