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The research of gas-liquid-solid flow in aeration tanks

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ABSTRACT

The characters of the gas-liquid-solid hydraulic flow in an aeration tank have enormous influence in treatment efficiency. The thesis modeled the three multi-phase flow characteristics in aeration tank, and combined with the measure of PIV. The simulation results agreed well with 3DPIV experiment results. The simulation results of flow structure reveal the internal circulation of the water in the tank and the water with upward flow in the center region and downward flow near the wall.

KEYWORDS

Gas-Liquid-Solid;
Hydraulic condition;
Numerical simulation;
PIV.

INTRODUCTION

Aeration tank is one of the chief units in urban wastewater treatment. Aeration in this process can represent up to 70% of the total energy expenditure of the plant. The hydraulic characteristics of aeration tank directly affect the activity of activated sludge and oxygen transfer efficiency. The cross flow changed the flow characteristics in the aeration tank. It made the active slud ge fully contact with oxygen, and also improved the oxygen transfer efficiency. The aeration is 3D. The 3D movement of the bubble influences the DO (Dissolve Oxygen) of the aeration tank directly, especially in the difference boundary conditions (etc. nearing the aerator or at the end of the corridor). The traditional method of the single point measurement can not get the whole message of the fluid, which can not give a comprehensive description in the fluid field. PIV(Particle Image Velocimetry) measurement is based on the method of optic, which can get the instantaneous velocity of the whole fluid. It is used in the researches of water jet; burning; the manufacture of the boat; aerospace; environment technology etc. Computational fluid dynamics (CFD) is more and more used to optimize aeration systems.

Wood[1], et al. used finite element software to simulate the four series pond under the condition of steady-state flow. The model is two-dimensional. In Vega et al.[2] study, MIKE 21 software was used to analyze the process of anaerobic pond under different conditions, showed the optimized design scheme of the oxidation pond. Salter et al.[3], Karama et al.[4] used PHOENICS software to simulate the different structural parameters of activated sludge reaction tank under different operating conditions. Cockx et al.[5] predict the concentration of oxygen in a gas lift circulation reactor with ASTRID software. Ji Min et al.[6] investigated the behavior of flow field in the moving bed biofilm reactor (MBBR). Feng Qian[7] built the aeration flow model. Combined with the measure of PIV(Particle Image

Velocimetry) and the technology of CFD. A bubbles formation process is simulated from the angle of flow dynamics of aeration (Li Yanpeng[8]). Almost no research has been reported in a tri-dimensional to simulate the aeration tank. Since the measurement pantograph has more influence on the flow field, a lab scale plug-flow aeration tank was modeled in this paper. The PIV and CFD software were used combined to analyze the three-dimensional gas-liquid flow in an aeration tank. The objective of this paper is therefore to get the flow characteristics of the air and the water, to analyze the influence of the different boundary condition.

MATHEMATICAL MODEL

This research supposed that the liquids and the gases is continuous phase. According to the mass, momentum and energy balance principle, three flow model was used to describe the gas-liquid solid three phase flow in the aeration tank. This model also supposed that the temperature of the water and air are same to the environmental temperature, so the energy equations were not taken into account[9-14].

Model of gas-liquid flow

(1)Three-phase mass conservation equations

The three-phase flow mass conservation equations for each

phase are considered as follows:

$$\frac{\partial(\alpha_q\rho_q)}{\partial t}+\nabla\bullet\left(\alpha_q\rho_q U_q\right)=\sum_{p=1}^{n}\dot{m}_{pq} \qquad \textbf{(1)}$$

Where U_q is the velocity of the phase q; the q can be liquid L, Solid S or be gas G; $\dot{m}_{pq}$ is the mass transfer from the phase p to phase q. And $\dot{m}_{pq}=-\dot{m}_{qp}$ due to the transfer equation, $\dot{m}_{pp}=0$. α_q is the volume fraction of phase q.

(2)Momentum equation

$$\frac{\partial}{\partial t}(\alpha_q\rho_q U_q)+\nabla\cdot(\alpha_q\rho_q U_q U_q)$$
$$=-\alpha_q\nabla p+\nabla\cdot\overline{\overline{\tau}}_q+\sum_{p=1}^{n}(\vec{R}_{pq}+\dot{m}_{pq}U_{pq})+\alpha_q\rho_q F_q \qquad \textbf{(2)}$$

where F_q is the drag force between the phase. $\overline{\overline{\tau}}_q$ is the press strain tensor of phase p. The forces between the phases are composed of the drag force. The drag force is expressed as follows:

$$F_q=F_{m,q}+F_{ym,q}+F_{lm,q} \qquad \textbf{(3)}$$

$F_{m,q}$ is the plus volume forceÿ$F_{ym,q}$ is the drag force. $F_{lm,q}$ is the magnus force. To ensure the precision and to reduce the computation time, only the drag and lift force is taken into consideration. Regardless of the gas-solid phases interaction force[15].

Here the main phase is the liquid phase. The bubble phase and the solid particles are the dilute phase. The Schiller - Naumann drag model is used to calculate the force between the liquid and the gas. The movement of the solid paricles in the aeration included translation, rotation which can accelerate the liquid. The Wen - Yu model used to model the Solid-liquid drag.

(3)Standard k-εturbulence model

Every phase have its' transport equation. Since the turbulent motion had a great influence on the transfer of the oxygen in the aeration tank, so the multiphase turbulence model was used.

Turbulence kinetic energy (k) equation:

$$\frac{\partial}{\partial t}(\alpha_q\rho_q k_q)+\nabla\bullet\left(\alpha_q\rho_q U_q k_q\right)=\nabla\bullet\left[\left(\mu_q+\frac{\mu_T}{\delta_k}\right)\nabla k_\alpha\right]+G_{k,q}-\rho_q\varepsilon_q \qquad \textbf{(4)}$$

Turbulence kinetic energy dissipation rate (ε) equation is (5), δ_k、 δ_ε is the Prandtl number of K and ε. G_k is the generation of turbulence kinetic energy due to the average gradient. $C_{3\varepsilon}=1.3$, $C_\mu=0.085$, $C_{1\varepsilon}=1.42$, $C_{2\varepsilon}=1.92$, $\delta_k=1.0$, $\delta_\varepsilon=1.3$ are counts.

$$\frac{\partial}{\partial t}(\alpha_q\rho_q\varepsilon_q)+\nabla\bullet\left(\alpha_q\rho_q U_q\varepsilon_q\right)=\nabla\bullet\left[\left(\mu_q+\frac{\mu_T}{\delta_\varepsilon}\right)\nabla k_q\right]+C_{1\varepsilon}\frac{\varepsilon_q}{k_q}G_{k,q}-C_{2\varepsilon}\rho_q\frac{\varepsilon_q^2}{k_q}-R \qquad \textbf{(5)}$$

The volume fraction of the liquid-gas equation:

$$\alpha_G+a_L+a_S=1 \qquad \textbf{(6)}$$

where α_G and α_L are the volume fraction of the gas and liquid.

Calculation domain and boundary conditions

A full scale aeration tank has been analyzed by the ratio (1:20). Air is injected at the bottom of the tank through the micro-porous aerator(r=0.5mm) through aeration tube. The dimension of it is 700*544*350. The efficiency depth is 0.2m. There are one inlets (d=0.025m) and one outlet(d=0.025m). The flow is assumed to be isothermal(the simulations take place with water and air at T=20ºC). The free surface is treated as pressure outlet, so did the outlet. The oxygen transfer from the free surface is neglected. The gas phase is treated as the first phase.

The mesh grid and the numerical method

Using 3D grid meshes to describe the aeration tank (Figure 1). There are both unstructured and structured grids in the tank. The grid has been refinement near the aerators, the inlets and the outlet. An upwind scheme is used to make the equation discrete.

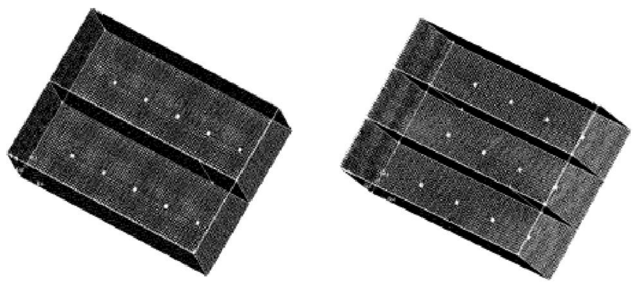


Figure 1 : The structure and the mesh of the aeartion tank

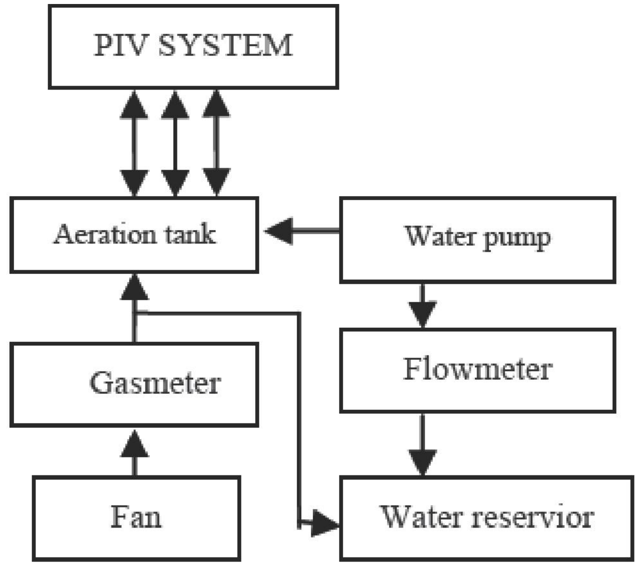
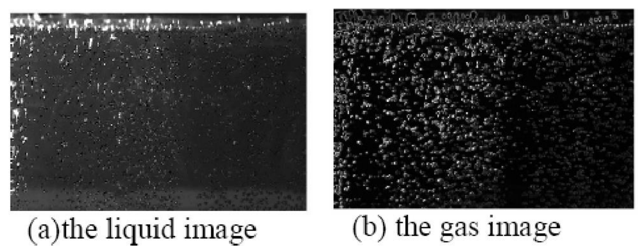


Figure 2 : Flow control system of aeration tank



(a)the liquid image (b) the gas image

Figure 3 : The image of each phase after the analyze of IPL

THE INSTRUMENTS AND THE METHOD OF THE EXPERIMENT

The instruments

The PIV is used in the experiment. The wavelength of the laser is 532nm. The PIV of the Dantec Dynamics A/S was used to test the lab scale tank. The different process conditions were analyzed in the section A. The hollow glass beads (r=50μm) are used as tracer of the liquid phase used. The proportion is 0.999. Two cameras were used to get the 3D flow which had the filter of 532nm.The flow control system was showed as figure 2. The software of the IPL of the Dantec Dynamics A/S was used to identify the two phases. The image of the gas and liquid was shown in (a) and (b) of figure 3.

The method of the experiment

The cross-correlation analysis and the average filter were used to analyze the image of the Fig.3. A series experiments of different aeration speeds and different quantities of the treatment water were determination at a certain time[16].

RESULT

Simulated results

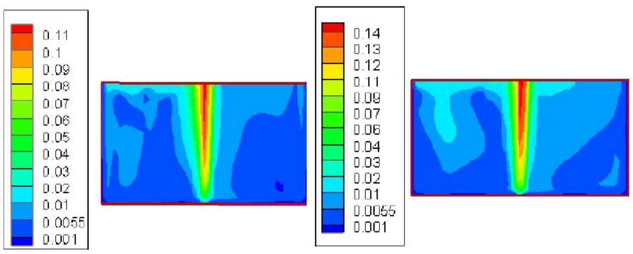
As shown in TABLE 1, the work conditions are only considering the change of water depth, number of corridors, and the air volume of the aeration tank.

TABLE 1 : The work condition of the experiment and the model

Operating mode	Physical condition			Length width ratiio	Width depth ratio
	Number of corridor	Aeration fluxes (L/H)	Depth (mm)		
NO.1	0.11	80	150	5.13	1.81
NO.2	0.13	160	150	5.13	1.81
NO.3	0.07	80	150	11.56	1.21

Guarantee the aeration tank of hydraulic retention time of 8.4 h. The aeration speed of the NO.1 condition is 0.074 m/s (80 l/h), the aeration speed of the NO.2 speed is 0.158 m/s (160 l/h) simulation.

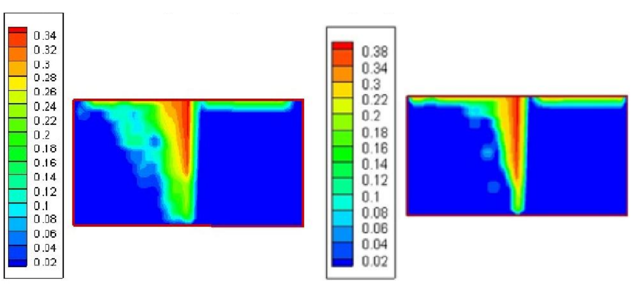
It is qualitative to the experimental observation of Cheng Wen (2001)[10], Li Yanpeng et (2007)[17]. As shown in Figure 4, the circulation flow will accelerate the velocity of each phase. In macro-scale, the circulation flow occupied the aeration tank. The bigger the turbulence is, the more circulation flows are in the aeration tank. It is more conducive to the gas and liquid mass transfer, to improve the dissolving oxygen (DO) in the tank.



a.NO.1 b.NO.2

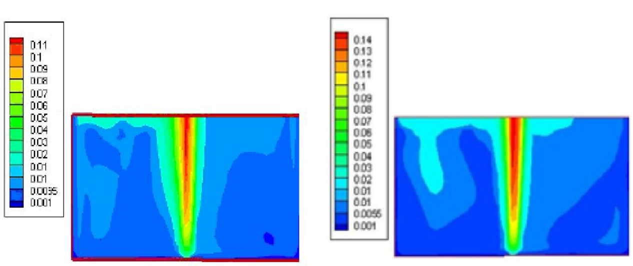
Figure 4 : The speed diagrams of the liquid phase at x=100mm(m/s)

As the increasing of the superficial velocity of the gas phase, the aeration tank's turbulence grew bigger. The bubble flow of the aeration tank changed gradually from uniform bubble to non-uniform turbulent state. Figure 4, Figure 5 and Figure 6 showed the speed diagrams of the different work conditions in the flow aeration tank. The velocity in the diagram is the synthesis speed velocity of the x, y, z direction speed (the cross-section's velocity diagram at x = 100 mm).



a.NO.1 b.NO.2

Figure 5 : The speed diagrams of the gas phase at x=100mm(m/s)



a.NO.1 b.NO.2

Figure 6 : The speed diagrams of the solid phase at x=100mm(m/s)

Figure 4 showed that the greater aeration speed, the more vortex are produced. It can provide good hydraulic conditions by the velocity gradient and the collision ratio causing by the vortex shearing and the inertia effect of centrifugation. At the NO.2 condition, the turbulent fluctuations of the liquid and the solid phase changed much, the circumflux nearing the aerators become larger. The velocity of the aerator at NO.1 condition is relatively smaller than that at NO.2 condition.

Figure 5, the gas phase focused on the center line of corridor in the aerator. Bubbles lift velocity is fast. The bubble plume vibrated slowly when the aeration at low speed. As the increasing of the superficial velocity of the gas phase, the liquid and the solid phase generate two obvious vortex structures around the bubble plume (Figure 6, 7 in NO.1 condition). The vortex structures are stable which rotating in the opposite direction with symmetry.

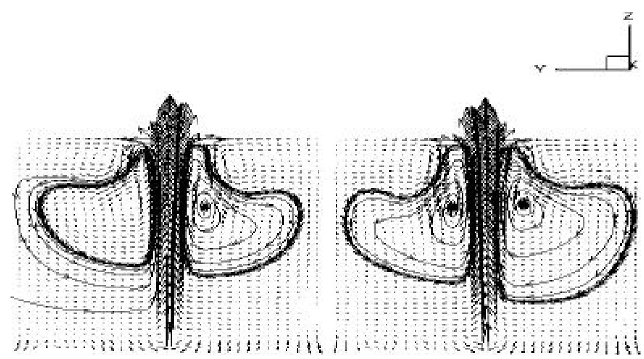


Figure 7 : The liquid phase's trace plused velocity vector at x=100mm(NO.1)

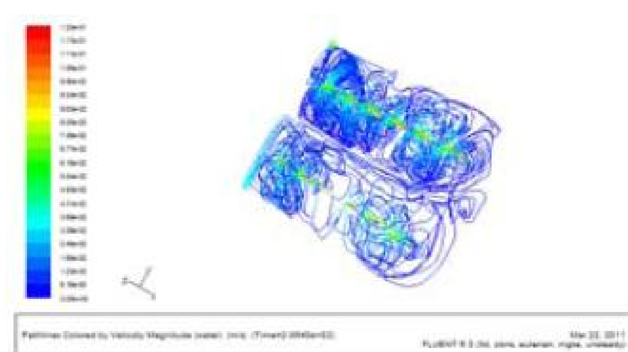
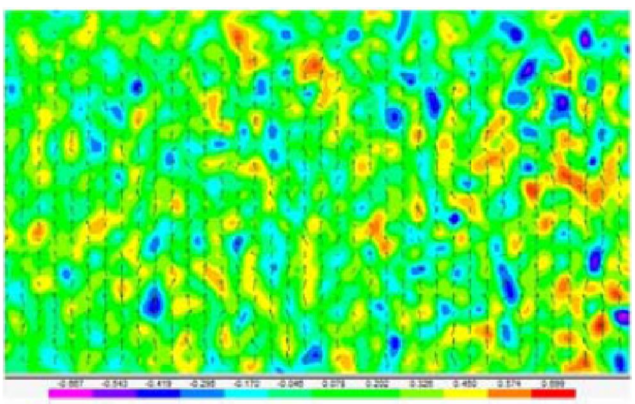


Figure 8 : The liquid phase's path line in the aeration tank (NO.1)

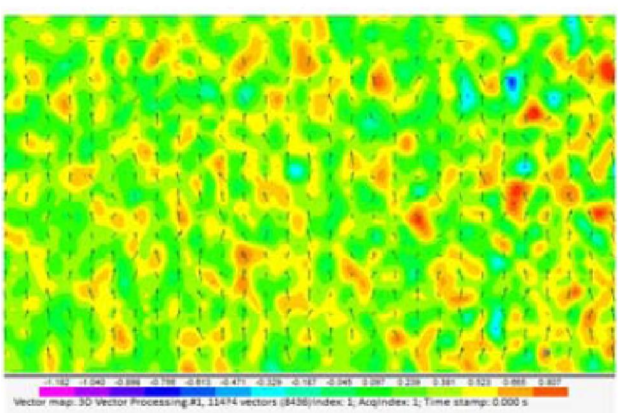
Figure 4, Figure 5, Figure 6 indicated that we can increase the velocity of gas phase in order to improve the velocity of particle collisions, to eliminate the "dead corner area". The greater aeration speed, the more vortex are produced. It can provide good hydraulic conditions by the velocity gradient and the collision ratio causing by the vortex shearing and the inertia effect of centrifugation. At the same time, the random scroll wraps the tiny granules together. The sludge flocs in the tank turned to be compacting and smooth. Then it can be easily settled in the subsequent process[18].

The following assumptions could be made to get the law in different operation condition.

- The different between the velocities of liquid and solid phases are not obvious. It suggests that the gas drive the liquid and the solid both to form the vortex. It can be used to promote the mass transfer between them, so to improve the DO concentration.
- The greater velocity of the aeration, the greater velocity of the gas phase in the tank.
- As the bubbles rising, the buoyancy increased, so the upward gas bubbles had the greater velocity. In this simulation, the lifting influence of the bubble size was not taken into considering.



(a) the 3D vector of gas phase



(b) the 3D vector of liquid phase

Figure 9 : The 3D vector of in the first corridor(y=140mm)

Eexperimental results

The figure 9 represents the 3D velocity vector of the gas phase (a) and the liquid phase (b) in the first channel of the aeration tank. The velocity of the direction y was bigger than the velocity of the direction x. The turbulence of the aeration tank increased significantly with the increasing of the gas phase velocity. The turbulent motion near the aerator was obvious and the circulation strength was bigger.

Figure 9 represents that the aeration axial and radial velocity has one difference in magnitude. Because of aeration flow is relatively slow (the radial velocity). The hydraulic retention of the aeration tank is long, so the aeration lateral velocity along the channel is very small. If the velocity along the corridors is large enough, it can shorten the generating time of the bubbles[17].

Simulated results and experimental results comparing

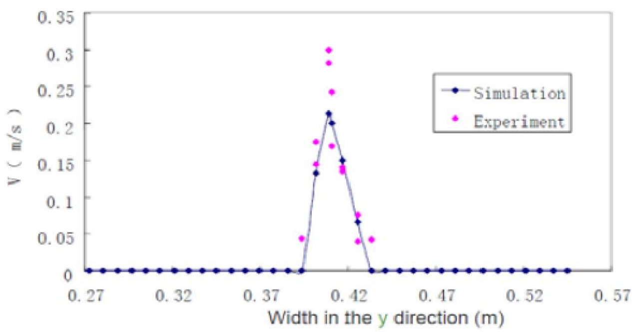
According to the experimental conditions showed in TABLE 1, the solid, gas, and liquid phase's velocities were measured by the 3DPIV. Some conclusions were showed in the TABLE 2.

TABLE 2 : The work condition of the experiment and the model

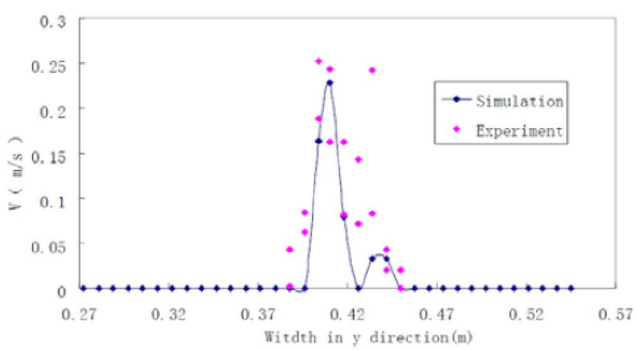
X Coordi nate	Simula Tion (m/s)	Experi -ment (m/s)	RE	X Coordi nate	Simula Tion (m/s)	Experi -ment (m/s)	RE
50	0.0048	0.0050	0.0400	250	0.0101	0.0130	0.2231
90	0.0059	0.0072	0.1806	300	0.0036	0.0030	0.2000
100	0.0070	0.0080	0.1250	320	0.0035	0.0032	0.0938
150	0.0074	0.0084	0.1195	360	0.0010	0.0010	0.0000
160	0.0027	0.0025	-0.0800	380	0.0030	0.0030	0.0000
200	0.0047	0.0075	0.3733	410	0.0052	0.0064	0.1875
210	0.0039	0.0058	0.3276	440	0.0030	0.0030	0.0000
220	0.0035	0.0054	0.3519	470	0.0123	0.0100	0.2300
230	0.0084	0.0072	-0.1667	490	0.0093	0.0100	0.0700
240	0.0103	0.0114	0.0965	570	0.0021	0.0029	0.2759

Figure10 showed the comparing results between the simulated results and the experimental results. Due to the bubble trajectories were not stable, so the gas phase velocity error is bigger at the position which is above the aerators in the tank. In addition to these places the bubbles rarely reached, so speed was near to zero.

Figure 11 showed that most of the experimental data and simulation error is less than 20%. 1500 pairs of simulation analysis, some points' errors are about 35%. The average error is about 14.3%. Simulation value and experiment results are basically identical to each other. The particles' scattering, rotation and the concentration of the solid may cause the errors in PIV testing. The gas-liquid-solid three phases' model is feasible to the lab scale aeration tank's PIV experiments.



a z=50mm



b z=120mm

Figure 10 : The speed of the liquid phase at x=100mm in condition 1

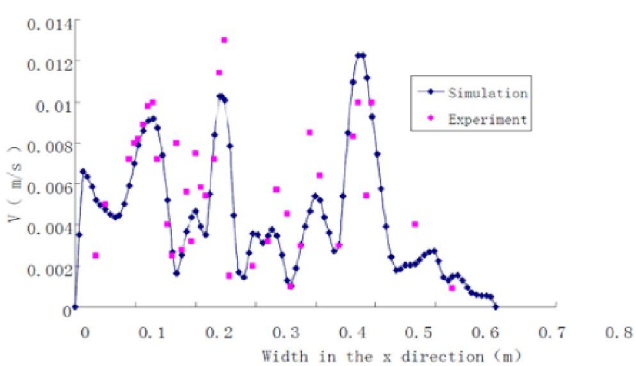


Figure 11 : The phase velocity comparison chart between simulation and experiment at y=520mm,z=120mm in conditon 1

CONCLUSIONS

The CFD simulation and PIV measurement were both used to analyze the flow field in the aeration tank. A numerical tool to simulate flow characteristics in aeration tank has been presented. During the modeling, different process parameters of aeration tank was simulated, and the gas-liquid-solid flow behavior in aeration tank was analyzed. Results show that:

The simulation results agree qualitatively with the lab scale aeration tank's PIV experiments. Results show that with the increasing of the superficial velocity in aeration, the liquid's and the solid's velocities of the aeration tank raised. So lots of the vortex generated. It is benefit to the DO diffusion and the pollutants degradation.

According to the experiment, in the process of bubble rising, the bubbles existed clustering. It made the bubble's size and speed change. So we need to pay more attention to the size of the bubbles.

In future research, the influence of the solid phase's concentration, rotation of the particles in the aeration should be taken it into consider.

This research can provide a scientific base for the wastewater treatment of activated sludge from the point of view of fluid dynamics. In addition, with the consideration for current calculation method and the insufficient compute capability, the gas-liquid-solid of the full scale aeration tank could be further analyzed on the basis of the results researched above, which provided the basis for adjusting the structure parameters of active sludge, optimizing the system diffusion properties, and improving the sludge treatment efficiency[12].

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