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Flow simulation and test analysis of the vortex clarifier tank reaction zone

Tong Zhengong
School of Civil Engineering of East China Jiaotong University, Nanchang, (CHINA)

ABSTRACT

Field tests were carried out to test the working conditions of vortex clarifier tank reaction zone in the presence or absence of vortex reactors, and both zeta potential analyzer and flocculation control device (FCD) were used to detect æ potential and associated structural changes. Fluent software was then applied to simulate the vortex scale and distribution of water flow in the vortex clarifier tank, in order to obtain detailed information of the flow field within the internal part of reactors. When chemical dosage and water input were held equal, results from field tests and numerical simulations were then compared. The results showed that both field tests and numerical simulations yielded similar results, thus proved the validity of numerical simulations, and provided new perspectives regarding the optimization of reactor design and operating parameters in the future.

KEYWORDS

The reaction zone of the vortex coagulation clarifier;
Numerical simulation;
Experimental.

INTRODUCTION

Developed by Jiao Tong University of East China, the vortex clarification technique has demonstrated its excellent technical and economic benefits in engineering practice[1]. However, due to the lack of in-depth understanding of whirlpool flocculation process and involved clarification mechanisms, the application of this technique is not well-guided, with the selection of system design parameters and operating parameters too random. As a result, an extended application of this technique in engineering practice is severely impeded. Fluent software is the most widely used CFD engineering application software to date, and it can be used to effectively deal with complicated flow and physical phenomena, and to provide optimized simulation results using different discrete format and numerical methods[2].

During the flocculation stages of water treatment, the main task is to create hydraulic conditions so that pharmaceutical chemicals and raw water could be well mixed to form condensed floc structure with good physical properties within certain amount of time[3]. At present, both empirical parameter method and physical simulation method are commonly employed for the design of reaction zone during the water purification process. However, variations among individual projects result in less accuracy of empirical parameter method, whereas physical simulation method is both time-consuming and expensive. This study first carried out field trials, followed by the method of numerical simulation. Results from both approaches were then analyzed and compared to further explore the most economical and practical method, and to provide new perspectives regarding the optimization of reactor design and operating parameters.

FIELD TEST OF VORTEX CLARIFIER TANK REACTION ZONE

The experimental system of vortex clarifier tank

The structure of vortex clarifier tank was as shown in Figure 1.

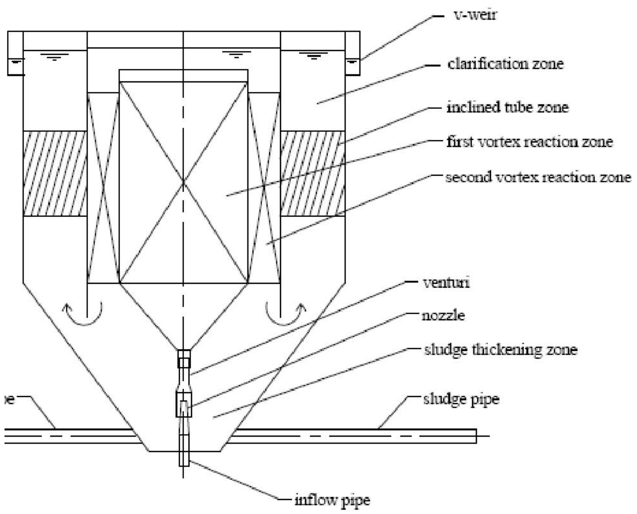

Figure 1 : The structure of vortex coagulation clarifier

Raw water with coagulant passed through the pipe mixer and reached the first vortex reaction chamber first, followed by the second reaction chamber (vortex reactors were installed within both reaction chambers as shown in Figure 2, with more information of vortex reactors found in related documents 4[4], and then left the second reaction chamber from its bottom and flew to the buffer zone; after then, floc particles with good precipitation properties settled down to the precipitation zone to undergo sludge thickening process, whereas pure water and small-sized floc particles were undergoing solid-liquid separation process via inclined tube setting in the precipitation zone. A small amount of concentrated sludge could then flow back to the first reaction chamber, and the actual amount could be manipulated through the operation lever installed at the top of the clarifier tank. By contrast, the remaining sludge was discharged through the annular mud tubes symmetrically arranged in the bottom of the tank.

Test water quality and related instruments

Water samples were collected from Kongmu Lake around the campus, with water quality test results as shown in TABLE 1.

Figure 2 : The vortex reactor

TABLE 1 : The experimental raw water quality

Influent flow	Influent turbidity	pH Value
8m³/h	19.3NTU	6.71
Zeta potential	UV_{254}	COD_{Mn}
-16.50mv	0.0703 cm^{-1}	8.16mg/L
Water temperature is about 17.2℃		

The main measured indicators included zeta potential, water turbidity, water temperature and pH. All required t instruments and equipment were as shown in TABLE 2.

TABLE 2 : Water quality monitoring projects and analysis methods

Testing item	Unit	Analysis method
Turbidity	NTU	TDT—2 turbidimeter
UV_{254}	abs/m	ultraviolet pectrophotometer
COD_{Mn}	mg/L	acidic titration method of $KMnO_4$
Zeta potential	mV	90 plus Zeta particle size analyzer
floc morphology		FCD analyzer

Test results

The working condition one showed the vortex clarifier reaction zone in the presence of vortex reactors as shown in Figure 2; the working condition two showed the vortex clarifier reaction zone in the absence of vortex reactors. Polyaluminium chloride (PAC was used as the coagulant[5], and the amount of water input in the experiment was 8m^3/h. Under conditions of same dosage application, the amount of added flocculants increased from 7.2mg/L to 33.6 mg/L gradually. Zeta potential analyzer was used to measure outflow zeta potentials with different effluent turbidity as shown in Figure 3.

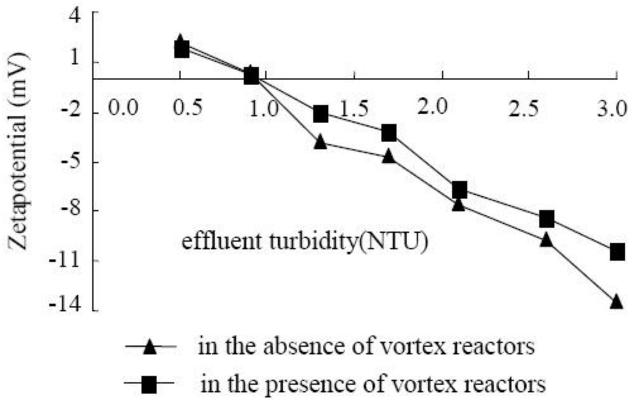

Figure 3 : The relationship between the effluent turbidity and zeta potential

It could be seen from Figure 3 that with an increase of flocculant addition, water turbidity started to decrease whereas zeta potentials started to increase. When both working conditions were compared, zeta potential increased more in the vortex clarifier tank with vortex reactors installed than the vortex clarifier tank without vortex reactors installed, with water turbidity between the range of 1NTU and 3NTU. Also, before zeta potentials were changed from negative to positive values, an increase of zeta potentials could promote collisions among floc particles, and thus led to the sinking process of condensed alum. When the amount of added flocculants to the clarifier tank with vortex reactors increased to 19.2mg/ L, corresponding zeta potential was close to the isoelectric point.

At this stage the outflow turbidity was around 1NTU. By contrast, for clarifier tank without vortex reactors, the amount of required flocculants was 28.08mg/L in order to make corresponding zeta potential close to the isoelectric point.

Figure 4 The relationship between dosage and the effluent turbidity with vortex reactor and without vortex reactor

Figure 4 reflected the relationships between outflow turbidity and the amount of added dosage under two working conditions. It could also be seen from this figure that under the same water turbidity, the clarifier tank with vortex reactors installed required less amount of added dosage compared to the clarifier tank without vortex reactors installed. Also, the trend was not obvious when water turbidity was around 2NTU. With an increase of flocculant addition, water turbidity kept decreasing. When water turbidity decreased to 1NTU, it could be seen clearly that the amount of added dosage to the clarifier tank without vortex reactors installed was two times higher than that of the clarifier tank with vortex reactors installed.

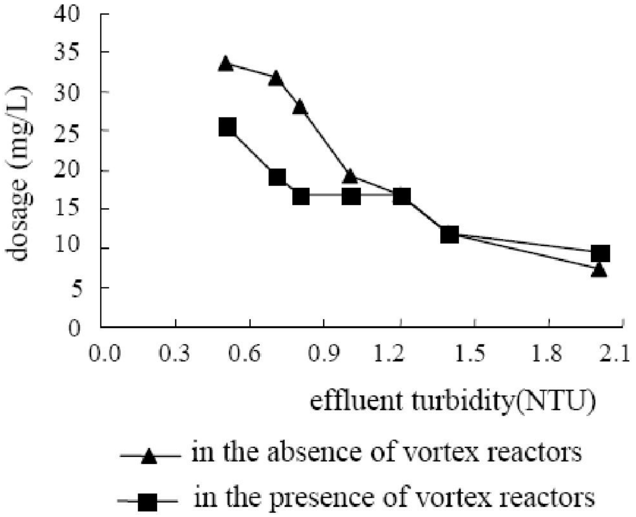

Figure 4 : The relationship between dosage and the effluent turbidity with vortex reactor and without vortex reactor

Figure 5 The dosages in condition of vortex reactor and without vortex reactor

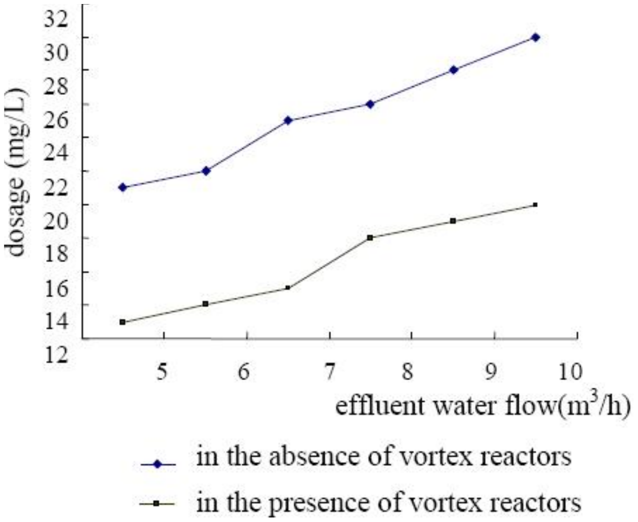

Figure 5 : The dosages in condition of vortex reactor and without vortex reactor

Figure 5 showed the relationship between the added dosage for the clarifier tank with vortex reactors installed and the added dosage for the clarifier tank without vortex reactors installed with water turbidity maintained as 1NTU. It could be seen from this figure that the amount of added dosage to the clarifier tank with vortex reactors installed was 30% lower than that of the clarifier tank without vortex reactors installed under different flow conditions.

Therefore, all above tests showed that the installation of vortex reactors had a significant impact on improving water quality, because the presence of vortex reactors increased flow resistance, caused the condensed status of floc particles, facilitated the accumulations of sludge layers, and led to the stable status of water outflow.

THE NUMERICAL SIMULATION OF VORTEX CLARIFIER TANK REACTION ZONE

The model and boundary conditions of vortex clarifier tank

The simulation part focused on the numerical simulation of the vortex reaction zone. A top-down approach was used for the modeling of vortex reactors, with a standard k-ε model specifically applied. On the other hand, the modeling of the reaction zone was based on boolean mergers and subtract operations of cylinder units.

Simulated variables

Turbulent kinetic energy k

Turbulent kinetic energy $k = \frac{1}{2}(\bar{\mu}_x'^2 + \bar{\mu}_y'^2 + \bar{\mu}_z'^2)$

The compaction level of alum could be manipulated via turbulence intensity σ

$$\sigma = \frac{1}{3}\frac{\sqrt{\overline{\mu_x'^2} + \overline{\mu_y'^2} + \overline{\mu_z'^2}}}{\bar{v}}$$

μ_x', μ_y', μ_z' —the pulse velocity of spatial points along x, y and z directions;

$\bar{v}$ —the average velocity of spatial points per unit time;

Higher values of indicated that the number of vortex flow that passed through stationary spatial points in a fixed period of time was larger, the intensity of vortex flow was higher, and the compaction level of alum was stronger. A comparison between the turbulent kinetic energy k and turbulence intensity showed that there was a positive relationship between these two. Therefore, the larger the k value was, the higher turbulence intensity was. Also, the number of vortex flow that passed through stationary spatial points in a fixed period of time was larger during that stage, with higher levels of intense turbulence, higher changes of collisions among floc particles, and thus stronger compaction levels of formed alum.

The dissipation rate of turbulent kinetic energy ε

The dissipation rate of turbulent kinetic energy referred to the energy released during particle collision process, and thus was also used to measure the amount of dissipated energy during energy transferring process.

Simulation results

The object of our numerical simulation was the vortex clarifier tank reaction zone.

The adopted boundary conditions were: water input was set at $8m^3/h$. For the clarifier tank without vortex reactors (the working condition one), the water flow rate was set at 0.79m/s, with a turbulence intensity at 4%. By contrast, for the clarifier tank with vortex reactors (the working condition two), the water flow rate was set at 0.79m/s, with a turbulence intensity at 4.17%. The numerical simulation image that showed how water body passed through the vortex clarifier tank reaction zone was displayed as follows:

Figure 6 was the velocity vector diagram of the first reaction zone of the vortex clarifier tank under working condition 1, which reflected the general distributions of tiny whirlpools. Because flow velocity was very high at the entrance, the change of velocity was dramatic for the whole tank. Specifically, velocity vectors were around the entrance, leading to entrainment effect. Because the size and the direction of water flow around the entrance varied a lot, obvious whirlpool was developed to facilitate an intensive mixture of raw water and coagulants, and thus to provide necessary conditions for the following flocculation reaction. Also, it could be seen that water flow velocity gradually slowed down after water flow passed through both reaction chambers, which thus created essential conditions for the collisions of tiny alum that formed during the initial flocculation stage, and the development of alum with larger size and higher compaction level.

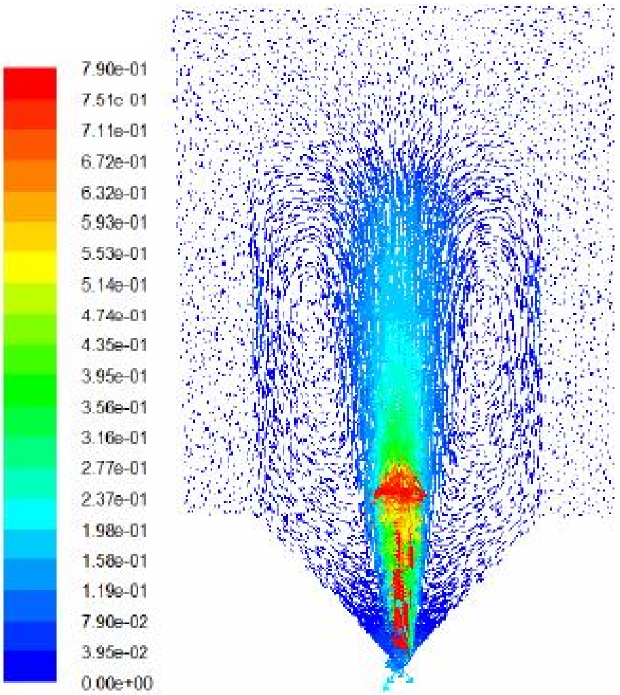

Figure 6 : The velocity vector of reaction zone under the working condition one

Figure 7 was the velocity vector diagram of the first reaction zone of the vortex clarifier tank under working condition 2, which was used to observe water flow patterns. It could be seen from this figure that the inlet velocity was relatively higher. After water flow reached vortex reactors, corresponding velocity decreased significantly. Numerous tiny whirlpools were developed, no matter whether water flow passed through vortex reactors directly or through gaps among reactors.

Also, more whirlpools with different sizes were formed under the working condition two than under the working condition one. This is because vortex reactors were installed in the middle of the tank to reduce the inlet velocity, which then facilitated the formation of whirlpools with different sizes and turbulence. Because the surface of vortex reactors was with a certain level of roughness, when water flow passed through the surface, many small-sized whirlpools were formed. Meanwhile, the internal and external velocity of vortex reactors varied to such a large extent that a certain velocity gradient was formed to facilitate the flocculation process. Turbulence could be considered as the result of different sized-whirlpools superimposed on the average velocity rate. According to Kolmogorov's theory of turbulence and the energy spectrum[6], the energy of the fluid exists within flow whirlpools, and is positively related to the size of whirlpools. When the size of whirlpools is similar to that of floc particles, flocculation reaction occurs at its peak level. Therefore, compared to working condition one, working condition two was better for the effective collisions among particles, and thus was more likely to enhance the flocculation effect.

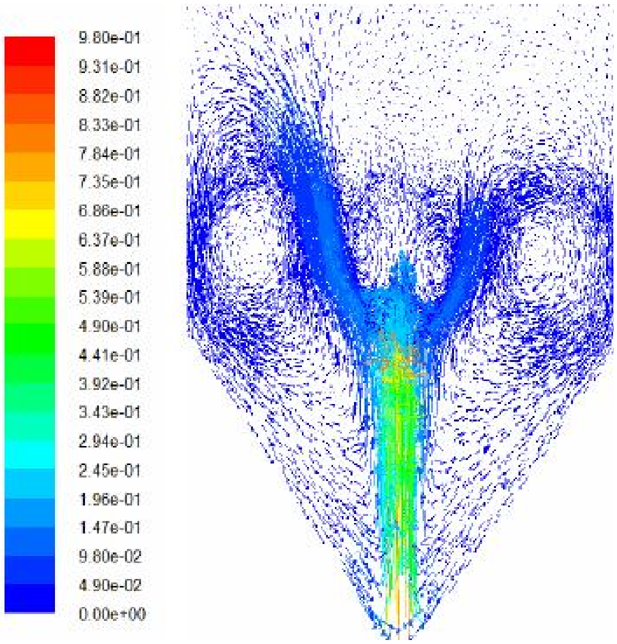

Figure 7 : The velocity vector of reaction zone under the working condition two

A COMPARISON BETWEEN EXPERIMENTAL TESTS AND NUMERICAL SIMULATIONS

For the field test results, a significant difference regarding turbidity removal efficiency existed between clarifier tanks with and without vortex reactors installed. To explain for this difference, we calculated turbulent kinetic energy k and kinetic energy dissipation rate ε when numeric simulations were applied to obtain three-dimensional flow field. Five cross-sections with different height were chosen from the model. The center axis fell in the middle of the clarifier tank, and the height of five cross-sections was (from the top to the bottom)-

0.4m, -0.5m, -0.6m, -0.8m and -0.9m, respectively. -

By selecting cross-sections with different height within the first reaction chamber, we obtained some parameter values based on numerical simulations.

Figure 8 showed the average change curve of cross-section velocity v with different height at the first reaction chamber. The corresponding velocity was two times higher under working condition 1 than that under working condition 2. With an increase of inlet flow input, corresponding slope values increased as well. As water flow passed through the tapered region and reached the position (1.2m) of the first reaction chamber, the slope value was significantly decreased, and this change of velocity curve was especially obvious under working condition one.

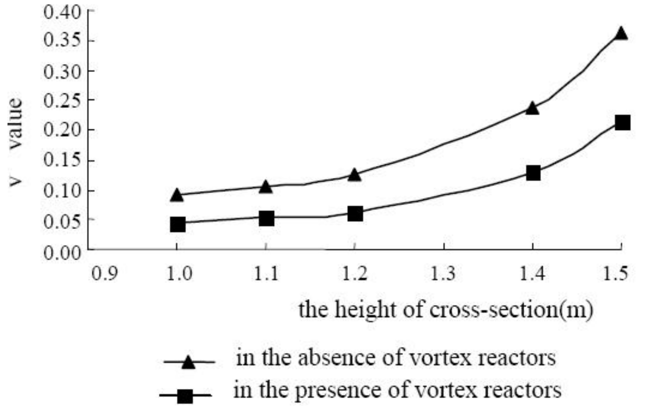

Figure 8 : The surface average curve of velocity in the first reaction zone of different cross-section

It could be seen from Figures 9 and 10 that as water flow reached the first reaction chamber through the tapered region, both turbulent kinetic energy k and turbulent kinetic energy dissipation rate ε under working condition one was significantly higher than that under working condition two. According to the theory of flocculation, the structure of floc particles was with large size and porous properties. At this stage, these particles were more likely to broke down under strong shear force. As a result, the clarifier tank without vortex reactors installed consumed more energy than the clarifier tank with vortex reactors installed. Also, compared to the tank with vortex reactors installed, floc particles were more likely to be broken with strong shear force and turbulent kinetic energy present when the clarifier tank did not have vortex reactors installed, which would then affect water quality.

The results also showed that with the same water turbidity conditions, more flocculants were required for working condition one. In contrast, working condition two had a better treatment effect with less chemical applied and higher functional efficiency. Under working condition one, the displayed jet flow, the velocity v, the turbulent kinetic energy k, and the turbulent kinetic energy dissipation rate ε were all with large values. Therefore, strong water shear force could easily break down floc particles and thus affect water flow effect. In contrast, due to the installation of vortex reactors for the case of working condition two, water flow encountered obstacles with flow velocity dramatically reduced, resulting in many micro-eddy currents with different sizes. The centrifugal force caused by the rotation action of eddy currents led to the radial movement of particles along a vortex axis, thereby increasing the collision probability of particles. As a consequence, a large quantify of alum flakes accumulated within the internal of vortex reactors. When these flakes were in contact with de-

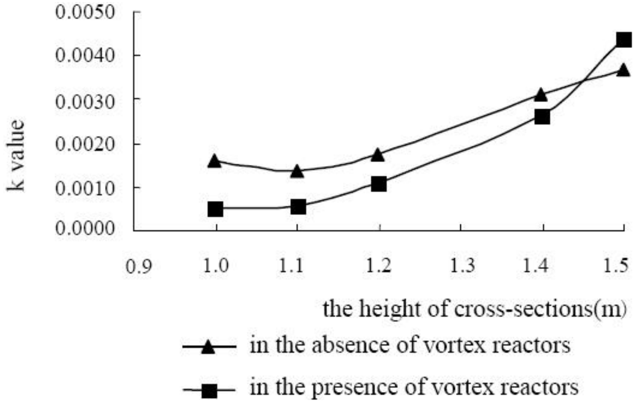

Figure 9 : The surface average curve of turbulent kinetic energy in the first reaction zone of different cross-section

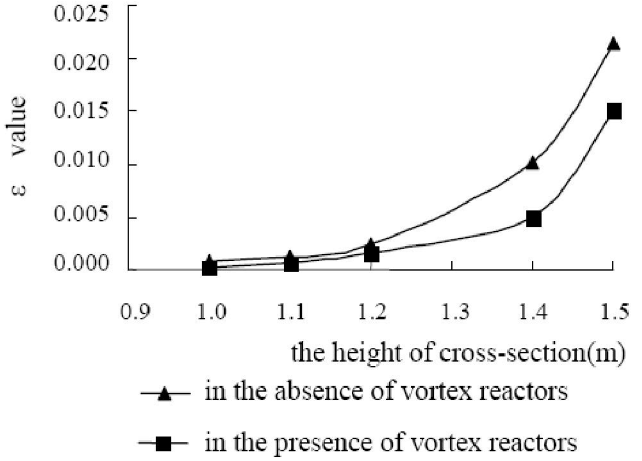

Figure 10 : The surface average curve of turbulent kinetic energy dissipation rate in the first reaction zone

stabilization gels in the water body, alum flakes got attached to these gels, followed by a dramatic increase in their sizes, which could then be broken into smaller pieces by water flow shear force. The installation of vortex reactors in the coagulation reaction zone dramatically reduced the quantity of flocculants required, and outflow water quality was better as well when compared to the reaction zone without vortex reactors installed[7].

CONCLUSIONS

Field experiments showed that given the same conditions, turbidity removal effect was better in the reaction zone with vortex reactors installed (the working condition two) than that in the reaction zone without vortex reactors installed (the working condition one). When the amount of chemical dosage and water flow were equal, outflow water quality was better for the working condition two than that of the working condition one. When the water turbidity was used as an indicator, nearly 30% of the flocculant dosage was saved for the working condition two than that of the working condition one. Fluent was used to simulate the flow field conditions of the vortex clarifier reaction zone, and to obtain detailed information, such as local flow velocity, short-circuit flow patterns, running tracks and so on. With an installation of vortex reactors, many micro-eddy currents were formed, which then created necessary conditions for effective collisions among particles. As a result, flocculation effect was better with more condensed floc particles in larger size, and outflow water quality was also dramatically improved.

Both field test and numerical simulations showed that turbidity removal efficiency was better for the working condition two than that of the working condition one, which also demonstrated, to some extent, the feasibility and correctness of the numerical model that we used. Compared with the field test, the numerical simulation method is faster and less costly. Therefore, further studies should be conducted on the application of numerical simulations on solving of practical engineering problems. Specifically, more sophisticated theories and advanced numerical algorithms are required to establish more versatile mathematical models to serve the purpose that results obtained from numerical simulations are closer to the actual situations. Therefore, predictive results from numerical simulations are more reliable and important in engineering practice. Moreover, an in-depth understanding of flow characteristics from the microscopic point of view could provide a new research approach for ûocculation kinetics.

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