Influence of Aeration Microporous Aperture on Oxygen Mass Transfer Efficiency in Terms of Bubble Motion Flow Field

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ABSTRACT: Microporous aeration has been widely used to restore eutrophic water bodies. The gas–liquid mass transfer in the aeration process has a significant influence on the improvement of water quality. Therefore, the influence mechanism of oxygen mass transfer is worth studying. However, the influence of bubble movement characteristics on oxygen mass transfer has not been systematically studied. Thus, the present study explored the influence mechanism of microporous apertures on oxygen mass transfer in terms of bubble motion characteristics by investigating the oxygen mass transfer process and the feature of bubble movement under different aeration microporous aperture sizes. The results showed that the mass transfer efficiency was reduced as the micropore aperture increased from 200 to 400 μm, and the reduction rate was 7.17% when the aperture increased from 200 to 300 μm, which was lower than that from 300 to 400 μm (19.17%). Furthermore, the micropore aperture showed a positive correlation with the time-averaged velocity field. With the increase in aperture, the bubble velocity gradient (from the center to both sides of the edge) increased from about 0.2 to 0.4 m/s, which increased the oxygen mass transfer effect. The increase of micropore aperture caused the increase of average Sauter bubble diameter and the decrease of specific surface area of bubbles. In addition, the negative effects of the reduction of specific surface area and the shortening of bubble residence time on oxygen mass transfer efficiency were greater than the positive effects of the increase of turbulent kinetic energy. When the aperture changes from 300 to 400 μm, the shortening of bubble residence time should have played a major role. This study provides some theoretical parameters for investigating the mechanism of oxygen mass transfer in microporous aeration.

1. INTRODUCTION

Eutrophication is a widespread water environment problem. The usual restoration measures include dredging,1 biological treatment,2 chemical flocculation,3 and artificial aeration.4 Dredging technology is complex and expensive and easily causes secondary pollution. Chemical flocculation can easily lead to new material pollution. Biological treatment requires high environmental conditions and is of low efficiency; so, it is not suitable for large-scale applications. Artificial aeration refers to the artificial intake of oxygen into anoxic water bodies.5 It can improve the concentration of dissolved oxygen (DO) in water, the activity of aerobic microorganisms, hydrodynamic conditions, and the self-purification ability of water. Because of its advantages of simple operation and low cost, it has been widely used. Microporous aeration has the advantage of high oxygen utilization rate because of the smaller bubble size, which leads to its longer residence time and larger gas–liquid contact area with water,6 and it has been applied in the rehabilitation of various municipal and industrial wastewaters and has achieved good results.7,8 Previous investigations showed that the water restoration effect is closely related to the oxygen mass transfer process.9,10 The linear microporous hose aeration applied in Tennessee Valley has an oxygen utilization rate of over 90% in deep water;11,12 however, the oxygen utilization rate is only about 15% with a relatively...
shallow water depth (2−5 m),13 which limits the application of the microporous aeration technology. Therefore, how to improve the oxygen mass transfer efficiency of microporous aeration is an urgent problem to be solved.

Thus, scholars have widely investigated the oxygen mass transfer process in microporous aeration. The results show that the oxygen mass transfer process is affected by various factors,14−17 including the aeration rate, the operating mode of the aeration device, the water depth, and the water quality conditions. However, scholars mostly focused on the influence of external parameters (aeration rate, water temperature, water quality, water depth, and layout) on the oxygen mass transfer process and water body restoration in previous studies. The bubble group produced by microporous aeration has obvious influence on the mass transfer between gas and liquid oxygen, but there is no systematic study. Bubble groups generated by microporous aeration belong to bubble plumes. Bubble plume movement is stochastic and has a relatively complex structure.28 Scholars have done a lot of research on this topic. Rensen found that the plume oscillation period is closely related to the flow rate.19 Xu indicated that the formation of an air vent section in the bubble plume in homogeneous media is affected by the initial momentum of bubbles.20 Cheng discussed the trends of instantaneous time-averaged velocity field distribution of bubble plumes under different aspect ratios of voidage and pressure.21 Wang obtained the specific distribution of gas-phase velocity field during aeration by particle image velocimetry (PIV), a velocity measurement technology.22 Qu found that the distribution interval of bubble diameter widens with the increase in the aeration amount, and its geometric average diameter also increases.23 However, these studies investigated the movement law and flow pattern characteristics of bubble plumes from the hydraulics perspective. The influence mechanism of oxygen mass transfer by combining the oxygen mass transfer process with the flow field of bubble plume movement is rarely reported.

The aeration rate, the microporous aperture, and the design of the aeration device itself will affect the movement law of bubble plumes during microporous aeration;24 thus, the gas−liquid mass transfer efficiency would be affected, and different water recovery effects would be produced. On this basis, the present study established a linear microporous hose aeration system and selected the micropore diameter as the influencing factor, obtaining the average velocity field and relevant bubble motion characteristic parameters of the plume flow pattern structure under different pore sizes by using PIV technology and image processing technology. In addition, the oxygen mass transfer process was monitored experimentally. Therefore, the influence mechanism of microporous aperture on oxygen transfer was explored in the aspect of bubble plume movement flow field, which provides certain theoretical reference for improving the mass transfer efficiency of microporous aeration.

2. RESULTS AND DISCUSSION

2.1. Influence of Micropore Size on Oxygen Mass Transfer. 2.1.1. Influence of Atmospheric Reoxygenation. Because the upper end of the plexiglass box is completely open, the influence of atmospheric reoxygenation should be considered. The steps are as follows: (1) clean water was added to the water tank to the specified height, and nitrogen was added to reduce the DO to 0 mg/L. (2) A DO meter was placed at the same position in the aeration oxygen mass transfer experiment to record the change trend of DO in water with time. As shown in Figure 1, the DO rose slowly in the first 4 days and reached 0.5 mg/L at the fourth day. In the later period, the rate of DO rose faster, reaching 5.0 mg/L at the 15th day. This trend was basically consistent with previous conclusions.25 The difference was that the DO in the current work rose more slowly in the early stage, which was probably because of the relatively deeper DO probe in this experiment. Combined with a later oxygen mass transfer experiment, the DO could reach saturation within a few hours under aeration conditions. Thus, the influence of atmospheric reoxygenation on the aeration oxygen mass transfer experiment can be ignored.

2.1.2. Influence of Micropore Size on Oxygen Mass Transfer. Figure 2 shows the change trend of DO concentration in water with time under different micropore aperture sizes and the same aeration rate (Q = 0.2 m³/h), and the experimental steps are shown in Section 2.2.1. The DO rapidly increased initially and then gradually increased. Moreover, the highest rate was obtained when the aperture was 200 μm, and the smallest rate was obtained when the pore size was 400 μm. Generally, the larger the aperture, the weaker the oxygenation capacity. A previous study showed that the normal living environment of aquatic organisms can be guaranteed when the DOC in water remains above 5 mg/L,26 and general aeration reoxygenation engineering takes 6 mg/L as the reoxygenation target. Figure 2 shows that when the micropore size was 200, 300, and 400 μm, the DOC increased from 0 to 6 mg/L for 13.08, 13.84, and 14.55 min, respectively.

The data of the aeration oxygenation experiment were analyzed according to the calculation method of oxygen mass transfer index in Section 2.2.1, and the results are shown in Table 1. Then, the influence of aperture on the oxygen
Table 1. Test Results of Oxygenation Performance of Freshwater under Different Micropore Aperture Sizes (Q = 0.2 m³/h)

| no. | d (μm) | Cₐ (mg/L) | T (°C) | Kᵢₐplanation (h⁻¹) | OC (g/h) | Eₐ (%) |
|-----|--------|------------|--------|---------------------|---------|--------|
| 1   | 200    | 9.058      | 18.178 | 4.689               | 9.088   | 16.229 |
| 2   | 300    | 9.376      | 18.071 | 4.353               | 8.437   | 15.065 |
| 3   | 400    | 9.407      | 18.048 | 3.519               | 6.820   | 12.179 |

The aeration system performance was analyzed in terms of the oxygen mass transfer coefficient (Kᵢₐ), oxygenation capacity (OC), and utilization rate of oxygen (Eₐ).

Based on the above analysis, we can see from Table 2 that the microporous aperture and oxygen mass transfer efficiency (Kᵢₐ, OC, Eₐ) showed a significantly negative correlation (R = −0.971). Table 1 shows that the oxygen mass transfer coefficient (Kᵢₐ) (from 4.689 to 3.519 h⁻¹), oxygenation capacity (OC) (from 9.088 to 6.820 g/h), and oxygen utilization (Eₐ) (from 16.229 to 12.179%) presented a declining trend when the microporous aperture increased from 200 to 400 μm. When the microporous aperture increased from 200 to 300 μm, the reduction rate of Kᵢₐ, OC, and Eₐ was 7.17%, which was significantly lower than the reduction rate of 19.17% as the microporous diameter increased by 300 to 400 μm. This indicated that the increase of aperture within a certain range would weaken the increase of oxygen mass transfer efficiency. This was consistent with Hu Peng’s research conclusion, however, the research conclusions of Yannick28 were slightly different, which showed that a 10% reduction in aperture increased Kᵢₐ by 15%, and conversely, a 10% increase in aperture decreased Kᵢₐ by 11%. Combined with the study of Zhuang,17 the difference was understandable. For this study, three gradients of microporous aperture could only represent the micropore size within a certain range. In addition, the influence of microporous aperture variation on oxygen mass transfer may have other rules under different aeration rates and aperture ranges.29

In this paper, we adopted an aeration rate and three pore diameter gradients. It was obviously not comprehensive to simply study the law of oxygen mass transfer, but this study was mainly analyzed through the combination of oxygen mass transfer monitoring results and bubble movement flow field.

The micropore aperture mainly affected the bubble size. Its effects were complex on oxygen mass transfer. The variation of bubble size and size distribution in the rising process was affected by the physical parameters of liquid fluid.30,31 The bubble size was a key parameter that determines the interaction between the water flow and bubbles.32 It had a significant influence on gas holdup, water flow field, and velocity pulsation intensity.33,34 Xiao et al. found that the bubble size had a great influence on the calculation of the water flow field.35 However, studies investigating the influence of micropore aperture on oxygen mass transfer mechanism were lacking.

2.2. Influence of Micropore Aperture on Bubble Flow Field Distribution Characteristics. 2.2.1. Influence of Aperture on Bubble Plume Flow Pattern. Figure 3 presents the bubble plume pattern and streamline diagram under different micropore aperture sizes using MATLAB and TECPLOT software. When the aperture was 200 μm, the plume showed slight bending during the movement, with a transverse diffusion range of 310 mm, and a smaller vortex structure formed in the middle area on the right side of the flow field (x = 400–450 mm, y = 200–400 mm). When the aperture of the plume was 300 μm, the transverse proportion of the bubble plume in the flow field decreased slightly, the transverse diffusion range was about 275 mm, the plume column was relatively vertical, and the left side of the plume had an obvious tendency to form hydraulic circulation. The transverse width of the plume was basically the same as that of the plume with an aperture of 300 μm. A larger vortex structure was formed in the left area of the flow field (x = 20–100 mm, y = 100–350 mm) when the aperture of the plume was 400 μm. The hydraulic circulation increased the degree of turbulence and promoted the two-phase gas–liquid exchange.

On the basis of the above results, the following can be concluded: the increase in micropore aperture promoted the formation of strong hydraulic circulation of the bubble plume. The result (in Figure 3) showed that the hydraulic circulation was obvious at 400 μm; however, it was not obvious at 200 and 300 μm. Therefore, the turbulent kinetic energy increases with the increasing aperture, which was conducive for gas–liquid oxygen mass transfer.

2.2.2. Influence of Micropore Aperture on Gas-phase Velocity Field. Once the system had stabilized, the shape of the bubble plume did not vary over time (data not shown). Figure 4 shows a cloud map of the average velocity of the plume under different aeration apertures. When the aperture was 200 μm, the gas-phase velocity was mainly located in the middle area of the aerator section, and the velocity was generally low (0.15–0.35 m/s). When the aperture aperture increased to 300 μm, the maximum velocity was located in the middle region. Furthermore, the movement velocity of a few bubbles reached 0.35–0.45 m/s. The number of bubbles around 0.35 m/s had increased significantly (yellow area shown in the velocity cloud image). When the aeration aperture reached 400 μm, the overall gas-phase velocity also increased accordingly, and the

| index | microporous aperture | Kᵢₐ Pearson correlation | OC Pearson correlation | Eₐ Pearson correlation |
|-------|---------------------|------------------------|-----------------------|-----------------------|
|        | sig. (double tail)  | 1                      | −0.971                | −0.971                |
|        | sig. (double tail)  | 1                      | 0.153                 | 0.154                 |
| Kᵢₐ   | Pearson correlation | 1                      | 1.000*                | 1.000*                |
|        | sig. (double tail)  | 1                      | 0.000                 | 0.000                 |
| OC     | Pearson correlation | 1                      | 1.000*                | 1.000*                |
|        | sig. (double tail)  | 1                      | 0.000                 | 0.000                 |
| Eₐ     | Pearson correlation | 1                      | 1.000*                | 1.000*                |
|        | sig. (double tail)  | 1                      | 0.000                 | 0.000                 |

*The correlation was significant at the 0.01 level (double tail).
number of bubbles between 0.35 and 0.45 m/s increased significantly.

On the basis of Figure 4, the following points could be summarized: (1) under each aeration aperture, the high bubble velocity area was mainly concentrated in the middle area, and the larger the aeration aperture, the higher the proportion of the high bubble velocity area. The higher the proportion of the high-speed region in the middle region, the higher the average velocity of the whole bubble plume. This means that on the one hand, the higher the bubble velocity, the greater the turbulent kinetic energy, which promoted oxygen mass transfer. On the other hand, a short average residence time was not conducive to oxygen mass transfer. (2) When the aeration aperture increased from 200 to 400 μm, the bubble velocity gradient (from the center to both sides of the edge) increased from about 0.2 to 0.4 m/s, which increased the relative flow rate between the bubbles and water, promoted the formation of hydraulic circulation, and accelerated the exchange between the bubbles and water. The corresponding calculation formula of $K_{L,a}$ was $K_{L,a} = 2D_d V_r/\pi d_b^2 \Delta \rho /d_b \rho^g$ and $V_r$ was the relative velocity between the bubbles and water flow, which improved $K_{L,a}$. The hydraulic circulation was relatively obvious, especially at 400 μm, which promoted the bubble wall effect, extended the bubble residence time, enhanced the gas–liquid mixing degree, improved the oxygen mass transfer coefficient and oxygenation capacity of the system, and further explained the microcosmic mechanism of the influence of the plume movement velocity on the oxygen

Figure 3. Bubble plume pattern and streamline diagram.

Figure 4. Gas-phase average velocity diagram.
mass transfer process. However, combined with the oxygen mass transfer experiment, $K_{L}a$, OC, and $E_A$ showed a declining trend, indicating that other factors play an important role in affecting the oxygen mass transfer process. As mentioned above, the shorter bubble residence time caused by increased velocity would weaken the oxygen mass transfer. However, the bubble size and specific surface area were also important factors affecting the oxygen mass transfer effect. In this experiment, how the changes of bubble residence time and bubble size affect the change of micropore aperture from 200 to 400 μm was worth exploring.

2.2.3. Influence of Micropore Aperture on Bubble Motion Parameters. Based on the above analysis, we can see from Table 4 that there was a significant positive correlation between oxygen mass transfer efficiency and the characteristic parameters of bubble motion, and the correlation coefficients with $d_{L0}$ and $S_b$ were $-0.909$ and $0.865$, respectively.

Table 3 illustrates the physical parameters of bubbles, such as the Sauter average diameter ($d_{La}$) and specific surface area ($S_b$). The average value but also the dynamics of the characteristic parameters of bubble movement at each spatial position should be established. Thus, research on oxygen mass transfer parameters of bubble motion can still reflect the mechanism of oxygen mass transfer to some extent.

was 400 μm, the bubble diameter occupied the largest proportion in the range of 0.90–1.0 mm and then decreased gradually with the increase in the diameter. (2) The bubble proportion relation in the same size range under different pore sizes showed that when the diameter range was 0.8–0.9 mm, the variation characteristics of the bubble proportion were as follows: 200 > 300 > 400 μm. When the bubble diameter ranged from 0.9 to 1.3 mm, the change rule of bubble proportion was as follows: 400 > 200 > 300 μm. When the bubble diameter ranged from 1.3–1.5 mm, the bubble proportion was as follows: 400 > 300 > 200 μm. When the bubble diameter was greater than 1.5 mm, the proportion of bubbles was very small under the three pore sizes.

Table 3 shows the change rule of the specific surface area of bubbles under different aeration aperture sizes, that is, gas–liquid contact area per unit volume within the region. As can be seen from Table 3, the specific surface area of the bubble decreased from 0.683 to 0.611 when the aeration aperture increased from 200 to 400 μm, which means that the gas–liquid contact area per unit volume decreases with the increase of the aperture. This was not conducive to oxygen mass transfer and to a large extent reveals the reason why oxygen mass transfer efficiency decreases with the increase in aeration aperture. The change of specific surface area and the equivalent diameter of the bubble from 200 to 300 μm was greater than that from 300 to 400 μm (Table 3), but the change of mass transfer parameters from 300 to 400 μm was greater than that from 200 to 300 μm (Table 1). This may indicate that the shortening of the bubble residence time caused by the increase of the bubble velocity from 300 to 400 μm played a major role in the oxygen mass transfer efficiency, which may indicate that the shortening of the bubble residence time to a certain extent would lead to insufficient oxygen mass transfer time, making it a major factor affecting the oxygen mass transfer process.

In addition, a previous study indicated that the local dynamic characteristics of $K_{L}a$ are related to the characteristic parameters of bubble movement at each spatial position, and the functional relationship between $K_{L}a$ and each spatial position should be established. Thus, research on oxygen mass transfer and bubble motion parameters should study not only the average value but also the dynamics of $K_{L}a$. Nevertheless, because of the different aeration apertures in the present study, the difference in the average value of the characteristic parameters of bubble movement can still reflect the mechanism of oxygen mass transfer to some extent.

![Figure 5. Proportion of bubble size distribution under different micropore aperture sizes.](https://dx.doi.org/10.1021/acsomega.0c05126)
3. CONCLUSIONS

The characteristic parameters of gas–liquid oxygen mass transfer and bubble movement flow field under different aeration micropore aperture sizes were studied to explore the influence of aperture on the oxygen mass transfer process from the perspective of bubble movement flow field. Relevant characteristic parameters, such as the time-average velocity field, average diameter of bubbles, and specific surface area, were obtained in the experiment based on the PIV system and related computer software. Oxygen mass transfer experiments were conducted simultaneously. The following conclusions are drawn:

(1) The mass transfer efficiency was reduced as the micropore aperture increased from 200 to 400 μm, and the reduction rate from 200 to 300 μm (19.17%) was lower than that from 300 to 400 μm (7.17%). The variation characteristics were slightly different with the change of aeration quantity and aperture range.

(2) The micropore aperture was positively correlated with the time-averaged velocity field. With the increase in aperture, the bubble velocity gradient (from the center to both sides of the edge) increased from about 0.2 to 0.4 m/s, and the relative flow velocity between the bubble and the water flow increases, which promoted the formation of hydraulic circulation, contributed to the transfer of oxygen from the bubble to the water body, and increased the oxygen mass transfer effect. However, the increase of bubble velocity reduced the bubble residence time, which may inhibit the efficiency of oxygen mass transfer.

(3) The increase in micropore aperture caused the increase of the average Sauter bubble diameter and the decrease of the specific surface area of bubbles. Combined with the variation trend of characteristic parameters in the oxygen mass transfer process, it is shown that the negative effects of the reduction of specific surface area of bubbles and the shortening of bubble residence time on oxygen mass transfer efficiency were greater than the positive effects of the increase of turbulent kinetic energy. When the aperture changed from 300 to 400 μm, the shortening of bubble residence time played an important role, which indicated that the decrease of bubble residence time caused by the increase of bubble velocity to a certain level became the most important factor to weaken the oxygen mass transfer efficiency.

4. MATERIALS AND METHODS

4.1. Experimental Materials and Equipment. This research includes two parts: first, the DOC was monitored by the four-probe oxygen DO meter (Figure 6); second, the bubble movement flow field was monitored by the particle image velocimetry system (Figure 7). Three different aeration micropore aperture sizes (200, 300, and 400 μm) at the aeration rate of 0.2 m³/h were used in the aeration experiment.

4.1.1. Oxygen Mass Transfer Experiment. The aeration device is a plexiglass box (15 mm thickness). It has a size of 60 cm × 45 cm × 100 cm (length × width × height) and a water depth of 90 cm. The main components of the system include an air compressor (LJ-1530E, Taizhou Bede Electromechanical Co., Ltd.), pressure gauge (AR2000-02, Jingang Pneumatic Enterprise Network Shop), gas flow meter (LZB-10, Shanghai Tianhu Instrument Factory), DO meter (PreSens, Regensburg, Germany), and a microporous rubber hose (Figure 6, the left side) (Wuxi Aerating Equipment Co., Ltd., Jiangsu, China). The hose is installed in the middle, 5 cm from the bottom of the pool. The hose is composed of a new type of chemical fiber-reinforced and improved plastic and has an inner diameter of 10 mm. The surface of the hose is set with...
4.1.2. PIV Speed Measuring System. PIV is a speed measurement technology based on diffraction optics. In this experiment, the PIV system from Dantec Dynamics A/S (Denmark) was selected. The system includes a digital image preprocessing and velocity vector calculation software and is composed of a lighting system, an image recording system, a control circuit, and a computer for synchronously extracting information (Figure 7). The laser collects the thin light plate, illuminates the flow field, and generally does not produce color difference; so, it is an ideal light source for the PIV lighting system. LDY300 laser is used in this system. The image is recorded by a LaVision high-speed camera at 1024 × 1024 pixel resolution. The lens controller can adjust the focal length according to the actual operating distance and external factors. The camera and computer are connected by a synchronous controller, and the captured images are automatically saved in real time (TIF format). To ensure the quality of the collected images, the rear glass of the shooting area is covered by a shading cloth. On the one hand, background noise will affect the normal signal as the laser light intensity is too high, and the shading cloth can reduce the shading light intensity. On the other hand, the ratio between the target image and the background image can be increased to improve the clarity of the bubble flow image.

4.2. Experimental Methods. 4.2.1. Oxygen Mass Transfer Characteristic Experiment. The oxygenation experiment of clean water aeration was conducted in accordance with the American ASCE oxygenation Test Standard for clean water. The experiment steps are as follows: first, add water to the aerator to the specified height and fix the position of the DO meter. Then, monitor the water temperature and DOC using the DO meter and create a water oxygen deficit by using the nitrogen filling method. Finally, conduct the aeration oxygenation experiment when the DO value of the water body drops to 0 and remains stable. Monitor the DOC and temperature in water constantly until the DOC is saturated. Stop the aeration and save the data.

The experimental principle is mainly based on the theory of double film. The oxygen mass transfer coefficient (Kla), aerobic capacity (OC), and oxygen utilization (EA) are the important parameters of the gas–liquid oxygen mass transfer process, where Kla would be represented by the following formula:

$$\frac{dC}{dt} = K_{la}(C_s - C_t)$$  \hspace{1cm} (1)

$$K_{la(20)} = K_{la} \times 1.024^{(20-T)}$$  \hspace{1cm} (2)

where $C_s$ [mg·m$^{-3}$] is the DO saturation concentration and $C_t$ [mg·m$^{-3}$] is the DOC in the tank at time $t$ (in min) (eq 1). When plotting ln ($C_s - C_t$) against $t$, the slope of the curve

Figure 8. Grayscale correction of PIV images. Images (a,c) and gray-scale distribution histograms (b,d) before (a,b) and after (c,d) grayscale correction.
gives \( K_a \). To eliminate the influence of temperature, \( K_a \) was corrected to 20 °C, and \( T \) is the actual water temperature at the time of the experiment (eq 2).

The oxygenation capacity and oxygen utilization rate are calculated by using eqs 3 and 4:

\[
OC = K_a a_{20} \times V \times (C_e - C_0)
\]

\[
E_a = E_l \times 100%/(N \times Q)
\]

where \( OC \) [mg·h\(^{-1}\)] is the oxygenation capacity, \( C_0 \) is the initial DO, \( E_a \) [%] is the oxygen utilization rate, \( N \) [mg·m\(^{-3}\)] is the weight of oxygen in 1 m\(^3\) air under standard conditions (with the value of 0.28), and \( Q \) [m\(^3\)·h\(^{-1}\)] is the aeration flow that was experimentally varied. For practical reasons, \( Q \) is expressed in L/h in the presented figures.

4.2.2. PIV Experimental Treatment Method. PIV measurements are obtained in a vertical plane (see Figure 7) at a water depth of 45–90 cm over a width of 45 cm, giving an observation area of 45 × 45 cm\(^2\). The area of observation is about 0.2–2 mm thick, as determined by the PIV equipment. This area is recorded by the PIV camera, which sends images to an image processing system in real time. DO is measured simultaneously along with the water temperature (accuracy of 0.01 °C) by a probe placed at a depth of 20 cm below the water surface and located exactly above the hose of the DO detector (Pre Sens, Regensburg, Germany). To ensure a clear water surface and located exactly above the hose of the DO

The experiment was started by opening the air compressor and adjusting the pressure gauge as per the readings of the rotameter. When the bubble flow was stable (in general, it takes less than 1 min to achieve a stable bubble flow; considering accuracy, bubble motion images were obtained after 3 min), the movement of the generated bubbles was observed in real time, with the images electronically stored at time intervals of 0.2 s. This shooting frequency had been optimized from the pilot experiments. A total of 25 images were recorded per experiment, covering a period of 5 s. In this condition, the bubbles could rise at least 45 cm.

The raw images should be processed before analysis to enhance the grayscale and improve image edge segmentation. Spatial gray transformation technology was used by applying the MATLAB software. It did not change the position of image pixels, but it only affected the grayscale value of each pixel (Figure 8). Histograms of the grayscale values of pixels of each raw image, which were in the range of 0–255 before adjustment (Figure 8b), were generated using the function IMHIST. However, the vast majority of pixels were in a narrow range of 8–28 only. The corresponding image was mostly dark. Furthermore, bubbles were hardly visible (Figure 8a). After extending the contrast, the distribution was more even (Figure 8d). Finally, the bubbles were clearly visible (Figure 8c).

The second correction was based on threshold segmentation technology. The edge, defined as the region within an image where the grayscale changed most strongly, was identified using PREWITT to improve the contrast in Figure 9.

The velocity of bubble movement was calculated from the generated images by comparing two images from two consecutive time points, as explained below. Because the laser was used in dual mode, the instantaneous velocity of individual bubbles could also be calculated. A set of two images was produced for each time point, which were only a few milliseconds apart. Depending on the gas flow (which was varied), this pulse interval time was varied between 6 and 10 ms, which ensured that the displacement was small enough to follow individual bubbles along their course and to calculate their instantaneous velocity. From the instantaneous velocities of multiple bubbles per time point, the velocity distribution of the flow field per time point was obtained.

The average velocity was obtained by dividing the observed displacement of the bubbles between two consecutive images for two time intervals. The signals of two consecutive frames (two time points) had to be matched to one and the same bubble, which was enabled by cross-correlation using the Adaptive Correlation module of the PIV software. Because of the large image area captured by the camera, each image was divided into a grid of 64 × 64 query windows (one window covered approximately 70 × 70 mm) to ensure that the bubbles did not move by more than half of a grid unit.

After obtaining the bubble displacement positions, their velocity \( w \) was calculated using eq 5

\[
\begin{align*}
\frac{dx}{dt} = &\ S_x \times k/dt \\
\frac{dy}{dt} = &\ S_y \times k/dt
\end{align*}
\]

where \( S_x \) and \( S_y \) (mm) are the particle displacements in the \( x \) and \( y \) directions, respectively; \( k \) is the actual length of a unit pixel; \( d_i \) (s) is the time interval between two time points; \( u(x, y) \) (m/s) is the velocity in the \( x \) direction; and \( v(x, y) \) (m/s) is the velocity in the \( y \) direction. The calculated bubble velocity \( w \) is given by the vector sum of velocities \( u \) and \( v \), and \( w \) was visualized in a heatmap using TECPLOT software.

The bubble size would be obtained by using the Shadow module in the PIV system. The bubbles in the flow field could be well identified through image preprocessing and could be statistically calculated to obtain the specific size distribution. Bubbles tend to be elliptic in actual movement (Figure 10). We could calculate the equivalent diameter \( d_e \) of the bubble,
which reflects the spherical bubble diameter with the same
volume as that of the elliptical bubble, by using eq 6.

\[ d_{lt} = (h_s l_t^2)^{1/3} \]

(6)

where \( d_{lt} \) (m) is the equivalent diameter, \( h_s \) is the short axis length of an elliptic bubble, and \( l_t \) is the long axis length of an elliptic bubble.

The geometric mean diameter (Sauter) \( d_{gs} \) was adopted to characterize the mean diameter of the bubbles, as shown in the following formula

\[ d_{gs} = \sqrt{\frac{\sum n_i d_{hi}^3}{\sum n_i d_{hi}^2}} \]

(7)

where \( n_i \) is the number of bubbles with \( d_{hi} \).

The surface area \( S_A \) of the bubbles was calculated as follows:

\[ S_A = 4\pi(d_{lt}/2)^2 \]

The volume of the bubble is calculated as follows:

\[ V = 4\pi(d_{lt}/2)^3/3 \]

The specific surface area of the bubble is calculated as follows:

\[ S_V = S_A/V \]

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