Numerical Simulation of Gas-Liquid-Solid Three Phase in Bubble Column

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Abstract. Based on the Euler-Euler-Lagrangian framework, the Euler-Euler two-fluid model coupled with population balance model (PBM) and the Discrete Phase Model (DPM) model were used to simulate the gas-liquid-solid three phase dynamic behavior in the laboratory bubble column. The non-Newtonian properties of the liquid phase was considered in the numerical simulation, and the cases with different numerical models were discussed. It is found that the peak value velocity of liquid phase decrease due to the solid phase. The gas holdup remains almost the same in different cases with or without solid phase. There is no obvious periodic oscillation plume in non-Newtonian fluid. The interaction between solid and liquid has an effect on the flow field, gas distribution and viscosity distribution. The flow field calculated by CFD+PBM+DPM model forms three obvious vortices, while the symmetrical vortex is formed by CFD+PBM+DPM model, which is located on both sides of the bubble column. The distribution of dynamic viscosity simulated by different numerical models is basically the same in vary cases.

Keywords: bubble column; gas-liquid-solid three phase; numerical simulation

1. Introduction
Bubble column is widely used in chemical and environmental fields [1]. The research on bubble column is helpful to improve the oxygen of bubble column, thus indirectly promoting microbial growth. Because the numerical simulation method can obtain more details about dynamic behavior and need less resources, more and more researchers are used this technology to study.

In the early stage, Fan et al. study the application of microporous tower aeration in petrochemical industry wastewater treatment, and achieved remarkable results [2]. Durán carried out experiments on gas holdup and oxygen mass transfer in bubble column under different concentrations of activated sludge [3]. The numerical simulation research of bubble column focuses on (1) the physical shape of bubble column and liquid physical factors, including different height width ratio, inlet shape and inlet location, liquid phase property, bubble plume characteristics, air velocity, and bubble size [4-7]; (2) numerical methods, such as multiphase model, turbulence model, drag force correction and PBM algorithm which was used in numerical simulation [8-11]. Ali et al. [12,13] investigated the liquid dynamic behavior in the bubble column by experiment and numerical simulation. Considering the influence of different drag force models and shape, they found that the simulation results of Euler-Euler framework are better than those of Euler-Lagrange framework, and different drag force models have no significant impact on velocity distribution. The PBM model considers the coalescence
3.1 Algorithm and Example Setting

3.1.1 Calculation Strategy

The sludge particles are injected into the bubble column at the same speed as the gas phase, and the injection process is completed within 1s. Then, the gas phase continuously injects at the apparent speed. At this time, the injection process of particles is stopped and the calculation is completed in 160s. Three kinds of numerical models are used for calculation, including Euler-Euler two fluid model coupling PBM model (E+P), Euler-Euler two fluid model coupling PBM and unidirectional DPM model (E + P + D), Euler-Euler two fluid model coupling PBM model and bidirectional DPM model.
(E + P + D + couple).

### 3.2. Example Setting

Three different calculation examples are set, as shown in table 1.

| Cases | 1 | 2 | 3 |
|-------|---|---|---|
| Coupling model | E+P+D+Couple | E+P+D | E+P |
| Time | 160s | | |
| Rheological properties | The data from Mohapatra et.al [20] | | |

### 3.3. Numerical Method

The equations were dispersed via the finite volume method in section 2; pressure and velocity were coupled via the Semi-Implicit Method for Pressure-Linked Equation (SIMPLE); the volume fraction item was treated using QUICK scheme; the diffusion item was treated using the central discretization scheme; the time item was treated using the first order implicit; other items were treated using the 2-order upwind discretization.

The inlet is set as velocity boundary condition, and the apparent velocity value is 0.0024 m/s. The outlet is set as developed boundary condition, and other physical boundary conditions are set as solid wall boundary conditions. The bubble sizes are divided into 10 different groups. Energy equation is not considered in the numerical simulation. The residual, time step and the maximum iteration are set as $10^{-5}$, 0.02s, and 40 steps, respectively.

### 4. Results and Discussion

#### 4.1. Flow Field

The vertical and axial velocity of monitoring points (0m, 0.225m, 0m) under different models are shown in figure 1. It can be seen from the figure that the velocity tends to be stable at 80s, indicating that the flow field of the bubble column is in a stable state. There are some obviously differences in three cases. The axial liquid velocity is very small in case 3, and the vertical liquid velocity is about 0.21 m/s. In case 2, the axial liquid velocity is also small, and the vertical velocity is less than that case 3. This is mainly due to the fact that part of the kinetic energy of the liquid phase is converted into the solid phase, which leads to the decrease of the liquid velocity. In case 1, the irregular movement of particles leads to the weak influence regularity, which makes the velocity also present a certain pulsation. At the same time, it can be found that the vertical and axial velocity around the axial 0.018m/s and the vertical 0.17m/s, respectively. What is more, the vertical velocity is less than case 2 and 3, mainly due to the particle and liquid phase. As can been seen from figure 1, when the calculation reaches at 80 s, the velocity tend to be stable.

![Figure 1](image1.png)

**Figure 1.** Velocity of monitoring points using different numerical models.
The flow field in the bubble column is shown in figure 2. It is found that the flow field in the case 2 and 3 are basically the same at 100s, and the stream are symmetrical at $x = 0m$ and $z = 0m$ section. This is mainly due to the gas phase driving the liquid flow. What is more, the center is located in the middle of the bubble column. The flow field in the case 1 shows that there are three different vortices in the cross-section. One vortex is in the negative direction of the x-axis and two vortices are in the positive direction of the x-axis. The reason is the non-uniform distribution’s particles.

As shown in figure 3, the vertical velocity of liquid phase at $z = 0m$ section is analyzed. It is found that the middle velocity is the highest and the velocity on both sides is the lowest in different cases. Compared with the other two cases, the peak value of vertical velocity in case 3 is the largest and its distribution range is larger; while the vertical velocity distribution of case 1 is obviously different from that of other two cases in the middle of bubble column. And, the distribution of large value area of vertical velocity is zigzag, which is different from the zigzag distribution of plume and velocity in bubble column under Newtonian fluid. This is mainly due to the interaction between the particles and the fluid, resulting in the unsteady state of the flow field, which is explained to a certain extent by the values of the monitoring points in figure 1.

4.2. Gas Phase Distribution
As shown in figure 4, the gas phase distribution at 100s shows that gas content is high in the bottom, and with the increase of height, the gas distribution area gradually increases. Compared with the other two models, the gas phase distribution in case 1 is not symmetrical, which shows the instability of
flow field and then affects the gas distribution.

![Figure 4](image1.png)

**Figure 4.** Gas phase distribution at 100s under different models (z = 0m section).

In order to quantify the aeration capacity in the bubble column, the gas holdup of the three cases are compared. The gas holdup simulated at 100s are basically the same, and the gas holdup in different cases are all around 0.00619 which is lower than 0.00671 simulated by Newtonian fluid. It is consistent with the research results of Durán et al [3].

4.3. **Dynamic Viscosity**

The higher the viscosity of the fluid, the weaker the fluidity. Therefore, comparing the dynamic viscosity, it is helpful to further reveal the reasons of velocity and gas-liquid phase distribution. As shown in figure 5, the dynamic viscosity distribution of z = 0m section in the bubble column is given. A v-shaped low value area of dynamic viscosity is formed from the bottom to the middle in the bubble column, which shows that the liquidity in this area is stronger than that in other regions. The peak value of dynamic viscosity simulated in case 3 is significantly higher than that case 1 and 2, which means that the particles can significantly reduce the dynamic viscosity. The main reason remains that the existence of particles will reduce the liquid phase velocity in the bubble column. As can been seen from figure 3, the maximum and minimum vertical velocity decrease more or less, especially the minimum velocity decreases greatly, which leads to high dynamic viscosity. We also found that the dynamic viscosity distribution in case 2 and 3 is symmetry at x = 0m section. The extreme value in case 3 is mainly distributed in the street corner at the bottom in bubble column. The extreme value in case 2 is mainly distributed in the middle of bubble column, which reflects that the gradient value of velocity in this part is small. That is the velocity has no great change. In case 1, there are obvious high value areas at the bottom of the bubble column, which shows that the liquidity in this area is the weakest.

![Figure 5](image2.png)

**Figure 5.** Dynamic viscosity distribution at 100s under different models (z = 0m section).
4.4. Particle Track

The trajectory sludge particles in the bubble column is shown in figure 6 below (case 1 and 2). It can be seen that there are 946 particles in z = 0m section, and the flow path of particles covers the whole bubble column. Only in the vortex center of the bubble column, there is no movement particles. Combined with the gas phase distribution, although the gas phase distribution is high, the sewage treatment capacity in this area is weak. At the same time, the particle trajectories in case 2 are symmetrical, which shows that the particle motion rises from the middle and descends along both sides. However, the distribution of particle trajectories in case 1 is complex, which means that the particle motion is different from that the case 2. What is more, particles rise in a curve and form three vortex tracks.

![Figure 6. Particle trajectories under different models at 100s (z = 0m section)](image)

5. Conclusion

The existence of solid phase can reduce the peak liquid velocity and liquid viscosity in bubble column, but has no significant effect on gas holdup. When the liquid phase is Newtonian fluid (pure water), the gas holdup in bubble column is higher than that of activated sludge (non-Newtonian fluid) in bubble column by 7.73%; there is no obvious periodic oscillation plume, and the distribution of gas phase is wide at the top and narrow at the bottom. It has an effect on the flow field, gas distribution and viscosity distribution due to considering the solid phase in simulation. The flow field calculated in case 1 forms three obvious vortices. And, the symmetrical vortex is formed in case 2, which is located on both sides of the bubble column. The gas distribution and viscosity distribution also show similar in different cases. But it has no significant effect on gas holdup. The distribution of dynamic viscosity is basically consistent in different cases. The distribution of low dynamic viscosity is v-shaped, and the peak dynamic viscosity is distributed at the bottom and center of both sides in the bubble column.

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