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NOTE

A Study of Kinetics on Induced-Air Flotation for Oil–Water Separation

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INTRODUCTION

Induced-air flotation makes use of the centrifugal force of a high-speed backspin impeller through which gas is introduced at the top and liquid at the bottom. The gas and liquid become fully intermingled and, after passing through a disperser outside the impeller, form a multitude of gas bubbles, thus completing the flotation separation process of a liquid–solid or liquid–liquid heterogeneous separation process of a liquid–solid or liquid–liquid heterogeneous system. The flotation machine used for treating oily sewage generally belongs to the four-cell series. Its good points are that the machine has a high removal efficiency for oil separation, shortens retention time, and has great treatment capacity. The device has been widely used in treating oily sewage in recent years (*1*, *2*). In order to provide a basis for establishing a method of design computation and for screening appropriate chemicals, this study was initiated to gain an understanding of the variables controlling the induced-air flotation process for oil–water separation. An experimental device for simulating tests has been developed. In order to analyze its mechanism, a kinetic model of oil–water separation has been put forward. By the use of the experimental result, correlative equations, which can estimate the parameters of the model, have been obtained.

MATHEMATICAL MODEL

Oil Removal Rate

The induced-air flotation system consists of four flotation cells. Oily sewage passes in series through various cells. A detailed drawing of the cell is shown in Fig. 1. An impeller with vertical paddles is located in the center with the axle. When the impeller spins, it introduces gas at the top and liquid at the bottom to give a mixture of gas and liquid which is then cleared out. When the gas and liquid pass through a multihole disperser outside the impeller, the tangential motion changes to radial motion, causing the gas to form minute bubbles. Oil particles and suspended solids come into contact with gas bubbles, become attached to the latter, and rise to the surface.

That the oil particles in the water inside the separation chamber can be carried by gas bubbles and caused to rise for separation is conditioned by (a) opportunities for contact and collision between oil particles and gas bubbles, and (b) the oil particles and gas bubbles that bump against each other must break through the water film so that the oil particles can enter the gas bubbles, become attached to them, and rise. Concerning the first condition, the probability of collision between oil particles and gas bubbles is proportional to the concentration of oil particles, so the oil removal kinetics can be expressed by an equation of the first-order type (*3*):

$$-dC/dt = k'C \tag{1}$$

However, this equation doesn't fit the results of experiments and the data of commercial units (*4*).

Concerning the second condition, in the case of smaller size oil particles, even when they come close to gas bubbles the kinetic energy they possess is still insufficient to squeeze out the water film between bubbles and oil particles, so that it is still impossible for oil particles to enter the bubbles and rise. Experiment has proved (*5*) that induced-air flotation is helpless in the face of oil particles smaller than 2 μm. Therefore, oil-removal kinetics through induced-air flotation should be expressed by a revised equation of the first-order type:

$$-dC/dt = k(C - C_L) \tag{2}$$

In this equation, C_L is the concentration of small oil particles which cannot be separated by induced-air flotation.

In regard to induced-air flotation of multistage series, the efficiency of

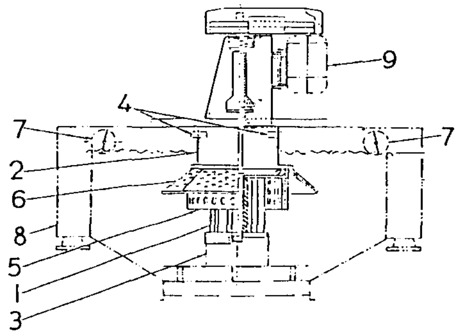

FIG. 1. Induced air flotation cell: (1) impeller, (2) gas intake pipe, (3) standpipe, (4) gas inlet, (5) disperser, (6) disperser hood, (7) skimmer paddles, (8) launder, (9) motor.

oil removal would be

$$\eta = 1 - \frac{1 + \frac{C_L}{C_0}[(1 + k\tau)^N - 1]}{(1 + k\tau)^N} \tag{3}$$

Kinetic Model of Oil–Water Separation

Because of the high-speed revolution of the impeller in the separation chamber, the velocity gradient in the flow leads to a relative motion between oil particles and gas bubbles, thereby producing chances for collision, i.e., the orthokinetic collision, as shown in Fig. 2(a). Only when oil particles enter the control volume, which has the center of gas bubbles as its center and $R = \frac{1}{2}(d_p + d_b)$ as its radius, is it possible for oil particles to collide with gas bubbles, as shown in Fig. 2(b).

Let the velocity gradient in the separation chamber be G and the number of bubbles per unit volume liquid be N_b. We derive

$$-\frac{dC}{dt} \propto G d_b^3 \left(1 + \frac{d_p}{d_b}\right)^3 N_b (C - C_L) \tag{4}$$

The void factor Φ is given by

$$\Phi = \frac{\pi}{6} d_b^3 N_b$$

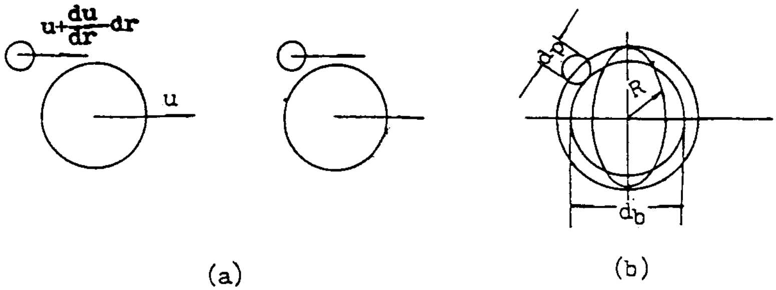

FIG. 2. The orthokinetic collision of oil particles and gas bubbles.

Hence,

$$-\frac{dC}{dt} \propto G\Phi\left(1 + \frac{d_p}{d_b}\right)^3 (C - C_L) \tag{5}$$

Compared with Eq. (2), we have

$$k = AG\Phi\left(1 + \frac{d_p}{d_b}\right)^3 (C - C_L) \tag{6}$$

On the basis of dimensional analysis, we also derive

$$G/n = A_1 \mathrm{Re}_L^a \tag{7}$$

$$\mathrm{Re}_L = \frac{nD^2\rho}{\mu}$$

Combining Eqs. (5) and (6), and letting $\zeta = AA_1$, we get

$$k = \zeta n\left(1 + \frac{d_p}{d_b}\right)^3 \mathrm{Re}_L^a \tag{8}$$

EXPERIMENT

The experimental device is shown in Fig. 3. It is a single-stage experimental unit. Its capacity is 3 L. Crude oil from the Daqing Oil Field is mixed with tap water and stirred violently to make an oil–water mixture. The oil concentration in water is measured through absorbance with a Model-UV-120-02 UV/VIS spectrometer at a wavelength of 380 nm. The

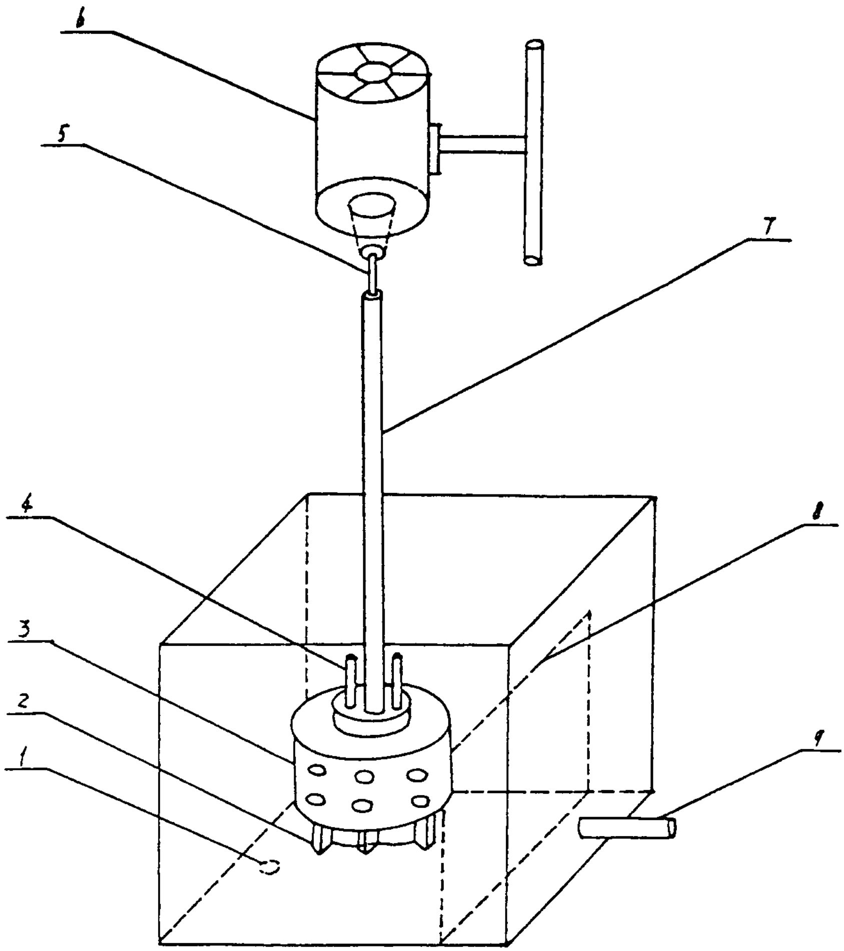

FIG. 3. The device for the experiment: (1) sampling pipe, (2) impeller, (3) disperser, (4) gas inlet pipe, (5) shaft, (6) motor, (7) shaft sleeve and bearings, (8) overflow lip, (9) foam outlet pipe.

size distribution of oil particles in water can be monitored by the disperse phase rise method. The diameters of gas bubbles in the water can be measured on a high-speed photograph. The gas flow rate so induced is measured with a gas meter.

EXPERIMENTAL RESULTS

Relationship for Estimating the Void Factor

By measuring the gas charging height under conditions of varying gas flow rate and static liquid height, the void factor Φ is

$$\Phi = \frac{H_g - H_s}{H_s} \tag{9}$$

It was found that Φ is associated with Fr_G, so it conforms to what is reported in the literature (*6*). From the results of the experiment, we have

$$\Phi = \frac{1.79 \times 10^4 Fr_G}{1 + 8.76 \times 10^4 Fr_G} \tag{10}$$

$$Fr_G = ug^2/gH_s$$

Parametric Estimation of Equation for Oil-Removing Kinetics

The experiment is performed in batches, hence, by Eq. (2):

$$C = (C_0 - C_L) \exp(-kt) + C_L \tag{11}$$

The oil concentration C was measured in water at different times t, iteration was done by the Newton method, and a least-squares estimation was performed to obtain the relevant parameters k and C_L.

Under conditions of different speeds of revolution, various initial oil concentrations, and various distributions of oil particles, experiments on 13 samples were conducted. The relative error of fitting of Eq. (11) was 13.3% at the maximum, and the mean figure was 4.4%.

If the limiting oil-removing concentration C_L is neglected, from Eq. (1) the oil concentration C at time t would be

$$C = C_0 \exp(-k't) \tag{12}$$

When the parameter k' is estimated by the same method, then the relative error is 56.4% at the maximum, and the mean figure is 13.9%. This shows that the kinetic model put forward in the present study conforms to the actual situation.

Parametric Estimation of Oil-Removing Rate Constant

When parameters ζ and a were estimated by the same method used for Eq. (8) under the condition of the nonaddition of chemicals, $\zeta = 7.06 \times 10^{-2}$ and $a = 1.09$. The relative errors of fitting both remain within 15%.

CONCLUSION

Through theoretical analysis, a mathematical kinetic model of induced-air flotation has been developed. Experimental data shows that the kinetic model provides a good fit with oil–water separation in induced-air flotation. This model can be used to predict oil removal efficiency and to evaluate the appropriate chemicals.

SYMBOLS

A	constant (—)
A_1	constant (—)
a	constant (—)
C	oil concentration (mg/L)
C_L	limiting oil concentration (mg/L)
C_0	oil concentration at beginning or inlet (mg/L)
D	diameter of impeller (m)
d_b	length—mean diameter of bubbles (m)
d_p	volume—mean diameter of oil particles (m)
Fr_G	Froude number (—)
G	velocity gradient (1/s)
g	accelerated velocity of gravity (m/s^2)
H_g	height of gas charged liquid (m)
H_s	height of static liquid (m)
k	oil removal rate constant (1/s)
k'	oil removal rate constant in Eqs. (1) and (12) (1/s)
N	number of flotation cells (—)
N_b	number of bubbles per unit volume liquid ($1/m^3$)
n	rotor speed (1/s)
Re_L	Reynolds number (—)
t	time (s)
ug	velocity of gas (m/s)

Greek Letters

η	oil removal efficiency (—)
μ	viscosity of liquid (Pa·s)
ζ	catching factor (—)
ρ	density of liquid (kg/m^3)
τ	retention time per cell (s)
Φ	void factor (—)

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