EXPERIMENTAL STUDY ON BUBBLING BEHAVIOR OF AERATORS IN WASTE WATER TREATMENT APPLICATION

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Abstract

Aerobic aqueous bioreactors can be successfully employed for waste water treatment. The special bacteria inside the water tanks can dissolve the organic pollutants, which are widely found in municipal waste water. The system can be designed to meet fast waste water discharge requirements with low energy consumption. Molecular oxygen needs to be provided to enhance the oxygen uptake and to maintain the desirable dissolved oxygen concentration so that the biomass or the bacteria can grow. Supply of the oxygen is generally implemented by micro-bubble diffusers or aerators. Therefore, the bubble motion in the water containers as well as the bubble size will affect the oxygen concentration and eventually the performance of bioreactors. This study is to investigate the bubble behaviors from two types of aerators with various settings. A Particle Image Velocimetry (PIV) system is adopted in an experimental setup having a small water tank to track the bubbles and their flow pattern. It is observed that for the propeller-type aerator small bubbles are initially generated and move towards the bottom of the tank, and the small bubbles later grow into big bubbles to travel upwards due to high buoyancy force. As they come out of aerator, eventually, the big bubbles just pass through the top part of the tank. The performance of aerator with porous material (airstone) is compared to that of the propeller-type aerator. Numerical results are presented to further confirm the experimental observation.

1. Introduction

Aeration (air bubbling) in stagnant water has numerous applications such as waste water treatment, aquaculture, recreational ponds cleaning, resorting lakes, rivers and harbors, and improving the water quality in variety of other installations. The flow dynamics of air bubbles play an important role of mixing and mass transfer in two-phase flows. The focus of this paper is on the study of aeration in aerobic aqueous bioreactor. The aerobic bacteria inside the bioreactor dissolve the organic pollutants. Although biomass provides the nutrients for the growth of the bacteria, sufficient oxygen supply is essential during the waste water treatment to enhance the molecular oxygen content and to maintain the desired oxygen level for the growth of bacteria. Supply of oxygen is commonly implemented by aerators and micro-bubble diffusers. The operation of aerators affects the flow field of air bubbles and the bubble size, which determine the oxygen concentration, mixing and thus the performance of bioreactors. Therefore, it is necessary to examine the behavior of bubble from different types of aerators.

1.1 Previous Research on Aeration

Previous work includes many experimental and numerical studies on the flow field of air bubbles. Motarjeni and Jameson[1] predicted the optimum air bubble size to study mass transfer from air bubble to water body for aeration in effluents and natural waters. Cameras with flash illumination were used for photographs. It is found that mass transfer is low for bubble size ranging in 2-5mm and there is need to develop bubbles less than 1mm for best bubble efficiency. Chen et al.[2] conducted experiments to investigate the bubble size distribution in aquaculture application. Their investigation revealed that bubble size increased with the airflow rate. The distribution of different air bubble size affects the mass transfer between the two phases. Using a PIV system Hout et al.[3] investigated the velocity field of the Taylor bubble rising in stagnant water. The velocity field was presented with the velocity vectors. The Taylor bubble accelerates the liquid to about 1m/s, which creates flow turbulence. Mayer et al.[4] performed the experiment for the comparison of various aeration devices by varying the air flow rates for air sparging in cross flow membrane filtration. The results showed the aeration system with multiple orifices is the best. Liu and Zheng[5] studied the behavior of air bubbles rising in stagnant water using a PIV system. For a single bubble in a rectangular column the study concluded that bubble rising path is associated with the viscosity of the liquid.

1.2 Recent Work on Air Bubbling

Related research work on the flows of air bubbles can also be found in recent years. Piroz[6] presented the numerical and experimental results to study the flow dynamics of a turbulent bubbly flows in aerated mixing tank. Small bubbles follow the flow pattern and tend to go downwards. Smolianski et al.[7] performed simulation to study the flow dynamics for single and group of bubbles and compared with experimental results. The air bubble motion and rise velocity are consistent with the experimental results. Bai and Thomas[8] measured the initial bubble size of gas injection in flowing water using high speed videos. An analytical model was used to calculate the bubble size. Volume of fluid method was adopted in numerical simulations of bubble formation. The analytical and numerical results showed good agreement with the experimental results.

1.3 Present Work

Aeration is implemented in different ways in variety of applications. The present work is to investigate the air bubbling behavior of an aeration system so that the performance of aerators in bioreactors can be eventually optimized for waste water treatment application. The PIV technique is adopted in an experimental setup of a water tank. The first aerator under study is a propeller-type aerator, where the propeller drives the air bubble as well as the water towards the bottom of the tank. The experiment is performed by using the aerator with different speeds of the propeller and the corresponding flow field, flow pattern and velocity vectors are analyzed. The second way of aeration is to place the porous stones at the bottom of the tank, and airflow is forced through the airstones. The air flow rate or inlet pressure can affect the air bubble size. Therefore, bubbling behavior and velocity field can be studied by changing the air flow rate through porous air stone. In addition, bubbling behavior is reported for two air stones with different distances between them. Finally, the numerical and experimental results are compared.

2. PIV System and Experimental Setup

2.1 Particle Image Velocimetry (PIV)

PIV is an optical technique used in a wide range of applications for the study of flow dynamics and velocity field measurements of fluids. The current PIV system from TSI, Inc consists of a solo YAG laser, Camera and Synchronizer. INSIGHT 3G software is employed to capture and process the images. Figure 1 shows the arrangement of PIV components. There are two types of lasers, two Nd:YAG lasers and Double Pulsed Nd:YAG laser. Two Nd:YAG lasers have two laser beams, and one laser is fired at a different frequency from the other. These two beams combine to form a collinear beam. On the other hand, the double pulsed laser fires twice during a single flash lamp discharge. The maximum time between two pulses is about 200 µs. This makes the double pulsed laser appropriate for flows with velocities of 1m/s and higher. In the current study the double pulsed Nd:YAG is used to illuminate the air bubbles. The laser beam is in the form of a vertical plane passing through the water tank providing enough illumination for the camera to capture two images for two pulses. These images are then processed to generate the velocity vectors and flow field using INSIGHT 3G.

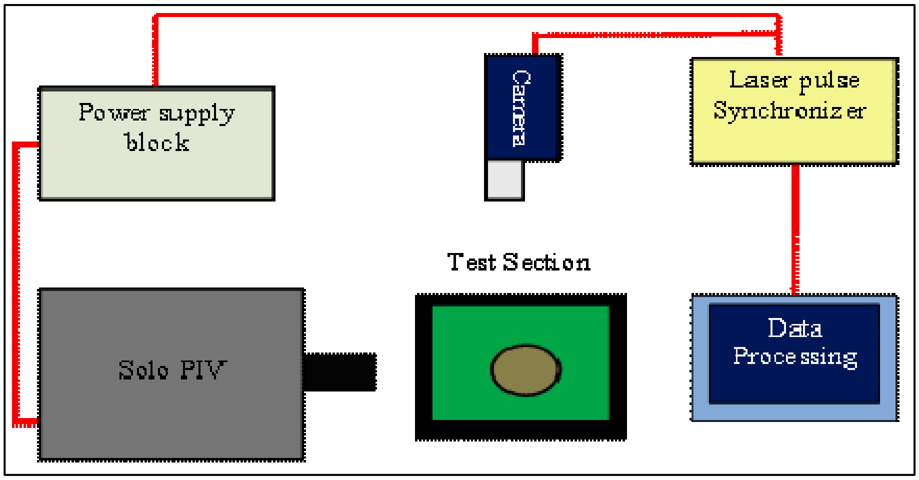


Figure 1 Components of Particle Image Velocimetry

2.2 Experimental Setup

The experimental apparatus consists of a rectangular water tank of 5 gallons and the aerator in addition to the PIV system. The laser equipment is aligned with the test section to pass the beam through the center of bubble flow. The direction of laser equipment and camera are perpendicular to each other. Black screens are arranged around the water tank to avoid reflection and for the same reason the aerator is rolled up with a black cloth. The experiment was carried out with tap water and the aerating device is located at the centre of the water tank. As mentioned earlier, the experiment was also conducted with the air stones by connecting one end of the hose to the air stone and the other to the compressed air pipeline. The air flow rate can be changed by adjusting the control valve. For the experiments involving two porous air stones a T-section is provided between the two air stones.

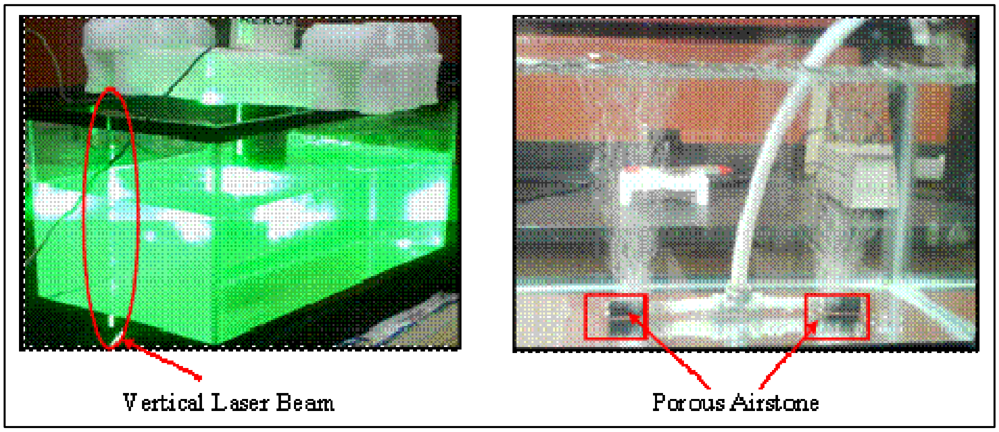


Figure 2 Experimental setup

3. Results and Discussions

Air bubbling induces local turbulence around bubbles in aqueous body and creates momentum in the water body. The flow of air bubbles is affected by buoyancy and surface tension and so the bubble size can vary in the water tank by either coalescence or break-up of the air bubbles. The pattern of air bubble rising is analyzed from the photographs presented in the following sections.

3.1 Air Bubbles Generated by Propeller-Type Aerator

The experimental setup is equipped with a propeller type aerator. Air bubbles are injected in stagnant water with the rotation of the propeller blades. The bubble size can be varied by changing the speed of the propeller blade. The propeller speed is controlled by the voltage setting of the power supply to the aerator. The bubble behavior with two different propeller blade speeds is presented in this section.

(1) High Propeller Speed
The arrangement includes a propeller type aerator in the water tank. In this case the images for rotating speed of 300 rpm are taken and processed using the 3G INSIGHT software. Figure 3 shows the flow pattern of air bubbles with vectors and also the velocity distribution showing magnitude at different positions in the water tank. It is found that the high propeller speed injects big-size bubbles that tend to reach upwards due to high buoyancy. However, very few small-size air bubbles reach almost the bottom of the tank and then coalesce and move upwards. The maximum bubble velocity attained during this test is 2.85m/s, which are for few bubbles while majority of the air bubbles fall into the range of 0.8-1.0m/s. It means big bubbles do not stay for a time long enough for the efficient mass transfer of oxygen. Finally, all the bubbles reach the top of the tank with slightly low oxygen concentration and are lost to atmosphere.

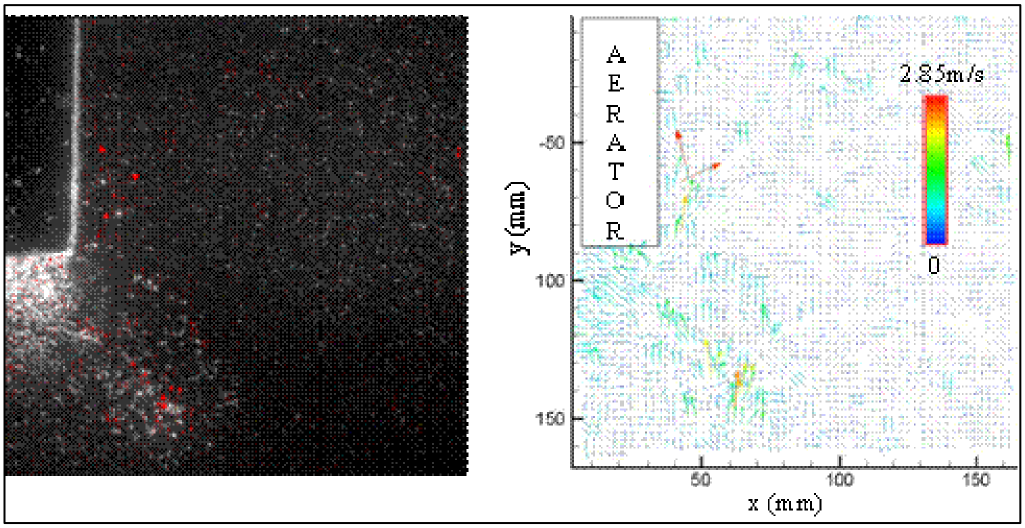


Figure 3 Flow field and velocity vectors for high propeller speed

(2) Low Propeller Speed
The propeller speed is lowered to 200 rpm by voltage setting to vary the bubble size. The flow field and the velocity vectors are presented in Figure 4. The aerator injects small and few bubbles, most of which move downward towards the bottom of the tank and some bubbles reach the bottom. It can be seen from the zoomed-in view of the flow field below the aerator that most of them going down. However, there are very few big-size air bubbles going up as soon as they come out of the aerator and the maximum velocity attained by these bubbles is 2.44m/s. Most of the air bubbles have the velocity of 0.6m/s or less. It means small air bubbles tend to stay for longer time, which could be efficient for mass transfer. In fact, there is a lot of research on the optimum size of air bubbles in aeration.

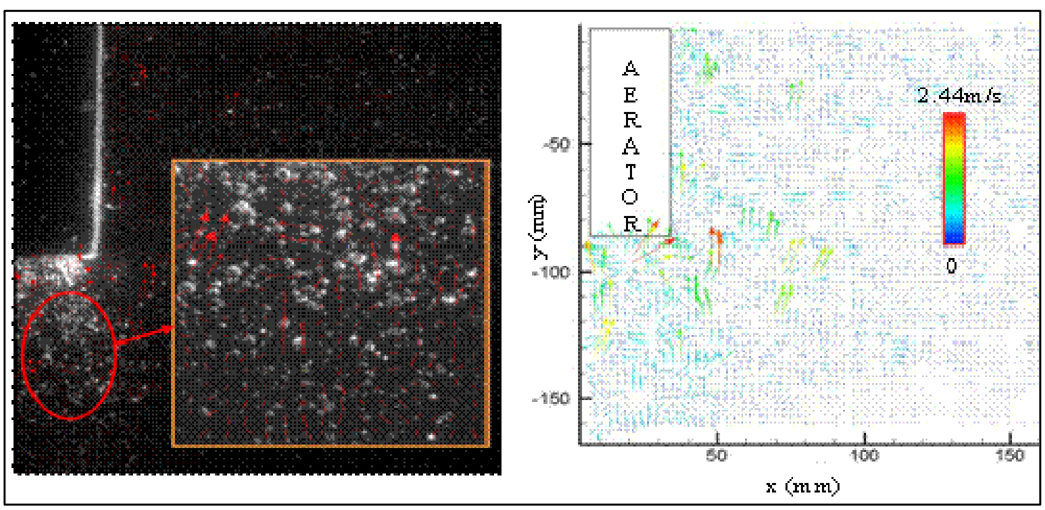


Figure 4 Flow field and velocity vectors for lower propeller speed

3.2 Air Bubbles Generated by Airstone-Type Aerator

While the momentum generated from the propeller can drive the bubbles downwards, the distance of penetration is limited due to the buoyancy force, especially for big bubbles. Therefore, the propeller-type aerator might not be a good option for a deep water tank unless there is a strong circulation flow in the tank. Therefore, experimental tests are also on the other type of aeration, airstones, with air bubbles injecting from the bottom of the tank.

(1) Airstone with Low Air Pressure or Flow Rate

For an airstone-type aerator the bubble size is mainly affected by the airflow rate, air stone pore size, and surface tension of the liquid. In this study the aim is to examine the behavior of the flow pattern and bubble size with the aerator located at the bottom of the tank as well as the effect of air flow rate. In general, the bubble size increases with increase in flow rate. In this case the flow rate of air is $0.062m^3/s$ with the maximum bubble size of 1.2mm while most of the air bubbles have the size of 0.7mm and below. The bubbly flow field and velocity distribution are presented in Figure 5 for the low flow rate case. As seen from the zoomed-in view of the flow field above the air stone the air bubbles come out of the airstone and then travel upwards, which is shown by the vector direction. The affected zone of air bubbles gradually spreads wide towards the top of the tank. Due to the coalescence the velocity increases for some of the bubbles up to 2.5m/s, while most of the air bubble has the velocities below 0.8m/s. The highest velocity of 3.62m/s is reached just above the air stone for few bubbles.

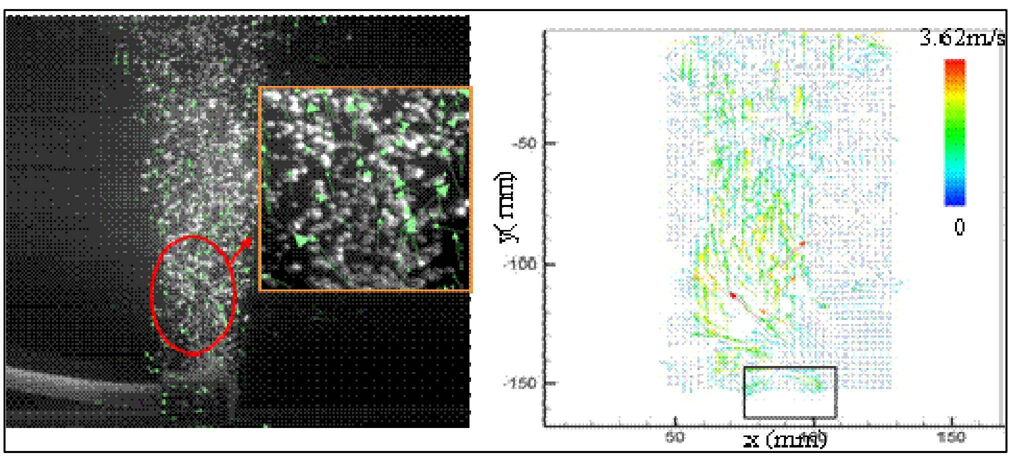


Figure 5 Flow field and velocity vectors for low flow rate

(2) Airstone with High Air Pressure or Flow Rate

The air flow rate is increased to $0.09\ m^3/s$ for generating bigger size bubbles with the maximum bubble size of 1.4mm and most of the bubbles have the size in the range 0.8mm to 1mm. Hence, the bubble increases with increase in air flow rate. Beside the bubble size the number of bubbles also becomes larger. In another words, more bubble are generated. Similar to the previous case the air bubbles coming out of the air stone rise upwards to the top of the tank. The bubbles are denser just above the air stone with the maximum velocity of 3.75 m/s as shown in Figure 6. Compared to the previous case the air bubbling region is wider starting from the air stone. Many bubbles coalesce to rise upwards quickly. Big bubbles create turbulence in the water body. Due to the high buoyancy the average velocity increases.

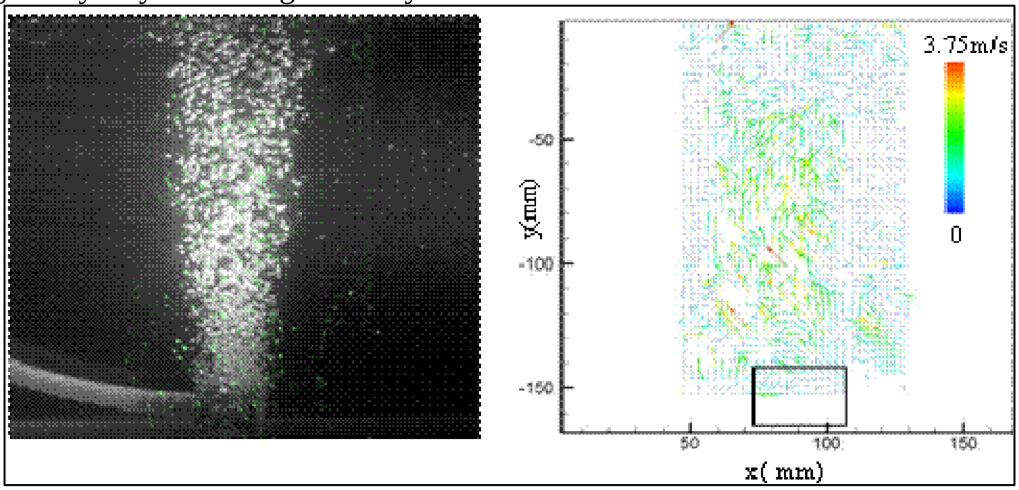


Figure 6 Flow field and velocity vectors for high flow rate

3.3 Interaction of Air Bubbles from Two Airstone Aerators

To make the bubbles distributed more uniformly in the application with a large water tank, multiple aerators will be placed strategically at the bottom. This section deals with the experimental investigation with the two porous air stones to study the interaction of air bubble column from different aerators. A T-section is used in the experimental setup to supply air equally to the two porous air stones. In the first case the two air stones are kept relatively far away from each other whereas in the second case they are moved closer.

(1) Air stones with Large Distance

When the airstones release the air bubbles in the aqueous phase the air bubbles move upwards. The bubbles are dense just above the air stone but later due to the break-up and coalescence they move away to have a wide distribution. The maximum velocity attained is 3.59m/s but majority of the bubbles travel with velocities less than 1.2m/s. The flow field and the velocity vectors are presented in Figure 7. For the distance under study, the interaction of air bubbles from the two aerators is not observable. They are just two separate air bubble columns.

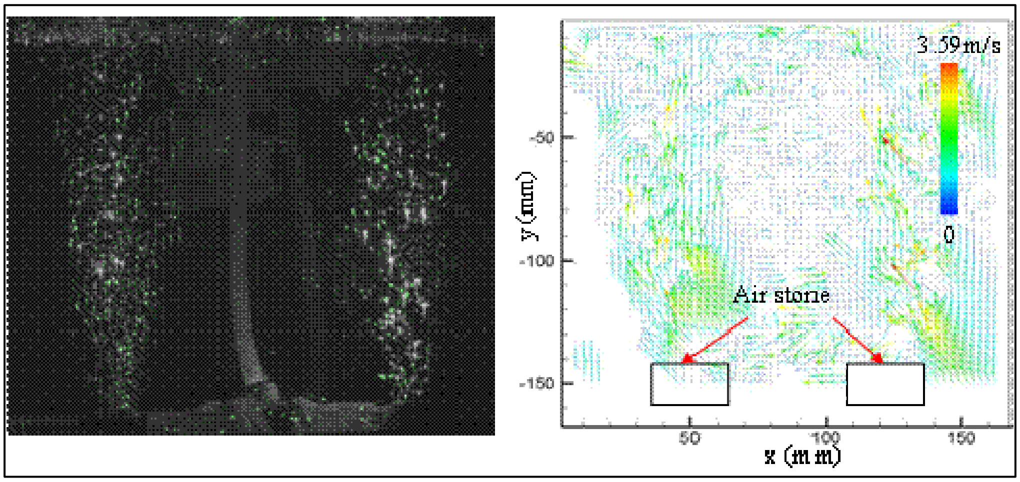


Figure 7 Flow field and velocity vectors for two air stone kept far

(2) Air Stones with Short Distance
When the two air stones are placed closer, it is observed that the air bubbling flow becomes unsteady. In one case, the air bubble flows from the two air stones are straight initially and then move closer or even merge together because of low pressure region between. After that the bubbles combine and travel upwards with high velocities. The flow field and velocity vectors are presented in Figure 8. The maximum velocity goes up to 3.74m/s and most of the bubbles have the velocities ranging in 1.8-2.0m/s. However, sometimes the flow pattern is observed to be straightly upwards.

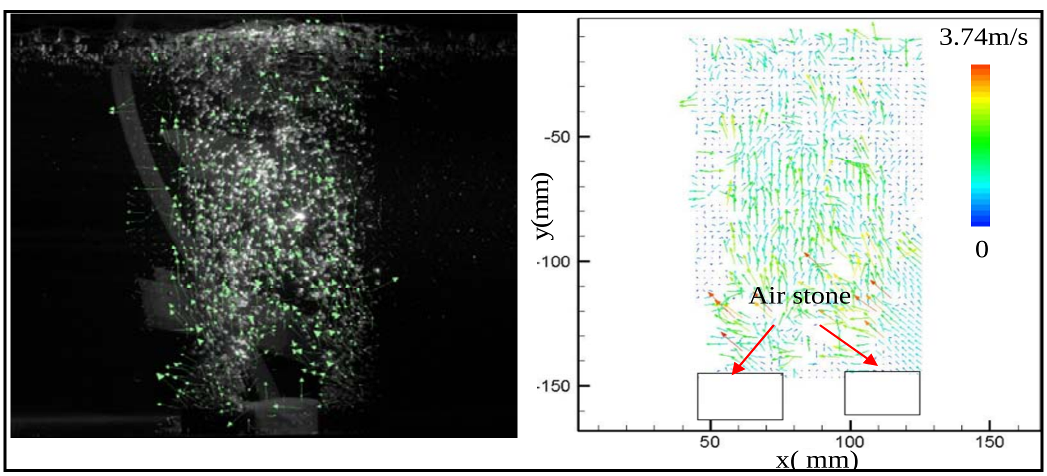
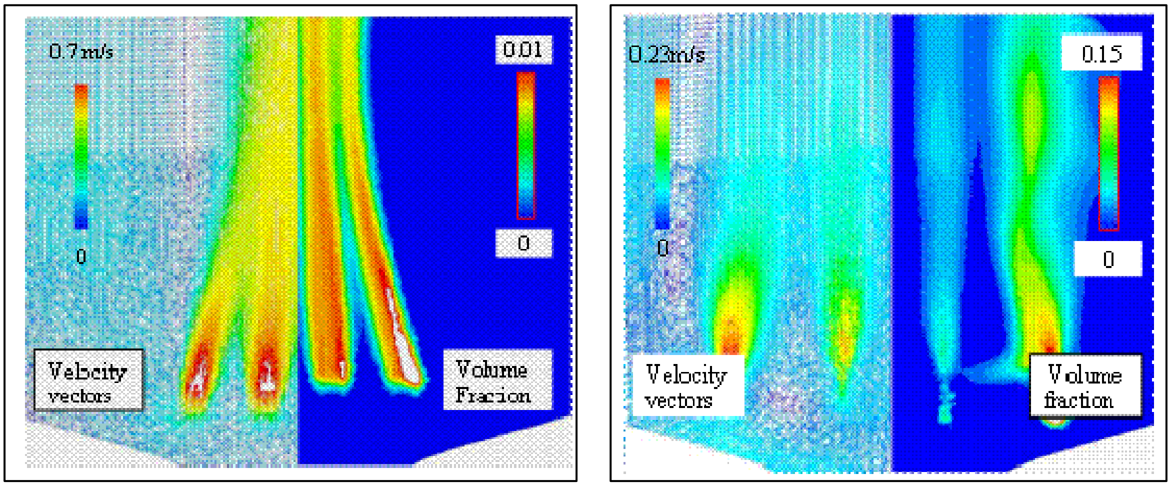


Figure 8 Flow field and velocity vectors of two porous air stone located closer

3.4 Comparison of Experimental Results of Two Airstone Aerators with Numerical Simulation
Computational fluid dynamics is adopted for the numerical simulation of the air bubbles in the two-phase flow. The 3D model of a bioreactor is created for the simulation of air bubbles in water using Fluent software. Mixture model is used to solve the two-phase flow in the simulation. The Navier-stokes equations and the equation of volume fraction are solved. Figure 9

shows the contours of air bubbles and velocity distribution for air bubble size of 1mm on a plane when the air bubble generators located at the bottom of the tank. The numerical simulation results for air sources located closer are shown in Figure 9(a). The maximum velocity is 0.7m/s which is just above the air source and also the velocity is high till the top of the tank due to the buoyancy of air bubbles. It can be observed that air bubbles rising upwards come closer after certain height due to the formation of low pressure zone between the bubble columns.



(a) (b)

Figure 9 Numerical results for two phase flow

Figure 9(b) shows the contours and velocity distribution when the air bubble generators are moved away. The contours of volume fraction show the air bubbles going to the top of the tank without any significant interaction. It can be seen that the tank has a more uniform distribution of air bubbles, which is essential for a good aeration. Furthermore, the velocity keeps decreasing from the bottom of the tank. This kind of bubbly flow also induces some turbulence for mixing.

By comparing the numerical results with the experimental test, it is seen the experiment shows some similar flow pattern and velocity fields. Therefore, the experiments and simulation can support each other, at least qualitatively. Details of the numerical simulation will be reported separately.

4. Conclusions

The behavior of the bubbles rising in the water tank was investigated using the PIV technique. The small air bubbles due to low buoyancy force have the tendency to stay in the aqueous body for long time so that the biomass or bacteria can have the desired oxygen content. The bubble size increases with air flow rate. Bubbly flows from single and multiple air sources have been studied experimentally and numerically. The distance between two aerators plays an important role for the bubbling pattern. Numerical results are consistent with the experimental observation.

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