FLOTATION CLASSIFICATION APPROACH BY CONTROLLING INTERACTIONS BETWEEN PARTICLES①

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ABSTRACT A novel classification approach termed the flotation classification approach based on controlling interactions between particles was introduced. It differs considerably from the conventional classification processes operating on mechanical forces. During test, the micro-bubble flotation technology was grafted onto hydro-classification. Selective aggregation and dispersion of ultrafine particles have been achieved through governing the interactions in the classification process. A series of laboratory classification tests for $-44\ \mu m$ kaolin and $-22\ \mu m$ quartz have been conducted on a classification column. As a result, about $-10\ \mu m$ classifying product can be obtained from the feeds of kaolin and quartz. In addition, two criteria for the classification were set up. Finally, the theoretical model of flotation classification has been presented based on surface thermodynamics and hydrodynamics.

Key words flotation classification interactions theoretical model

1 INTRODUCTION

It is usually a strict requirement of special functional materials to have evenly distributed or even single particle clusters. Most of the traditional classifying approaches act on macro fields of physical force like gravity, inertia or centrifugal forces. These forces are of a certain proportion to the volume or the mass of the particles. The smaller the particle size is, the more difficult the classification is. At present, several special types of ultrafine classifiers with respective advantages have been designed and manufactured both at home and abroad, such as the intense whirling fluid classifiers, the mini-hydrocyclones and the field-flow classifiers, which, with the specially made devices, operate by increasing the intensity of mechanical force and enlarging the gaps of macro force fields between particles[1]. However, it would be very hard to achieve such gaps of macro force fields in colloid particles. Besides, there is a demand for high precision processing, high production cost and substantial energy consumption.

In the second half of the 1980s, scientists in Japan began to turn their eyes to a new area——micro forces and came up with an understanding of the importance of particle interaction to the classification. They have provided some classifying ways through controlling interactions[2]:

(1) The isopic aggregating classification; (2) The heteropic aggregating classification (A)——solid particle system with particles as carrier; (3) The heteropic aggregating classification (B)——solid-gas system with micro bubbles as carrier; (4) The electrophoresis classification.

At the moment, there have not been mature techniques to match these approaches. The author's opinion is that unless the particle interaction law is brought to light, real progress cannot be made in the classification

① Received Apr. 5, 1995; accepted Jun. 27, 1995

of ultrafine particles.

2 PRINCIPLES

Interactions between particles include electrostatic forces, Van der Waals forces, hydration-hydrophobic forces, steric forces, magnetic forces, hydrodynamic forces etc, which are connected with particle size[3]. The classical DLVO theory has successfully illustrated stability of colloid particles but has failed to describe aggregation and dispersion of hydrophobic-hydrophilic particles. However, the latest extended DLVO theory considering electrostatic forces, Van der waals forces together with hydration-hydrophobic forces can precisely describe the stability of hydrophobic-hydrophilic particles.

Dispersion, aggregation and flocculation are the forerunning techniques of looking into the problem of classification. The best classifying efficiency is achieved only when the particles are fully dispersed and stabilized. Therefore, it would be quite necessary and significant to start from interactions to study classification.

Flotation is undoubtedly the most important and versatile mineral separating processing technique on the tri-phase interface of solid-liquid-gas. Interactions between particles play an important role in the aggregation between the hydrophobic particles attached by reagents.

Similarly, chemical reagents are added to the classifying process to alter the surface properties between particles and disperse the particles fully.

In the meantime, micro-bubbles are used to carry particles. Thus, classification is also scientific technology separating on the tri-phase interface of solid-liquid-gas like flotation processing.

Generally speaking, the graft of flotation into classification makes it easier to control the dispersion and aggregation behavior of the particles. The tiny bubbles are good for the concentration of fine particles. The addition of froth allows the classified products to concentrate in the bubbles so that there is little moisture, which is favorable to the following processes: filtration and drying.

3 EXPERIMENT METHODS

The size of quartz product was under $-22\ \mu m$ and its analysis of substance phase is shown in Table 1. A sample of pure kaolin, which was obtained from Hengyang Jiapia kaolin company in Hunan province, was concentrated through immersing, pounding pulp, classifying, removing iron. Its analysis of substance phase is shown in Table 2.

Zeta potentials of kaolin and quartz were measured by the electrophoresis instrument produced by Brookhaven Company in America (Fig. 1). Particle size was measured by the laser size measuring instrument produced by Leeds Northrup Company in America.

The classifying device was a glass column whose length can be verified (Fig. 2). Minus $40\ \mu m$ micro-bubbles were produced by sintering glass split with many micro hole. Flow and pressure of air could be controlled to effectively raise particles with certain size. Reagents were used to control pulp condition.

Table 1 Analysis of quartz substance phase

Component	Al_2O_3	Fe_2O_3	SiO_2	TiO_2	K_2O
Content /%	98.38	0.0042	0.008	0.089	0.088

Table 2 Analysis of kaolin substance phase

Component	$A_{12}O_3$	Fe_2O_3	SiO_2	TiO_2	K_2O
Contenrt /%	28.24	0.65	56.20	0.24	0.23
Component	Na_2O	CaO	MgO	Consume	
Content /%	0.22	0.36	0.30	7.54	

Experiment methods are described as follows:

(1) Experiment of dispersion and aggregation

Inorganic electrolyte, pH regulators, dispersing reagents SP were added into the pulp; optimum conditions were determined for the

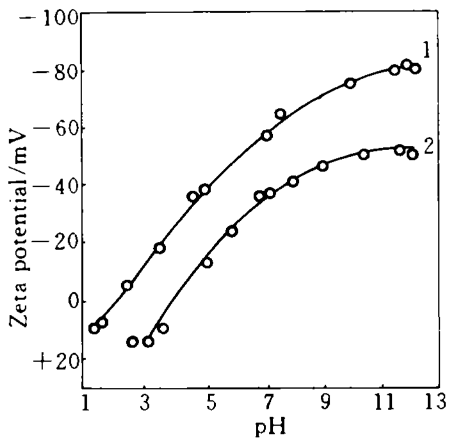

Fig. 1 Zeta potentials of kaolin and quartz in the range of pH 0～12
1—quartz; 2—kaolin

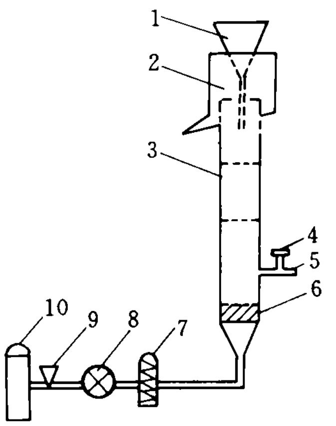

Fig. 2 Model of classifying device
1—funnel; 2—area of scraping froth; 3—classifying column; 4—on-off switch; 5—continual classifying feed pipe; 6—micro-bubble device; 7—rotor flowmeter; 8—pressure meter; 9—on-off switch; 10—nitrogen bottle

dispersion and stabilization of the classification particles through such conditional tests as settlement tests, cloud point tests and Zeta-potential and particle size measurement.

(2) Experiment of single classifying column on the basis of above test

A series of conditional tests including air pressure, flow, amount and kind of frothers, raising height of froth have been conducted to determine the optimum hydrodynamic conditions for the classification.

The last test results are obtained under the optimum conditions.

Feeds and classifying fine fraction which were carried by air-bubbles were immediately measured after treatment by ultrasonic device which can keep the particles dispersed. The coarse fraction which cannot be raised by micro-bubbles were to be filtrated, dried and weighted.

4 RESULTS AND DISCUSSION

4. 1 *The Conclusions of Conditional Tests*

The conditional tests' results about interaction factors are listed as follows:

(1) The tests must be conducted in high pH(>10) due to the lower isoelectropoints of kaolin and quartz. The electrostatic forces can increase repulsion between fine particles.

(2) Inorganic electrolyte can compass surfacial double-electrosphere between particles so as to make particles aggregate, so inorganic electrolyte can not be added in classifying column.

(3) The dispersing reagents can much increase the hydration energy so that the particles can fully disperse.

The conditional test results about hydrodynamic factors are listed as follows:

(1) Ultrasonic wave with certain intensity is used to not only mix reagents but also prevent particles from aggregation.

(2) Air pressure, amount of flow and the raising height of froth have much important influence to the classifying process with tight connections. The matching ratio of the three factors has been obtained through cross tests.

4. 2 *The Optimum Results of Experiment*

The commonest method of representing

the classifying efficiency is using a performance curve which relates the percentage of each particle size in the overflow to the particle size. The closer to vertical the slope is, the higher the efficiency is. The slope of the curve can be expressed by taking the points at which 75% and 25% of the feed particles report to the overflow. These are the d 75 μm and d 25 μm sizes respectively. The efficiency of separation is given by:

$$E = \frac{d_{75} - d_{25}}{2d_{50}} \tag{1}$$

Another criterion is the recovery of size fraction which can be expressed by:

$$E_A = \frac{G_1 \varepsilon_A'}{G_0 \varepsilon_A} \tag{2}$$

where E_A is the recovery of A size fraction; G_0, G_1 are weight of feed and overflow respectively; ε_A, ε_A' are percentage of minus A size in the feed and in the overflow respectively. The Tromp curves of feed and overflow for classifying column are given in Fig. 3 and Fig. 4. The optimum condition of classifying process is shown in Table 3. The final results are calculated and expressed in Table 4.

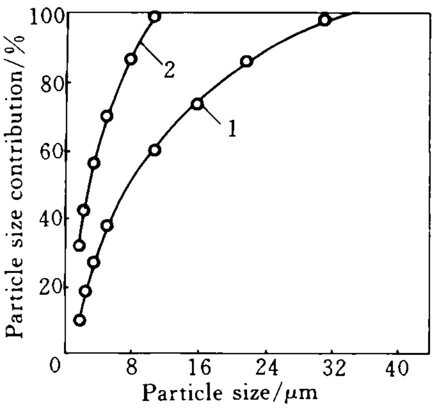

Fig. 3 Particle size distribution of feed and overflow of kaolin
1—feed; 2—overflow

Fig. 3, Fig. 4 and Table 4 show the apparent efficiency of classification. The largest particle size of feed is 44 μm (kaolin) and 22 μm (quartz), while that of overflow is 11 μm (kaolin) and 1 0 μm (quartz), which keep fine fraction of about minus 10 μm remove from coarse fraction. For the kaolin, the classifying efficiency is 87. 50% and the recovery of −2 μm size fraction is over 90%. According to the isoelectric point of Kaolin (4. 2) and quartz (2. 0), pH condition was adjusted

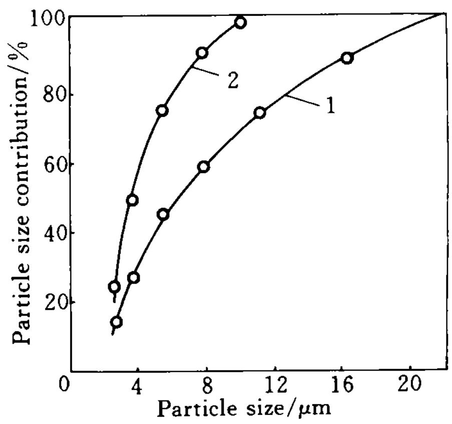

Fig. 4 Particle size distribution of feed and overflow of quartz
1—feed; 2—overflow

Table 3 The optimum condition of classifying process

Factors	Kaolin	Quartz
pH	10±0. 2	10
Pressure/MPa	128	10. 80
Flow/mV·min^{-1}	3	3
Amount of frother/mg·L^{-1}	4×10^{-4}	6×10^{-4}
Raising height of froth/cm	21. 56	21. 76
Numerical value	8	12

Table 4 The calculation results of classification

Sample	G_0 /g	G_1 /g	d_m /μm
Kaolin	6. 663	2. 029	2. 8
Quartz	5	3. 04	3. 8

Sample	−2 μmE /%	−5 μmE /%	−10 μmE /%
Kaolin	92. 78	58. 35	49. 10
Quartz	75. 60	67. 62	56. 81

to increase electrostatic energy which hinders aggregation of particles. SP reagents were added to increase repulsion due to hydration structural forces which have played key role in the dispersion of particles.

4.3 *The Theoretical Model of The Flotation Classification*

A static flow exists in the classifying column without turbulent flow. In disperse system, of course, hydrodynamic forces are acting and the degree of aggregation is determined by competition between the surface and the hydrodynamic forces. According to the Van Oss' surface thermodynamic approach, hydration forces which are mainly responsible for the interfacial interactions are manifested at short distances that they are of interfacial origin[4].

It is important to note that the classifying efficiency is determined by the surfacial and hydrodynamic factors. There are matching relations between the two factors. The theoretical model about the collision between fine particles and fine air bubbles will be further discussed.

It is clear that in the classifying process, the hydrodynamic forces include gravity, buoyancy, shearing force and fluid resistance force, and the interactions should include electrostatic force, Van der Waals force and hydration force. Fig. 5 and Fig. 6 show the geometrical model and interaction model about collision between fine particles and fine air bubbles.

Hydrodynamic factors:

(1) Shearing forces

$$F_{rs} = 6\pi\mu R_p U_r = \frac{R\pi mu R_p}{R^2 \sin\theta} \cdot \frac{d\varphi}{d\theta} \quad (3)$$

$$F_{ts} = 6\pi\mu R_p U_t = \frac{6\pi\mu r_p}{R^2 \sin\theta} \cdot \frac{d\varphi}{dR} \quad (4)$$

where U_r and U_t are respectively the radial velocity and tangential velocity of fluid; φ the stream function; θ the cylindrical coordinates of the streamline; μ the viscosity of fluid; and R, R_p are respectively radii of bubble and particle.

(2) Resistance force

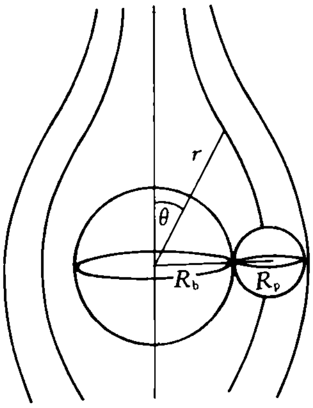

Fig. 5 The geometrical model of collision between fine particles and bubbles

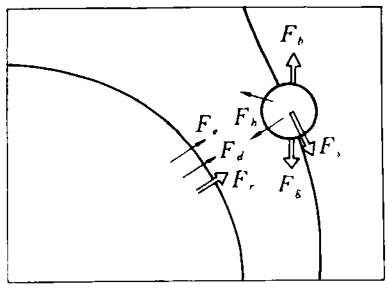

Fig. 6 Interaction model of particles and bubbles

$$F_r = 6\pi\mu R_p U_{rp}\beta \quad (5)$$

where U_{rp} is the radial velocity of particle and β is the stokes correction factor.

(3) Gravity-buoyancy forces

$$F_{gb} = (3/4)\pi R_p^3 \cdot (\rho_p - \rho_f) g \quad (6)$$

where ρ_p and ρ_f separately are the density of particle and fluid.

Interfacial interaction:

(1) Electrostatic force

$$F_e \frac{2B_1 x[\exp(-2\kappa H) - B_2 \exp(-\kappa H)]}{1 - \exp(-2\kappa H)} \quad (7)$$

$$B_1 = \frac{\varepsilon R_p R_b (\psi_p^2 + \psi_b^2)}{4(R_p + R_b)} \quad (8)$$

$$B_2 = \frac{2\psi_p \psi_b}{\psi_p^2 \psi_b^2} \quad (9)$$

where ψ_p and ψ_b respectively are the surfacial potential of particles and bubbles; κ^{-1} is the

Debye length.

(2) Van der Waals forces

$$F_d = \frac{A_{123} R_p R_b f}{6h^2 (R_p + R_b)} \quad (10)$$

where h is the interacting distance; A_{123} is the effective Harmark constant, which can be expressed as:

$$A_{123} = (\sqrt{A_{11}} - \sqrt{A_{22}})(\sqrt{A_{33}} - \sqrt{A_{22}}) \quad (11)$$

where A_{11} and A_{33} respectively are interfacial interaction Harmark constants of particles and bubbles in vacuum; A_{22} that of medium 3 in vacuum.

(3) Hydration forces

$$F_H = \frac{C R_p R_b}{R_p + R_b} \exp(-\frac{h}{D_0}) \quad (12)$$

where C is the constant; D_0 the delay length. Thus, dynamic balance should include the following two equations:

$$m_p dU_{rp}/dt = F_{is} + F_r + F_{gb} + F_d + F_o + F_H = 0 \quad (13)$$

$$m_p dU_{tp}/dt = F_{is} + F_{gb} \sin\theta = 0 \quad (14)$$

U_{rp} and U_{tp} can be calculated from the two equations so that new position of particles can be determined by the following equations:

$$r_{new} = r_{old} - U_{rp} \Delta t \quad (15)$$

$$\theta_{new} = \theta_{old} + U_{tp} \Delta t / r \quad (16)$$

where Δt is the time step used in the numerical simulation. The theoretical model is finished.

5 CONCLUSION

A novel ultrafine hydro-classifying technique has been discussed from the angle of controlling the interaction between particles which play key role in controlling selective aggregation and dispersion. Micro-bubble flotation techniques are grafted on the classification process, for which this process is termed the flotation classification. As a result, micro 10 μm particle size fraction can be separated from the feed of −44 μm fraction. Finally, the principle of classification is discussed in terms of surface thermodynamics and hydrodynamics.

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(Edited by Li Jun)