Flow Visualization and Characteristics of Vertical Gas-Liquid Bubbly Flow Around a Rectangular Cylinder (Bubble Size Effect)

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Abstract. The present study deals with the effect of the bubble size, from small bubble scale to normal scale ($d_b=0.25$~$2.6$ mm), on the flow passing through a rectangular cylinder in an upward gas-liquid bubbly flow. Extensive visualization experiments are conducted and a digital camera and a high-speed camera analyzed the flow, while PIV analysis by the volume cross-correlation method is conducted to observe the differences in the flow pattern. In order to further understand the effect of bubble size, the pressure distribution along the pipe and the cylinder surface are measured. From the results taken, the drag force is calculated and compared to the case of single phase-flow. Furthermore, the fluctuation phenomena generating from the Karman vortex street downstream the cylinder are investigated, and how the intensity and frequency are affected by the bubble size and gas fraction is presented. The experiments are conducted under two different Reynolds number $Re$, and volumetric gas fraction ranging from $\alpha_v=0$~$5\%$, giving valuable information regarding the changes that occur due to bubble size differences and the relation it has with volumetric gas fraction.

1. INTRODUCTION
The emission of Karman vortex street of two vortex rows with opposite circulations for a gas-liquid two-phase bubbly flow past an obstacle(s), which is encountered in many industrial components, has been widely investigated and several studies exist.

These studies found in bibliography, are conducted under various parameters such as Reynolds number, gas fraction effect or cylinder’s geometry effect (Dian, 2002; Hara et al., 1982; Hulin et al., 1982). In the recent years advanced personal computers are used and several models are suggested in order to conduct numerical analysis of the flow mechanism around an obstacle(s) (Shakouchi et al., 2004; Sugiyama et al., 1999). From these results, valuable information and deeper understanding on the flow pattern and mechanism has been achieved through the years.

The vibration phenomenon of a circular cylinder in cross flow was studied extensively by Hara et al. (1982), while the two-phase flow-induced vibration was introduced by Pettigrew (1994) and the characteristics of the unsteady behavior of two-phase flow is mentioned on Yokosawa et al. (1986) work.

The vortex emission behind bluff bodies, wake and drag of were studied and presented by Hulin et al. (1982), Roshko (1955) and Shakouchi et al. (2004). The results presented refer to various conditions of Reynolds number and void fraction. Furthermore, extensive numerical analysis on flow characteristics around cylinder, is presented by authors like Inoue et al. (1986) while numerical
analysis has been conducted with different methods like Uchiyama et al. (1996) or Sugiyama et al. (1999).

From the above-mentioned studies, some include photographic and visualization material showing the flow pattern of the generated flow.

As seen, most if not all the work done so far, do not mention the effect of bubble size. Separate studies for micro-bubbly flows, or agitated bubbly with cap form bubble flows can be seen in bibliography. A study dealing with the same flow conditions but under different bubble sizes from small scale to normal scale $d_b = 0.27 - 2.6$ mm however, have not been conducted, at least to the authors knowledge.

In the present study, the effect of the bubble size mean diameter under constant flow conditions and different gas fraction values are investigated. The differences on flow characteristics; such as flow pattern and vortex shedding frequency, with special attendance on visualization experiments with high speed camera and PIV analysis are introduced. The results will help to understand and explain how studies from individual authors, even conducted under similar conditions have shown different results. Moreover, the visualization material shows the undeniable changes occurring due to bubble size difference to the flow system. In addition, it is well known that in the industrial field, depending the application used or seen, a variation of bubble sizes into the gas-liquid system exists. By this, it will help understand and explain several situations and conditions that were not made clear so far.

2. EXPERIMENTAL CONDITIONS

2.1 Apparatus

Figure 1 shows the experimental set-up. A rectangular test section was used and made of a transparent acrylic resin channel in order to conduct visualization experiments. The device has $L = 2400$ mm in length, $D = 90.0$ mm in width and $H = 45.0$ mm in depth. A test cylinder of $d = 30.0$ mm made of brass is mounted at the center of the channel perpendicular to the two-phase flow rigidly. The distance from the bottom of the test section to the front side of the test cylinder is 1520 mm and the coordinates are shown.

A pump gives the required amount of water flow rate, where water was storage in a tank. The water temperature was maintained constant at $T = 20^\circ C$. The mixture of water and gas were separated at the top of the device and water was re-circulated at the water tank. The water and gas flow rates were measured by float type flow meters. For the experiments, $\text{CO}_2$ gas was used as a driving gas because of the controllability of bubble size and to
reduce collision phenomena before the test section and was provided by a pressurized tank as shown. The bubble generator (Shakouchi et al., 2006) in the form of a simple orifice nozzle is given in Fig.2. The pipe diameter is of 5.0 mm and the orifice diameter is 2.0 mm, which gives a contraction area ratio of $A_r=0.16$. The shear stress generating due to the orifice jet effect was used for breaking up the induced gas from the two stainless steel pipes of diameter 1.0 mm, attached on the side of the orifice head as shown. The gas is induced at the sides and is entrapped into the jet, while changing the water flow rate of the nozzle under a given gas flow rate, manages to control the generated bubble size, due to the shear stress force change occurring. The flow rates are measured by float type flow rates like before.

2.2 Experimental Conditions and Procedure

In the following the condition under which experiments were conducted are presented. Two different Reynolds numbers were used at $Re=0.5 \times 10^4$ and $1.0 \times 10^4$ of which Reynolds number is defined as follows:

$$Re=U_{wm}d/\nu \quad (1)$$

where, $U_{wm}$ is the water mean velocity in the flow passage and the cylinder diameter is taken as a characteristic length.

The experiment was subject to the bubbly flow regime. Although there is some slip velocity between phases, for simplicity and convenience we assume that the relative velocity between phases in the axial direction can be neglected for the time being. Thus, we apply the homogeneous model and the void fraction which express the volume ratio of the gas phase in the flow, was varied from $\alpha_c=0$–5% in the experiments and is given form the following expression:

$$\alpha_c= \frac{Q_g}{Q_g+Q_w} \times 100 \quad (2)$$

where $Q_g$ and $Q_w$ are the volume flow rates of the gas and the liquid phases.

It was mentioned above that the bubble size control was conducted by varying the volumetric water flow rate exiting from the orifice nozzle. Adjusting it from $Q_{w^\prime}=0$–3.5 l/min per single nozzle allowed a mean bubble size variation of $d_b=0.27$–2.6 mm, while the gas value range was $Q_g=0$–2.4 l/min in total. Below in Table 1, the relation between gas fraction, volumetric water flow and mean bubble size is given.

Pressure holes of 0.7 mm diameter are drilled along the sidewall of the test section and a water manometer measures the pressure in respect to the reference point. In addition, ten pressure holes of same diameter were drilled at the front and rear side of the test cylinder and the pressure difference from the reference point, for different bubble size was also measured.

| Water jet flow rate (per single water nozzle) | Mean bubble size $d_b$ [mm] | $\alpha_c =1.5\%$ | $\alpha_c =5\%$ |
|----------------------------------------------|-------------------------------|--------------------|------------------|
| $Q_{w^\prime}$ [l/min]                      |                               |                    |                  |
| 0                                           | 2.6                           | 2.6                |                  |
| 1                                           | 0.7                           | 0.9                |                  |
| 3.5                                         | 0.27                          | 0.27               |                  |
A semi-conductor type pressure transducer measures the pressure fluctuation downstream at \( y/d = 14 \). From the pressure transducer results, through the oscilloscope (Kanomax, TDS 2002 series), FFT analysis was conducted and the fluctuation amplitude was calculated. The pressure fluctuation was recorded for continues \( 2.5 \) s and \( 2.5 \) KHz. For each flow condition, data were recorded for \( 30 \) times and the mean value was considered and presented in the present study.

It is noted at this point that the experiments were carried out after the \( \text{CO}_2 \)-water mix was re-circulated enough time within the loop system in order to bring it in a saturated state. This was done to make sure that the generated bubbles do not dilute within the system, which would cause the decrease of bubble size and reduction of gas fraction.

2.3 Visualization Experiments

A 5 mm slit of light provided by three halogen lights was used for the flow passage illumination, while an extra light from the back of the flow passage was used in some cases. The bubble size distribution was measured by the photographic images taken by a NIKKON D70 at 3600 FPS. For each bubble size cases, more than five hundred bubbles from several different photographs were measured. Since there were cases that the bubbles were not round but more spherical, the axial and vertical diameter was accounted and divided by two \( (d_b = d_x + d_y / 2) \).

The overall flow pattern under different flow conditions was observed and recorded by a digital video camera with. Plastic beads of which density is approximately the same as that of water and mean diameter of \( 0.3 \) mm were used as tracers for single-phase flow (DIAION HP21). For the case of \( \text{CO}_2 \)-water two-phase flow the bubbles were used as tracers since they reflect the light and give good traceability.

A high speed photographing system (CCD camera, PHOTRON, FASTCAM M3PIV3/100K), with a Micro-NIKKOR 105mm lens was used for the image processing, with the shutter speed set at \( 1/2000 \) s and frame rate at \( 500\)FPS. The velocity vectors were extracted by PIV using the volume cross-correlation method to reproduce the complicated two-phase flow pattern and give the differences occurring due to bubble size effect. For the PIV analysis, two patterns were extracted. In the first, real time of \( 0.2s \) was extracted and the local instantaneous bubble velocity distribution was extracted in order to see the flow deviation. In the second, a total of more than \( 7s \) was taken, which allowed obtaining the mean velocity distribution.

3. RESULTS and DISCUSSIONS

3.1 Pressure Distribution and Drag Force

The pressure distribution along the sidewall vertical axis is measured under constant flow conditions and varying the bubble mean size. Results for \( Re = 0.5 \times 10^4 \) and \( \alpha = 1.5\% \) is illustrated in Fig.3. The vertical axis denotes the pressure coefficient which is a non dimensional value given from the equation shown below:

\[
C_p = 2(P_i - P_o - P_e) / (\rho U_m^2) \quad (3)
\]

where, \( \rho \) is the two-phase flow density and \( U_m \) is the mean velocity of the two-phase flow upstream. \( P_i \) expresses the pressure value at a given point and \( P_o \) is the pressure measured at the reference point and \( P_e \) the vertical elevation pressure.

The cylinder is illustrated for better understanding and is located between \( y/d = 2 - 3 \), while the single-phase pressure distribution is also illustrated. The pressure decreases due to the friction effect and at the front corner of the cylinder an even more rapid decrease begins due to the increase of velocity. After it passes the narrow region, a further slight decrease continues from the generation of large-scale
vortices that eventually generate the Karman vortex street. A slight recovery is observed right after and finally it follows its decrease due to frictional factors again. The pressure recovery differs clearly depending on the bubble size. For \( d_b = 2.6 \) mm, the pressure recovery is the highest. That is due to the fact that larger bubbles tend to flow towards the center of the flow passage and less bubbles concentrate to the sidewall. On the other hand for smaller bubbles, \( d_b = 0.9 \) mm, where the size is small enough, bubbles flow throughout the whole area and near the sidewall, which leads to these kind of results. However, it is noted that the pressure gradient is almost the same for different bubble sizes, and the gradients is affected more by flow conditions rather bubble size, as shown in Fig.4.

Again, the pressure distribution pattern is the same like the previous condition. Naturally the pressure values obtained vary since the flow conditions are different. It is shown that the bubble size effect becomes smaller than for lower Reynolds number, which leads us to a first conclusion that the bubble size affects the pressure values more, under low velocity conditions.

Although it was considered that small bubbles would have the minimum pressure loss, it was found that the large bubbles that flow into the middle region show it instead. In addition, the uniform size bubbles of \( d_b = 0.9 \) or 1.2 mm, had the maximum pressure decrease along the whole measured area.

After the measurements at the sidewall, the pressure distribution was measured at the front and rear surface of the cylinder itself, in order to investigate if the bubble size affects it. Since measurements on a two-phase flow are very difficult and unstable, each point is measured several times and the mean value is given on the graphs.

Figures 5 (a), (b) illustrate the effect of the bubble size on the cylinders front and rear surface pressure distribution for the same flow conditions mentioned above. The vertical axis denotes the non dimensional pressure coefficient and is given from the following equation:

\[
C_p' = 2(P_i - P_0) / (\rho U_{tm}^2) \quad (4)
\]

It is expressed in the same way as above (Eq.3) with the difference that the elevation effect is not considered in this case. The pressure has the highest value at the center of the front side of the cylinder, Fig.5 (a), and decreases gradually in the direction of both sides. As
mentioned, the pattern is similar but a change on the pressure values is seen depending on the mean bubble size.

On the front side, the overall pressure value is affected by the mean bubble size, and the maximum pressure is obtained when $d_b=2.6$ mm, while the minimum is obtained when small size bubbly flow exists. That happens since large bubbles flow towards the center and more bubbles hit directly the cylinder’s surface.

On the rear side, the pressure is almost the same under certain $\alpha_v$. The maximum pressure is obtained when $d_b=2.6$ mm, while the minimum is obtained when small size bubbly flow exists. For that, the balance between the vortex generation area and bubble entrainment is considered. If the case of single-phase flow is considered as the standard value, then by inserting a bubble flow, although the mechanism remains the same the values change due to the interaction effect and thus the bubble entrainment into that region. Diameter bubbles of $d_b=0.9$ mm, are still easily entrapped into the vortex region and their density difference generates an even lower pressure core. When the flow is consisted by small bubbles, the flow characteristics show closer similarities to that of single-phase as it will be shown in a later section. For the case of large bubbles, even though that in our experiment the mean value is $d_b=2.6$ mm, it was mentioned that large bubbles exist inside the flow passage as it can be seen from Fig.8 as well. These sizes are entrapped more difficultly and wider gas free zone exists at the rear point of the cylinder, providing the results seen in this graph. From the pressure distribution measurements it was made apparent that the bubble size affects the flow pattern and characteristics in a flow past an obstacle.

In Fig.5 (b), where the Reynolds number is increased, it is shown that the bubble size effect is almost zero. That, in combination with the sidewall results, leads to the conclusion that the bubble size affects the flow in relatively low velocity values, at least concerning pressure phenomena.

From the pressure distribution and their differences due to mean bubble size effect on the front and rear surface of the rectangular cylinder the drag is considered. The drag $D_r$, on the cylinder’s surface is calculated according to the $C_{pi}$' and is defined as the difference force exerted on the front and rear surfaces:

$$D_r = \frac{\int_{-d/2}^{d/2} C_{pi} \, dx \,}{d}$$

(4)

From the given results of pressure coefficient from the front and rear side of the cylinder, the drag $D_r$, acting on it can be retrieved easily, as illustrated in Fig.6. For low gas fraction, the effect of bubble size is relatively smaller than the higher gas fraction case. A minimum is seen when the size is at small bubble scale, and slightly higher values are taken for the two other mean sizes. It is also shown that the values are slightly smaller than the case of single-phase flow. When increasing the gas fraction, the effect of the bubble size becomes considerably larger, where except the small bubble

![Fig.6 Bubble size effect on drag, $D_r$](a) $Re=0.5 \times 10^4$

![Fig.6 Bubble size effect on drag, $D_r$](b) $Re=1.0 \times 10^4$
size case, the drag increase considerably more compared to the single-phase flow.

For an order of $\alpha_e=1.5\%$, the amount of larger bubbles is significantly small, as verified through visualization as well. Decreasing the bubble size, small bubbles spread throughout the whole flow passage, while medium size bubbles have a tendency to flow more near the wall region than in the middle. Larger bubbles, as known, flow towards the middle of the flow passage and hit directly the cylinders surface at low rates. This is why at $\alpha_e=1.5\%$, the drag takes the lowest value when $d_b=0.7\text{mm}$, since a larger amount of bubbles pass through the cylinder than hit directly to it.

When the gas fraction increases at $\alpha_e=5\%$, bubbles exist throughout the whole flow passage, even still maintaining their flowing characteristics. Increasing the mean bubble size, the drag increases, and the maximum value is seen when $d_b=2.6\text{ mm}$, since large bubbles flowing in the middle of the flow passage hit directly the front surface of the cylinder. For higher Reynolds number of $Re=1.0 \times 10^4$ the bubble size effect is considerably decreased and shows that the differences occur due to gas fraction difference and not bubble size. That is also in good agreement with the results obtained from the wall side pressure distribution.

As it shows, the values are very close to that of single-phase flow with $\alpha_e=5\%$, having slightly lower values.

In the next section, the effect of bubble size distribution on fluctuation phenomena is introduced and discussed.

3.2 Pressure Fluctuation
The vortex shedding frequency $f$ is studied under different bubble sizes. Figure 7 (a) illustrates the oscillation frequency results when FFT analysis is applied for $Re=0.5 \times 10^4$, $\alpha_e=1.5\%$, at vertical position downstream of $y/d=14$. The horizontal axis denotes the oscillation frequency, and the vertical denotes the oscillation amplitude, or differently said, the intensity. On the horizontal axis range is set at 10Hz, since at higher frequencies the values were very lower and was not in the interest of the specific study.

Three main peaks are shown for all the cases, while the most intense oscillation is seen at $f=0.6\text{Hz}$ for the three different bubble sizes, with a clear difference on the amplitude when the flow is consisted of small bubbles.

For $d_b=2.6\text{ mm}$, another two peaks with very close frequency are measured at $f=1.6$-$2.2\text{Hz}$. On the other hand, when $d_b=0.7\text{mm}$, the second peak has almost the same intensity as the first and its frequency is at $f=2.2\text{Hz}$, almost the same as before. When the bubble size decreases to small scale, relatively small peaks appear at lower frequencies than the other two cases of 1.4 and 3.2 Hz. The amplitude is drastically lower and the differences from larger bubbles are obvious. A clear explanation has not yet been found at the present stage and more analysis and investigation is required.

For $\alpha_e=5\%$, Three main peaks are shown for all cases of bubble size. The first dominant peak, which is the stronger as well, has the same frequency value at $f=0.6\text{Hz}$ at all cases but the amplitude differs depending on the bubble size. It is clear that when the bubbles have a small size the amplitude is quite lower than the other two cases and this result comes to agreement with the previous condition and makes it even more certain that is caused due to the cylinder effect.

The second and third peak have different frequencies for $d_b=0.9$ and 0.27 mm, with a value at $f=2.4$ and 5 Hz, while when the bubble size increases at $d_b=2.6 \text{ mm}$ the oscillation frequency tends to take lower values at $f=2$ and 4.6 Hz. It is pointed that both frequencies have a difference of 0.4 Hz and that fact...
leads us to the assumption that these oscillations might be related to the bubble size. Moreover, the fluctuation amplitude decreases when the bubble size decreases, showing that it affects the intensity of the fluctuation as well.

The first peak of high amplitude and low frequency is considered to be the effect of the Karman vortex street, since the frequency has been steady and independent from the bubble size variation. Even under different sizes, the effect of the cylinder and the Karman vortex street is considered to be similar. The difference on the amplitude can be explained considering the bubble size effect and the results given from the velocity distributions above. For the other two peaks, a theoretical explanation would be that the oscillation factor is composed of a mixture of frequencies, generated by the obstacle existence, bubble existence and small eddies on the side surface, since the amplitude is measured there.

It is noted that in both gas fractions the bubble size affects significantly the oscillation amplitude, showing that the smaller the bubbles the less the intensity power acting on the sidewall downstream.

3.3 Visualization and PIV Measurements

Figure 8 (a), shows the instantaneous visualized flow pattern and the equivalent PIV analysis results of the two-phase bubbly flow, for $Re=0.5 \times 10^4$ and $\alpha_v=5\%$ with $d_b=0.27$mm. The white colored parts denote the bubbles in the flow passage. The flow passage is filled with the existence of small bubbles, and the dead water region that was observed behind the obstacle for larger bubbles, as it will be shown later, has been totally disappeared as shown in the photographic material. The small-scale size bubbles are easily entrapped into the region, since the buoyancy force acting on them is significantly small and shows very close flow characteristics with that of single phase. The velocity vector scale at the downstream region does not indicate the entrapment of bubbles inside the region just behind the obstacle as the picture, but that is due to the fact that the bubbles besides of being too small, the movement was difficult to be tracked from the PIV analysis, since they were extremely slow. However, from visualization results it was clear that a difference depending on the bubble size exists at the rear point region. The maximum bubble velocity has obviously decreased at the side area of the minimum

![Fig.8 Visualized flow pattern and PIV analysis (Effect of bubble size)](image-url)
flow passage and the effect of the bubble size is considered as the reason for that result. It is also noted that the velocity value expressed is very close to that of single phase traced.

Figure 8 (b), shows the results at the same flow conditions but bubble mean diameter at \(d_b=2.6\)mm. The gas-liquid bubbly flow separates at the front corners of the cylinder and forms a high local void fraction area on the two sides of the cylinder as well as the front side, where the separation area exists. A mix of relatively large bubbles of approximately 3~4mm and small ones can be observed at the illustration taken. A dead water region, which contains no bubbles, or few bubbles occasionally just behind the cylinder is observed clearly through the picture. The bubbles swarm in this region, which oscillates and develops into Karman vortex at the down stream reaches to the sidewalls of the flow passage. The velocity vector given by PIV is shown and the increase of bubble velocity between the cylinder and the sidewall caused due to the flow area decrease is observed. The generation of the Karman vortex street is clear. Again, a clear path of the Karman vortex street is illustrated.

From the PIV analysis results the local bubble velocity distributions at \(y'/d=0, 1.5, 6\) are extracted and the differences due to bubble size are shown in Fig.9 (a–c) for two different Reynolds number and \(\alpha_v=5\%\). The results present the mean velocity value of a total recording time of 8 seconds, in order to secure that several passes have occurred during that time and present the average values and not the instantaneous ones.

At \(y'/d=0\), which is at the center of the obstacle, the increase of velocity due to the decrease of flow passage is shown. In all three cases, the maximum velocity appears at the center of the space between the sidewall and the cylinder wall. The velocity decrease at the sidewall of the flow passage is considered to be due to the wall friction. Although the velocity pattern is similar for all cases, a clear difference on the velocity itself can be seen, depending the mean bubble size.

\[ \text{Fig.9 Bubble size effect on local velocity distribution (} \alpha_v=5\%\text{)} \]
The bigger the bubbles the higher the overall velocity becomes, with a maximum difference of approximately 80 mm/s.

The next graph illustrates the velocity distribution at position $y'/d=1.5$. The distribution pattern is the same for all the conditions, with the maximum velocity still obtained at $x/d=-1.1$ which is the center of the flow passage between obstacle and wall. Clear differences however can be seen in the velocity values. As mentioned above, the smaller the bubbles the lower the velocity. Especially at the region just behind the obstacle the effect of the bubble size is clearly shown. When $d_b=0.27$mm, negative values of velocity are extracted. That denotes a downward flow, which are the small bubbles entrapped into the vortex region generated there. When the bubble size is $d_b=0.9$mm, the negative velocity seen previously does not exist anymore. Although the velocity is very low, meaning that the downward force due to vortex acting on the bubbles and buoyancy force are nearly close to equilibrium, positive values are seen. For the bigger size of $d_b=2.6$mm, even higher velocity is seen and the effect of the bubble size is clear.

At an even downstream location of $y'/d=6$, the velocity differences are even greater. For the case of small bubbles the influence of the Karman vortex street still exists, showing a slight decrease of velocity at the center of the flow passage and having maximum values at the same position from the previous two graphs. Increasing the bubble size the velocity becomes almost the same with a decrease shown at the sidewall area where the wall friction exists. For the largest bubble size, opposed to the other two cases, maximum velocity is obtained at the center of the flow passage. That means that the effect of the Karman vortex street is not that strong and that the bubbles tend to flow into the center.

From visualization analysis it was made apparent that the bubble size affects the overall flow pattern as well the local velocity distribution. The smaller the bubbles the more they tend to have similarities with that of single phase flow and more they get affected by the Karman vortex street generated behind the obstacle. Increasing the bubble size, the overall velocity increases and effect of vortex becomes less.

4. CONCLUSIONS
Investigation on flow pattern and characteristics past a rectangular cylinder in a gas-liquid bubbly flow were conducted. The effect of the bubble size, with a variation from small scale to relatively large was conducted, using a laboratory developed control mechanism. From the experiments the following results are given.

The pressure distribution on the sidewall of the flow passage was measured. The maximum pressure drop varies with bubble size for low Reynolds number, with the medium size bubbly flow showing maximum decrease, while for higher $Re$ the effect becomes very small. The pressure gradient remains the same even when the bubble size differs.

The pressure values at the front and rear side of the cylinder surface showed an obvious effect due to the bubble size for low Reynolds number. On the other hand, increasing the water velocity, the $C_p'$ values where not affected by the bubble size, showing that a relation between $Re$, gas fraction and bubble size exists.

FFT analysis was conducted and three main fluctuations were obtained. For $d_b=2.6$mm the frequency values are lower than the other two cases and the effect of buoyancy force is considered. Moreover, the amplitude takes its minimum value when small bubbles flow exists and it was made clear that the bubble size affects the fluctuation intensity.

Extensive visualization experiments were conducted and differences on bubble entrapment into the vortex region behind the obstacle, as well as at the downstream was made apparent.

From PIV analysis it was found that the bubble size affects the total and local velocity distribution and value. In general, the smaller the bubbles (micro bubbles) the velocity shows a resemblance to that of the theoretical value of single-phase flow. The larger the bubbles become, the higher the local velocities at certain locations get affecting the overall flow pattern downstream and Karman vortex street.
NOMENCLATURE

\( A_r \)  Contraction area ratio of orifice nozzle  [-]
\( C_p, C_{p'} \) Pressure coefficient  [-]
\( C_D \) Drag coefficient  [-]
\( D_r \) Drag of cylinder  [-]
\( D \) Width of test section  [mm]
\( \bar{d} \) Width of cylinder  [mm]
\( d_b \) Bubble diameter  [mm]
\( f \) Vortex shedding frequency  [Hz]
\( g \) Gravity  [m/sec^2]
\( H \) Height of experimental section  [mm]
\( L \) Length of experimental section  [mm]
\( P \) Pressure  [Pa]
\( Q_{w/g} \) Flow rate of water or gas  [m^3/s]
\( Re \) Reynolds number (=\( U_{\text{av}} \bar{d} \nu \))  [-]
\( x/d, y/d \) Distance ratio  [-]
\( T \) Water temperature  [°C]
\( U_{\text{av}} \) Mean velocity of two-phase flow  [m/s]
\( U_{\text{wm}} \) Mean velocity of water flow  [m/s]

Greek Letters

\( \alpha_v \) Volumetric gas flow rate ratio
\( \nu \) kinematic viscosity of water  [m^2/s]
\( \rho \) density  [kg/m^3]

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