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Study of the Influencing Factors of Sedimentation Separation of Polymer-Contained Sewage in Gravity Sedimentation Tank

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ABSTRACT

Gravity sedimentation tank is one of the key equipment in the process of oil field sewage treatment, whose separation performance directly affects the treatment efficiency. Polymer-contained sewage is difficult to deal with for its characteristics of large viscous and serious oil-water emulsification. In order to improve the treatment efficiency, we carried out a series of numerical simulation and experimental researches to analyse the separation law and the influencing factors of polymer-contained sewage in gravity sedimentation tank. The results show that flow vortexes exist in the gravity sedimentation tank, and the aqueous phase envelops part of the oil droplets, flows out of the tank from the water-outlet, thus affecting the treatment efficiency. The oil content and suspended solid content in the treated sewage decrease with the prolonging of the sedimentation time. With the increasing of polymer concentration in the raw water, the diameter of emulsifying oil droplets become smaller and the oil removal rate decreases at the same sedimentation time. By prolonging the sedimentation time appropriately, the treatment efficiency of the polymer-contained sewage can be improved.

INTRODUCTION

Generally, oil production sewage is treated by gravity sedimentation and filtration (Li 2008). After reaching the treatment standard, the sewage will be injected back into the formation to reduce environmental pollution and enhanced oil recovery. Gravity sedimentation tank is one of the key equipments in the process. It has the advantages of simple structure, large amount of treatment and so on. In order to improve the efficiency of the tank, scholars have done many relevant researches (Mahdi 2012, Lakehal 2009, Kokal 2006, Wang 2006).

In terms of theoretical research, scholars generally believe that the oil droplets are subjected to gravity, buoyancy and resistance in the water, and mathematical models are established (Patricia 2008, Tamayol 2008, Simmons 2002). Lu (1998) analysed the force, movement and trajectory of the oil droplets in the water based on droplet dynamics theory. He believes that the relevant force analysis in oil-water gravity separation process can be calculated by Stokes solution directly. The acceleration effect in the process of gravity sedimentation can be neglected, and the terminal sedimentation velocity can be used in the calculation of droplets movement. In the experimental research, the oil droplets floating up law in the oil-water gravity separation is studied through simulating the experiment device. The results show that the oil-water mixture has a strong turbulence around the inlet, and oil-water two phase exists vertical mixing in some degree (Sun et al. 2009). Relatively stable flow field of sedimentation area benefits the large diameter oil droplets float to the top to form oil layer.

In the treatment of water flooding oil production sewage, the existing process and equipments have achieved good results. While polymer flooding oil production sewage has the characteristics of high viscosity, serious oil-water emulsification, strong ability of carrying suspended solids, strong resistance of oil droplets and suspended solid in floating or sinking. These cause a bad treatment effect of gravity sedimentation tank, as well as a lower treatment quantity, so it is difficult to meet the production requirements. Therefore, scholars do relevant researches on the polymer flooding oil production sewage to improve the treatment efficiency (Zhou 2009, Zhang 2007, Ma 2013).

The wetting coalescence technology is introduced into the sedimentation process and a coalescing oil-water separator is developed (Chen 2008). Combining the coalescing oil-water separator and filter equipment, polymer flooding oil production sewage is disposed, and oil and suspended solid are well removed. The new process designed in research is that the raw water passes through a coalescence reactor with a pro-oil filter firstly to enhance oil droplets collision coalescence, then sedimentation and filtration processes are conducted.

In this paper, numerical simulation and experimental research methods are conducted to analyse the influencing factors and the law of sedimentation separation in the gravity sedimentation tank. It is also based on CFD calculation results to analyse the flow field of oil-water separation process and its influencing factors on separation effect to guide the laboratory experiments and verify the reliability of the numerical simulation results.

NUMERICAL INVESTIGATIONS

The oil droplets calculated in the Lagrangian frame are discrete particles. By calculating the continuous phase flow field and combining with the flow field variables to solve the stress of each particle, the velocity of particles is obtained and the trajectory of each particle is tracked (Brennan 2001, Goula 2008). This deterministic trajectory model assumes that the particles do not interfere with each other and do not have the concept of particle turbulent diffusion. However, in fact, the turbulent diffusion of particles does not only exist, but also plays an important role in the calculation. Therefore, the interaction between particles and turbulence needs to be considered in the model, the calculation is carried out by the particle random trajectory model or the particle cloud model. Particle random trajectory model adopts the random method to consider the influence of the instantaneous turbulent velocity on the particle trajectory. The particle cloud model is to track an average trajectory determined by the statistical average value. The distribution of particle concentration in the particle group is assumed to obey the Gauss probability distribution function, the development and changing process of particles is also expressed by probability. Because the low oil concentration is 5% in the process of gravity separation, the oil droplets do not aggregate to form particle group. Therefore, the particle random trajectory model is used to simulate the movement law of discrete phase oil droplets.

Mathematical Model

Basic control equations

(1) Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \vec{u})=0 \qquad ...(1)$$

(2) Momentum equation

$$\frac{\partial(\rho u)}{\partial t} + \mathrm{div}(\rho u \vec{u})=\mathrm{div}(\mu \mathrm{grad} u) - \frac{\partial p}{\partial x} + S_u \qquad ...(2)$$

$$\frac{\partial(\rho v)}{\partial t} + \mathrm{div}(\rho v \vec{u})=\mathrm{div}(\mu \mathrm{grad} v) - \frac{\partial p}{\partial y} + S_v \qquad ...(3)$$

$$\frac{\partial(\rho w)}{\partial t} + \mathrm{div}(\rho w \vec{u})=\mathrm{div}(\mu \mathrm{grad} w) - \frac{\partial p}{\partial z} + S_w \qquad ...(4)$$

***Turbulence model*:** The flow characteristics of gravity sedimentation tank is complex. Therefore, the RNG $k-\varepsilon$ turbulent model is suitable for the high strain rate and large curvature streamline.

(1) Turbulent kinetic energy equation

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(a_k \mu_{eff} \frac{\partial k}{\partial x_j}\right) + G_k + \rho\varepsilon \qquad ...(5)$$

(2) Turbulent diffusion term equation

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left(a_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right) + \frac{C^*_{1\varepsilon}\varepsilon}{k} G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad ...(6)$$

Where, $\mu_{eff} = \mu + \mu_t$, $\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$, $C_\mu = 0.0845$,

$a_k = a_\varepsilon = 1.39$, $C^*_{1\varepsilon} = C_{1\varepsilon} - \frac{\eta(1-\eta/\eta_0)}{1+\beta\eta^3}$,

$C_{1\varepsilon} = 1.42$, $C_{2\varepsilon} = 1.68$, $\eta = (2E_{ij} \cdot E_{ij})^{1/2}\frac{k}{\varepsilon}$,

$E_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$, $\eta_0 = 4.377$, $\beta = 0.012$.

Discrete phase model

(1) The single particle motion control equation

Derived from the second law of Newton,

$$m_p \frac{d_p v_p}{d_l} = F_D + F_G \qquad ...(7)$$

In the oil-water gravity separation process, densities of the two phase are similar and the gravity plays an important role:

$$F_G = g(\rho - \rho_p) \qquad ...(8)$$

In addition, the drag force which aqueous phase impose on oil droplets:

$$F_D = C_D A \frac{\rho}{2}(u - v_p)\left|u - v_p\right| \qquad ...(9)$$

Where, C_D is the resistance coefficient,

$$C_D=0.424 \qquad \mathrm{Re}_p > 1000 \qquad ...(10)$$

Where, Re_p is Reynolds number of particle, defined as

$$\mathrm{Re}_p = \frac{\rho d_p \left|u - v_p\right|}{\mu} \qquad ...(11)$$

(2) Particle random trajectory model

Due to the influence of turbulence, fluid has fluctuating velocity at each moment and direction. Fluctuation velocity of fluid influences the velocity and locations of particles in the flow field all the time, so the influence of turbulent fluctuation must be considered in the calculation. The instantaneous velocity of fluid is the sum of the average velocity and the turbulent fluctuation velocity. Thus, the particle random trajectory model are:

$$\frac{dv_{px}}{d_t} = \frac{1}{\tau}(u + u' - v_{px}) \quad ...(12)$$

$$\frac{dv_{py}}{d_t} = \frac{1}{\tau}(v + v' - v_{py}) \quad ...(13)$$

$$\frac{dv_{pz}}{d_t} = \frac{1}{\tau}(w + w' - v_{pz}) \quad ...(14)$$

Where, relaxation time of particles is $\tau_p = \frac{\rho_p d_p{}^2}{18\mu}$, presenting the turbulent diffusion characteristics of particles. u' and other parameters can be obtained by turbulent kinetic energy:

$$u' = \zeta\sqrt{\frac{2}{3}k}\,, v' = \zeta\sqrt{\frac{2}{3}k}\,, w' = \zeta\sqrt{\frac{2}{3}k} \quad ...(15)$$

Where, ζ is the random number, $-1 \le \zeta \le 1$. The fluctuating velocity obtained by the above formula satisfies the Gauss distribution.

(3) Interaction between discrete and continuous phase

In the study, it can be considered that sparse particles move in continuous phase for oil concentration is only 5%, particles are far away from each other and collision chance is small, so the actions between particles need not to be considered. In the calculation, considering the coupling interaction of the two-phase, when the particle passes through the control body of each continuous phase, the momentum value of continuous phase transfers to discrete particle can be calculated by the momentum change of the particle. The particle momentum changing value can be calculated according to the following formula.

$$F = \sum\left[\frac{18\mu C_D Re_p}{24\rho_p d_p^2}\left(v_p - u\right)\right]\dot{m}\Delta t \quad ...(16)$$

This momentum exchange is used as the momentum source to calculate the following flow field of the continuous phase, thus, the effect of particle on the continuous phase is obtained, and the coupling calculation is realized.

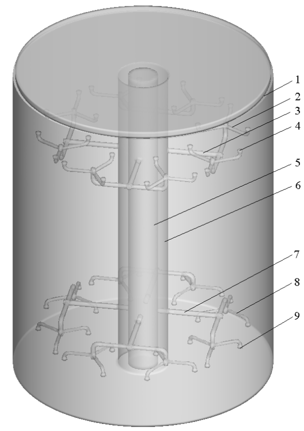

Fig. 1: Geometric model.

1- oil-outlet; 2- water branch pipe; 3- water main pipe; 4- inlet; 5- center column cylinder; 6- center reaction drum; 7- water collecting main pipe; 8- water collecting branch pipe; 9- water-outlet

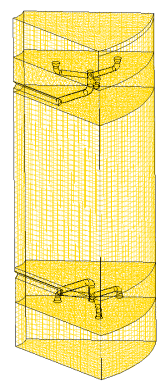

Fig. 2: Discrete grid.

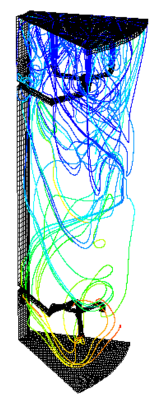

Fig. 3: Movement trajectories of oil droplets.

The nomenclature used in the mathematical model are given in Table 1.

Geometric Model and Mesh

Fig. 1 is the geometric model of the 1200 m^3 gravity sedimentation tank. Considering the cost of numerical simulation, based on the symmetry of the geometric model, a 1/8 model is selected as numerical model, while the boundary between adjacent bodies is defined as symmetry. The mesh is shown in Fig. 2.

Physical Properties

The physical properties of different polymer flooding oil production sewage are mainly embodied in the oil droplets diameter and polymer concentration. According to the results of physical property tests of polymer flooding oil production sewage, three kinds of simulated water are defined and the specific physical property are given in Table 2.

Table 1: Nomenclature.

ρ	First phase density	d_l	First phase droplet diameter
t	Time	F_D	Drag force
$\vec{u}$	Velocity vector	F_G	Volume force
u, v, w	Velocity component	C_D	Resistance coefficient, 0.424
p	Differential pressure	Re_p	Particle Reynolds number
μ	First phase dynamic viscosity	ρ_p	Particle density
λ	Constant, −2/3	τ_p	Particle relaxation time
S_u、S_v、S_w	Source term	ζ	The random number, [-1,1]
m_p	Particle weight	$\dot{m}$	Particle mass flow
d_p	Particle diameter	Δt	Time interval
v_p	Particle velocity		

Table 2: The physical properties of simulated water.

	Properties of continuous phase (water)		Properties of the discrete phase (oil)			
	Density (kg/m^3)	Dynamic viscosity (mPa·s)	Density (kg/m^3)	Dynamic viscosity (mPa·s)	Diameter (μm)	Volume concentration (%)
Sample 1	998.2	2.0	866.0	22.5	40.0	5.0
Sample 2	998.2	4.0	866.0	22.5	30.0	5.0
Sample 3	998.2	8.0	866.0	22.5	25.0	5.0

Table 3: The raw water quality (May 2014).

Station	Oil content (mg/L)	Suspended solid content(mg/L)	Polymer concentration(mg/L)	Viscosity (mPa·s)
B1	291.0	88.6	73.71	1.1
B2	207.3	40.5	158.30	1.1
B3	212.5	44.6	374.63	1.3
B4	203.8	109.7	725.91	3.7
B5	218.1	121.3	1343.39	5.8

Solving Method

The finite volume method is used for numerical discretization, and the control equations are converted into algebraic equations which can be solved by numerical methods. SIMPLEC algorithm is used for pressure velocity coupling. PRESTO format is used for pressure gradient items. For the space discretization, a central difference scheme with two order accuracy is used in diffusion terms, and QUICK format is used in the discretization of the convection term, and a first order implicit scheme is used for the discretization of the time term.

EXPERIMENTAL RESEARCH

In laboratory experiments, the separation characteristics and influencing factors of polymer flooding oil production sewage are studied with different oil content, suspended solid content, and polymer concentration. The B1~B5 sewage station with large differences in water quality is selected in a production area of Daqing oil field. The untreated sewage from the one-level gravity sedimentation tank of each station is sampled to carry out the experiment. The raw water quality is given in Table 3.

In the actual production, the gravity sedimentation tank keeps a constant temperature of 40°C, and sedimentation time is 6~12h. Thus, the experimental program is designed as follows. Under the constant temperature condition of 40°C, the sewage is settled in the glass sedimentation column. At times of 0, 2, 4, 6, 8, 10, 12, 18, 24h, samples are taken from the lower part of the column. By analysing the oil content and suspended solid content in the water, we know how the

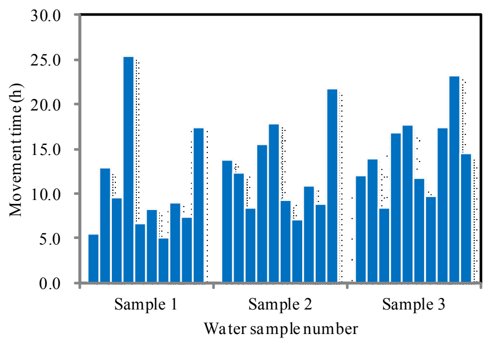

Fig. 4: Movement time.

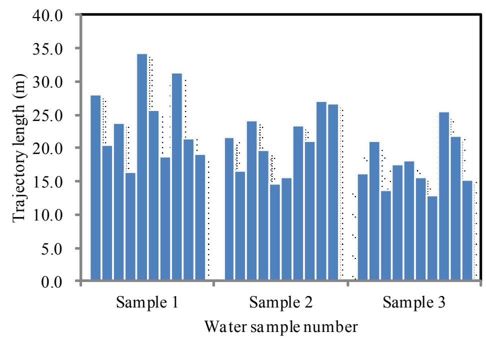

Fig. 5: Trajectory length.

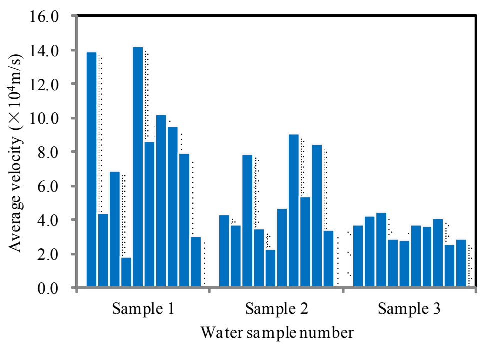

Fig. 6: Average velocity.

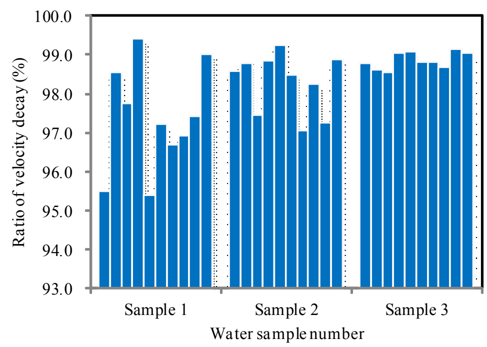

Fig. 7: Ratio of velocity decay.

polymer concentration, oil droplets diameter and sedimentation time affect the treatment effect.

RESULTS AND DISCUSSION

Movement Characteristics of Oil Droplets

Movement trajectory: The trajectory of the discrete phase oil droplets in the gravity sedimentation tank is an objective description of the process and effect for the oil-water gravity separation. By simulation, oil droplets trajectory can be obtained intuitively which is difficult to be measured in actual production. Take water sample 1 (Fig. 3) as an example, a large number of oil droplets get into the gravity sedimentation tank from the inlet, and then move to the top of the tank. The trajectory is disordered and a part of the oil droplets flow out of the tank through the oil-outlet. However, there exists a considerable portion of oil droplets which do the winding and downward movement and flow out of the tank through the water-outlet. These oil droplets do not separate with water under the action of buoyancy. They flow out of the tank through the water-outlet enveloped by aqueous phase. As a result, oil and water do not separate from each other completely in the tank.

The calculated three kinds of water samples release 72 oil droplets respectively. The oil removal rate obtained by counting the quantity of oil droplets flow out of the tank from the oil-outlet is 51.3%, 46.1% and 38.6% respectively. With the increase of water samples viscosity, the diameter of oil droplets become smaller, and it is more difficult for oil droplets to separate from the water. Aqueous phase with high viscosity envelopes more oil droplets to escape from the water-outlet instead of floating up to the top of the tank and leave from oil-outlet, leading to the decline of oil removal rate.

Movement distance and time: The position of each oil droplet at different times can be obtained by the discrete phase model, and the trajectory length and movement time of the oil droplets are obtained after the treatment. In each water sample, 10 oil droplets, which escaped from water-outlet, are randomly selected to study the movement characteristics.

The distribution of movement time of 10 oil droplets, which are randomly selected in the tank of water sample, one is shown in Fig. 4. The movement time of the oil droplet 4 is the longest, reaching 25.5h, and the movement time of the oil droplet 7 is the shortest, which is 5.1h. The theoretical sedimentation time of oil-water mixture in the tank is 10h under this treatment capacity. However, the oil droplets are not in accordance with the ideal state of 10h sedimentation, the sedimentation time of 30% oil droplets is

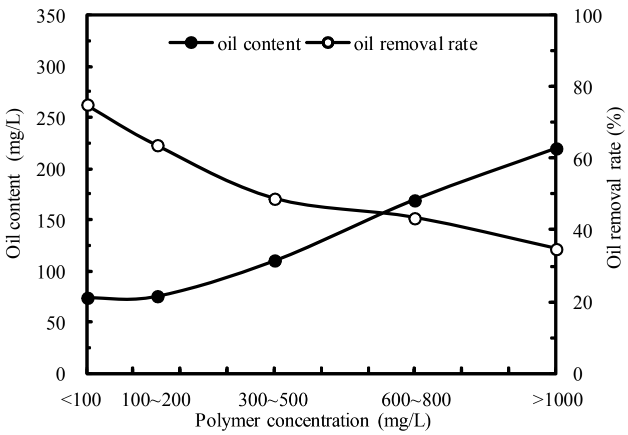

Fig. 8: Effect of polymer concentration on the oil content and oil removal rate in water. (static sedimentation for 10h)

more than 10h. With the viscosity increase of the water samples two and three, the sedimentation time of oil droplets in the tank is gradually prolonged, sedimentation time of 60%~80% oil droplets is more than 10h. Improving the sedimentation time does not have the same effects on each oil droplet. With the increase of the viscosity of water quality, it is more and more difficult to improve the separation effect of oil and water by merely prolonging sedimentation time.

Fig. 5 shows that the length of movement trajectory of oil droplets is larger than the height of the tank which is 13.39m. The average trajectory length of oil droplets in water sample 1 is 23.99m. The trajectory length of oil droplet 5 is the longest, reaching 34.3m. It shows that the oil droplets do not carry out the ideal vertical sedimentation movement. In fact, they carry out rotary and back mixing movement, suggesting that there exist flow vortexes in some areas of the tank. With the increase of the water viscosity, and the trajectory length of oil droplets in the tank slightly decrease, the average trajectory length of oil droplets in water sample 2 and 3 are 21.09m and 17.81m respectively.

In water sample 1, oil droplet 4 has the longest movement time and oil droplet 5 has the longest trajectory length. However, their respective movement distances and time are not directly proportional. Fig. 6 shows that the oil droplets average velocity of each water sample is inhomogeneous, and the highest and lowest speed even differ in an order of magnitude. The maximum average velocity of water sample 1 (oil droplet 5) is 7.9 times of the minimum value (oil droplet 4). It also confirms the existence of the mixed flow and swirl flow in the tank. With the increase of water viscosity, the oil droplets average velocity of three kinds of water samples shows a downward trend, which is 8.07×10^{-4} m/s, 5.28×10^{-4} m/s and 3.51×10^{-4} m/s respectively.

As shown in Fig. 7, the velocity field in the tank changes dramatically. The oil droplets of three water samples flowing into the tank produce a great decay and are all exceeding 90%. Define the velocity decay ratio of 98% as the limit, there are 3, 7 and 10 oil droplets over the limits respectively. With the increase of aqueous phase viscosity, the velocity decay of oil droplets is more severe.

Studying from four aspects of movement time, trajectory length, average velocity and velocity decay, numerical simulation results reveal the influence of water quality, viscosity, oil droplets diameter and flow field on the movement of oil droplets in polymer flooding sewage gravity sedimentation tank. The results of numerical simulation are taken to guide indoor experiments to study the law of gravity separation and its influencing factors, and the rationality of the numerical simulation results are verified.

The Influencing Factors of Gravity Separation

Polymer concentration: Fig. 8 shows that with the increase of polymer concentration of raw water, the oil content of the treated water shows an increasing trend after the same sedimentation time (10h). This is due to the increase of polymer concentration leading to water viscosity increase, as well as the viscous force between oil droplets and water. It is difficult for the oil droplets to float. So the oil droplets form a relatively stable dispersion system in the aqueous phase. Therefore, the graph shows that with the increase of polymer concentration, the oil removal rate decreases. When the polymer concentration of raw water increases from 73.71mg/L to 1343.39mg/L, the oil removal rate decreases from 74.62% to 34.96%.

Oil droplets diameter: Fig. 9 shows the diameter distribution of oil droplets of the raw water in B1~B3 station. With the increase of the polymer concentration, the distribution characteristic width and median diameter of oil droplets in water becomes smaller. The median diameter of three kinds of water samples (73.71mg/L, 158.30mg/L, 374.63mg/L) are 41.71, 26.20 and 22.47 μm respectively.

As shown in Fig. 10, after the sedimentation of 10 hours, the distribution of oil droplets diameter in water is still wide and the median diameters of residual oil droplets are generally smaller, which are 19.46, 17.76 and 14.15μm. This illustrates that in the gravity separation, the residence time of large diameter oil droplets in glass sedimentation column is shorter. It is easier to float up to the liquid surface and be removed. The B1 station has a lower polymer concentration in raw water and the median diameter of oil droplets is larger. Compared with the other two stations, more oil droplets with larger diameter are removed by sedimentation, so its oil removal rate is the highest, reaching 74.62%, while oil

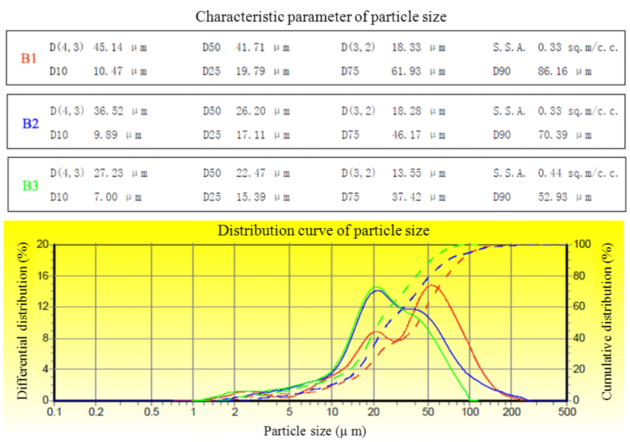

Fig. 9: The diameter distribution of oil droplets in raw water.

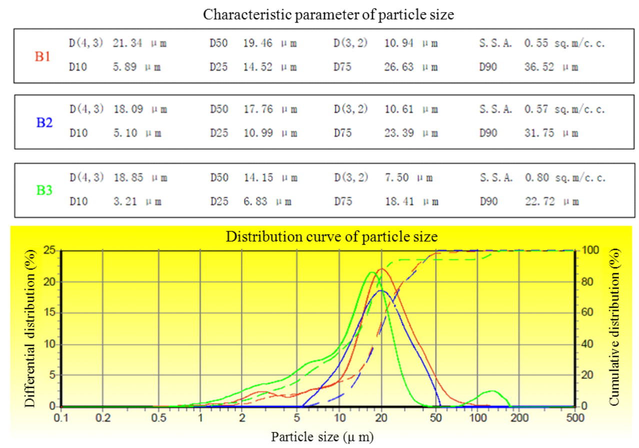

Fig. 10: Diameter distribution of oil droplets after static sedimentation for 10h.

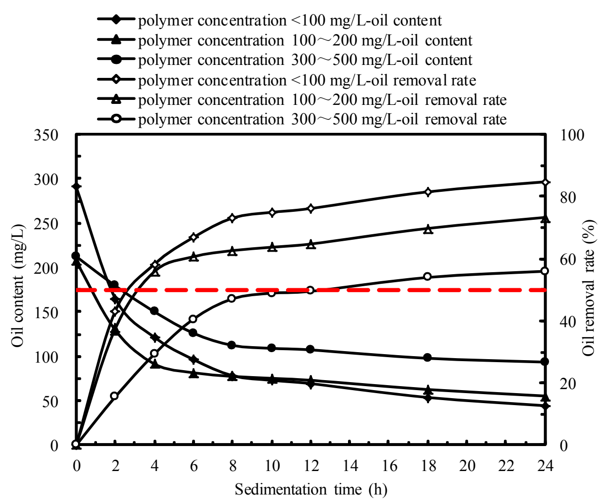

Fig. 11: Oil content changes with the sedimentation time.

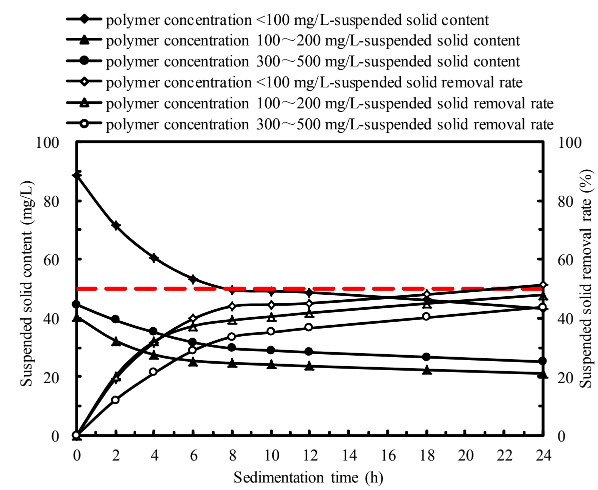

Fig. 12: Suspended solid content changes with sedimentation time.

removal rates of B2 and B3 stations are relatively low at 63.68% and 48.31%.

Sedimentation time: ***Oil content changes with the sedimentation time:*** As shown in Fig. 11, the oil content in water decreases with the sedimentation time. With the increase of the polymer concentration in water, the separation efficiency decreases at the same sedimentation time. After sedimentation for 10h, the oil removal rate of the three kinds of water samples (73.71mg/L, 158.30mg/L, 374.63mg/L) is 74.62%, 63.68% and 48.31% respectively.

Suspended solid content changes with sedimentation time: As shown in Fig. 12, the suspended solid content in water decreases with the sedimentation. When the polymer concentration in water is different, the changing characteristics of suspended solid content with sedimentation time are different. With the increase of polymer concentration, the separation efficiency decreases at the same sedimentation time. After sedimentation for 10h, the suspended solid removal rate of the three kinds of water samples (73.71mg/L, 158.30mg/L and 374.63mg/L) is 44.53%, 40.49% and 35.09% respectively.

Oil droplets diameter distribution changes with sedimentation time: As shown in Fig. 13, with the sedimentation process continues, the median diameter of oil droplets in 0~10h decreases rapidly, and more oil droplets are separated from water. After sedimentation for more than 10h, the changing speed of median diameter of oil droplets turns down, and the median diameter value gradually tends to be a fixed value. These results indicate that, for sewage with high concentration of polymer, the oil-water separation effect cannot be improved continuously and significantly only by extending physical sedimentation time. After a long

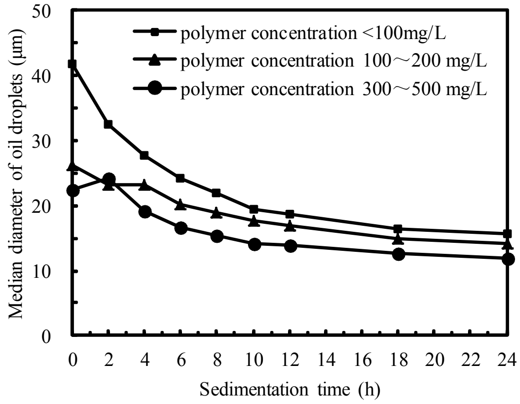

Fig. 13: Distribution of oil droplets diameter changes with sedimentation time.

sedimentation time, the distribution of oil droplets diameter is still wide (Fig. 9, Fig. 10), the median diameter is smaller relatively, and the remaining oil droplets are difficult to separate from sewage.

CONCLUSIONS

The movement trajectory of oil droplets in the gravity sedimentation tank is simulated and analysed by using the discrete phase model. Oil droplets carry out rotary and back mixing movement, and swirl flows exists in some areas of the tank. Aqueous phase envelopes part of the oil droplets flowing out of the tank from the water-outlet, oil-water cannot be separated completely, influencing the treatment effect. The numerical simulation and experimental research both show that the oil content and suspended solid content in the treated sewage decreases with the prolonging of the sedimentation time. However, if the sedimentation time is too long, the median diameter of oil droplets becomes smaller, the distribution of oil droplets diameter is still wide which makes it more difficult to be treated and the improvement of treatment effect is not obvious. With the increase of polymer concentration in raw water, the oil-water emulsion is more serious, and the diameter of oil droplets becomes smaller. Besides, the oil removal rate decreases at the same sedimentation time.

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