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Flow of gas-liquid-solid system and its application in packed flotation column①

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[Abstract] A packed flotation column, which is packed with multiple board ripple packings, was described. Based on comprehensive steady state models, chemical reactor developed previously in chemical engineering subjects, have been extended to packed flotation column for mineral separation. The experimental results verify that tanks in series model is better than axially-dispersed plug flow model to describe flow pattern in the collection zone of column by RTD (residence time distribution), and the error of experimental data and calculated data of both models are 0.07% ~ 0.1% and 0.18% ~ 0.45% respectively. And, RTD of gas phase was also considered, results also show that gas in the whole column appears plug flow. The cleaning process through adding wash water in froth zone of column was described, and the effect of superficial air velocity and superficial wash water velocity on the cleaning action of froth zone were discussed. Flotation experiment for single column was conducted for phosphate ores. The recovery for P_2O_5 was 85.8%, and the grade was 26.8%.

[Key words] packing; flotation column; mixing; phosphate ores
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1 INTRODUCTION

Packed flotation column, in which mineral is enriched through bubbling and absorption separation method, is a kind of effective flotation processing device explored in 1980s' and is an evidence of successfully applying chemical unit, operation and device to mineral process and a outcome of cross and osmosis among different subjects[1].

In recent twenty years, many previous works on flotation column mixing were carried out for opened flotation column, which are commonly used in chemical engineering applications as gas/liquid contactors[2~4]. Most of them suggested that mixing was one of the most important considerations in opened column scale-up, and give out expression for the axial dispersion coefficient as a function of column construction and operative condition based on axially-dispersed plug flow of bubble and slurry phases. Yianatos et al[5] also studied the cleaning action in opened column flotation froths, and a model based on plug flow was developed and shown to fit the grade profiles through the froth. However, reliable scale-up procedures for packed flotation column have not been established, resulting in situations where packed column is not capable of meeting their original design capacities. One of the difficulties in packed column scale-up is the lack of quantitative information relating the degree of mixing inside the column to operating and construction parameters.

To packed flotation column, which is a high effective separation device, the bulk of present work focused on its flowing and mixing characteristics. Flowing has been investigated in a packed flotation column through the determination of the residence time distribution (RTD) of the liquid and gas phase, since it is known that the efficiency of the flotation process is largely a function of the fluid flow characteristics of the system. The interpretation of the experiment results is done through two models describing the mixing process in the column. The simplest models are either the axially-dispersed plug flow (ADPF) model or tanks in series model, and described by Eqns. (1), (2) respectively[6]:

$$c(t) = \left(\frac{Pe \cdot \tau}{4\pi t^3}\right)^{\frac{1}{2}} \exp\left[\frac{Pe}{4}\left(2 - \frac{t}{\tau} - \frac{\tau}{t}\right)\right] \quad (1)$$

$$c_N(t) = \frac{N}{\tau(N-1)!}\left(\frac{Nt}{\tau}\right)^{N-1} \exp\left(-\frac{Nt}{\tau}\right) \quad (2)$$

where c is the concentration of some liquid species, Pe is the Peclet number, N is number of tanks in series and τ is mean residence time. It can be seen that $Pe = \infty$, or $N = \infty$ represents for plug flow condition and $Pe = 0$, or $N = 1$ represents for perfectly mixed condition.

On the other hand, packed flotation column can prevent hydraulic entrainment for fine particle by maintaining a net downward flow of water through the froth. To further investigate the relationship between superficial gas rate and superficial wash water rate, the cleaning actions of in packed column flota-

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tion froths are discussed based on tracer on-line test methods.

2 EXPERIMENTAL

Experimental apparatus is shown in Fig. 1. The whole column is packed with multiple ripple board. The direction of packing ripple in neighbor sections is cross vertically. The direction of the slope angle φ of two neighbor board ripple in every section is opposite, and neighbor pieces of ripple form triangle passage whose angle is equal to 2φ. The triangle passage among four neighbor contacting points consists of a mixing space.

The mineral slurry containing target and non-target mineral particles is usually considered as homogenous fluid, and it is fed at a certain height of the column. It flows counter-currently with tiny air split by the packings when the air is introduced from the bottom of the column. The whole column can be assumptily divided into collection zone in which particle and bubble aggregate is formed due to their collision and adhesion and fine flotation (froth) zone in which froth layer is stabilized by wash water added from the top of the column, and target mineral particles are enriched.

In order to determine the fluid flowing and mixing, impulse input for liquid phase or step input for gas phase has been adopted. The impulse input signal (tracer, saturated aqueous solution of KCl) to the packed column was assumed to be the δ function pulse input in feed and wash water line. Step input signal (nitrogen instead of air) is transferred in air input line. The output signal was detected by on-line conductivity instrument in different detect locate of the top, bottom and inner of the column, or gas chromatograph in locate of top, and output signal was inputted to computer by A/D converter.

3 RESULTS AND DISCUSSION

3.1 Fluid flowing and mixing in collection zone

When mineral slurry and air are fed into the packed bubble column, they are separated on the section of each piece of packing and then influx into the triangle passage of the packing, in which flow through shape of "Z" channel from radial mixing, while radial and axial flowing and mixing near the wall of the column is taken place. Then flowing in contrary direction and mixing on the other section of the same piece of packing is led. The behavior of fluid flowing and mixing is shown in Fig. 2.

From Fig. 2 it is interesting to note that the behavior of column, as seen by its RTD, depended also upon the relative position of column. For instance, at 10 cm above feed inlet, or 10 cm below feed inlet, the "perfect mixing" can be observed for curve 1 and curve 2, whereas curve 3 is different from the case near feed inlet, it represents the fluid flowing of collection zone. It is obvious that fluid flowing in collection zone is between plug flow and perfect mixing. Further, to inquire into the laws of flowing and mixing of mineral slurry and air in the collection zone, and to compare the deviation of applying for ADPF model and tanks in series model, both model parameters are calculated as Table 1 shown.

Table 1 shows a set of data obtained in the present work by varying the length-to-diameter (H_c/D) of the collection zone, wash water rate (J_w) and air flow rate (J_g), respectively. The model parameters

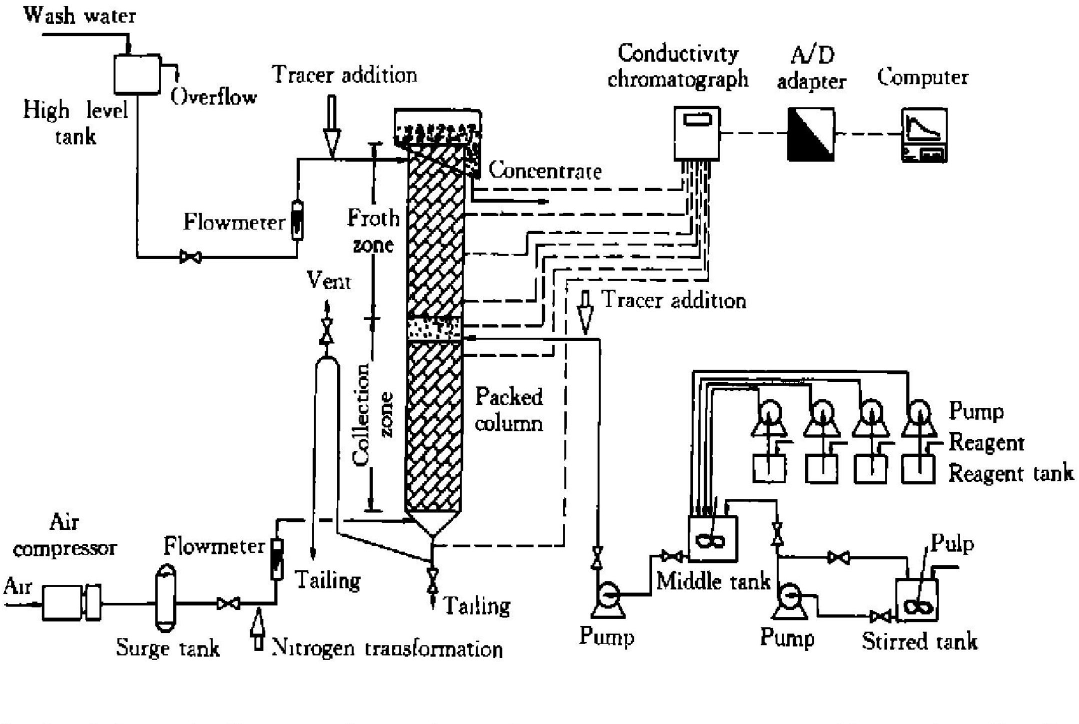

Fig. 1 Schematic diagram of experimental apparatus to measure residence time distribution

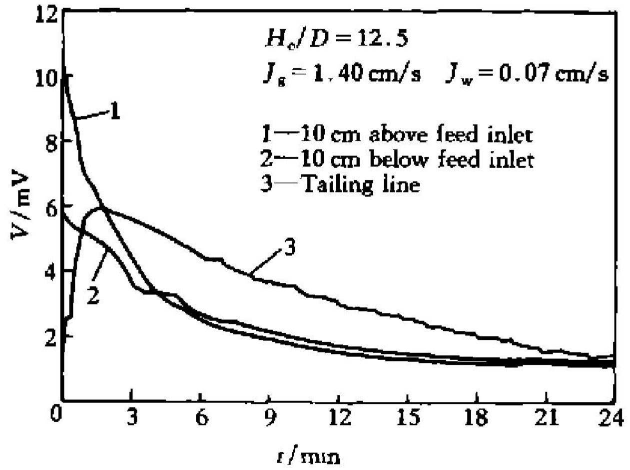

Fig. 2 Curves of voltage vs time of different positions in collection zone

τ, *Pe* and *N* value are estimated by the method of the Simple Method, and an optimum value of τ, *Pe* and *N* is selected by the objective function P[7]. The objective function P is defined as $\varphi=\sum(c_{\text{exp}}-c_{\text{cal}})^2/\sum c_{\text{exp}}$, where c_{exp} is the measured normalized concentration at time t and c_{cal} is the fitted concentration, as in Eqns. (1) or (2).

In case A, length-to-diameter and wash water rate were held constant while the air flow rate was varied. It can be seen that as J_g increases from 1.40 cm/s to 1.58 cm/s, model parameter *Pe*, *N* increase slightly. This shows that fluid back-mixing level is lowered because of the action of gas-liquid counter-current being intercepted and led to channel, wall flowing and dead zone are reduced within the column. Thus, fluid axial mixing degree decreases and radial mixing increases. In special, as $J_g=1.94$ cm/s the affects are obvious.

In case B, the effect of wash water rate on model parameter *Pe*, *N* is not obvious. As shown in Table 1, the value of *Pe* is from 0.74 to 0.73, and *N* is from 1.24 to 1.27, while wash water rate is varied from 0.04 cm/s to 0.14 cm/s. This finding is also supported by the work of Shah et al[8], which showed that the effect of water rate on fluid mixing could be ignored while J_w is lower than 3 cm/s.

In order to illustrate the effect of column geometry on mixing, RTD's have been measured over a wide range of length-to-diameter H_c/D. These results are shown in case C, in which the changes in *Pe* or *N* are tabled as a variable of the H_c/D ratio. As shown, the H_c/D ratio has a significant impact on column mixing. The results are identical with the work of Dobby and Finch, which showed that mixing parameter is a function of column diameter[9].

Table 1 also gives out objective function P. The comparison of results based on ADPF model with tanks in series model, it is obvious that tanks in series model is more appropriate to packed bubble column.

3.2 Fluid flowing and mixing in froth zone

Since function of fine flotation (froth) zone and collection zone is different, in this zone the design can follow the conventional column design procedure[10]. Through measurement of the RTD of mineral slurry in different froth sections in fine froth zone by impulse input tracer method in feed line, the results are shown in Table 2 (Detector 1, 2 and 3 are located 5 cm, 10 cm and 40 cm above interface respectively). It can be seen that under the same gas flow rate, with the distance away from the interface of two zones increasing, the back-mixing occurs in location of detector 1 or 2.

Table 1 Model parameters of ADPF and tanks in series in collection zone

No.	Parameter			ADPF model			Tanks in series model		
	$J_g/(\text{cm}\cdot\text{s}^{-1})$	$J_w/(\text{cm}\cdot\text{s}^{-1})$	H_c/D	τ/min	*Pe*	P/%	τ/min	*N*	P/%
A-1	1.40	0.07	12.5	20.28	0.74	0.35	14.56	1.24	0.09
A-2	1.58	0.07	12.5	20.62	0.74	0.36	14.61	1.24	0.09
A-3	1.76	0.07	12.5	20.76	0.84	0.38	15.43	1.27	0.08
A-4	1.94	0.07	12.5	20.76	0.95	0.29	17.61	1.42	0.10
B-1	1.40	0.04	12.5	20.28	0.74	0.35	14.62	1.24	0.09
B-2	1.40	0.11	12.5	19.20	0.73	0.45	13.03	1.26	0.08
B-3	1.40	0.14	12.5	18.20	0.73	0.37	12.53	1.27	0.09
C-1	1.40	0.07	23.4	20.16	0.88	0.26	15.62	1.29	0.09
C-2	1.40	0.07	28.7	20.05	1.34	0.20	19.11	1.32	0.08
C-3	1.40	0.07	35.7	19.84	2.27	0.18	26.61	1.42	0.07

Table 2 Model parameters of ADPF and tanks in series in froth zone

No.	J_g /(cm·s^{-1})	J_w /(cm·s^{-1})	Detector	ADPF model			Tanks in series model		
				$\bar{\tau}$/min	Pe	P/%	$\bar{\tau}$/min	N	P/%
D-1	1.40	0	1	8.84	0.40	2.05	5.33	1.05	1.29
D-2	1.40	0	2	9.78	0.38	2.49	5.85	1.00	1.07
D-3	1.40	0	3	10.96	1.09	0.58	6.52	5.24	4.44
E-1	1.40	0.02	1	10.89	0.74	0.86	5.78	1.22	0.39
E-2	1.40	0.02	2	7.95	0.43	1.28	4.34	1.12	1.34
E-3	1.40	0.02	3	10.94	6.22	0.49	16.67	6.49	5.13
F-1	1.40	0.04	1	13.34	0.66	1.37	7.06	1.11	0.36
F-2	1.40	0.04	2	12.35	0.57	1.17	6.57	1.19	0.65
F-3	1.40	0.04	3	11.23	7.73	0.50	15.5	7.30	5.68
G-1	1.76	0	1	7.10	0.35	3.40	4.63	0.93	1.59
G-2	1.76	0	2	7.87	0.41	1.74	5.05	1.04	1.84
G-3	1.76	0	3	10.35	0.85	0.74	6.27	1.37	1.18
H-1	1.76	0.02	1	9.48	0.46	1.86	4.77	1.02	0.32
H-2	1.76	0.02	2	6.84	0.37	2.60	3.95	0.95	1.16
H-3	1.76	0.02	3	9.04	3.87	0.22	6.35	8.49	3.11
I-1	1.76	0.04	1	10.47	0.48	2.16	5.32	0.98	0.28
I-2	1.76	0.04	2	8.60	0.43	1.34	4.64	1.12	1.09
I-3	1.76	0.04	3	9.12	4.26	0.19	9.74	7.49	3.90

When tracer is inputted from wash water line, as Fig. 3 shows, the distribution ratio of wash water on the top of the column is calculated by material balance. The experimental results also show that 91% wash water is drained from the top of the column under the experimental condition, and 8% wash water enters into collection zone of the column through the interface of collection zone and froth zone in order to provide a net downward bias flow rate[5]. Thus, wash water is evidently very effective in preventing untargeted mineral from reaching the concentrate.

3.3 Flowing of air in whole column

Using step input method in the experiment, that is, using nitrogen instead of air as flowing phase and oxygen as tracer reagent, gas chromatograph was used to determine the dissolved amount of oxygen which is in turn used to determine RTD function $F(t)$ of gas. Fig. 4 shows that gas in the column appears plug flow[6].

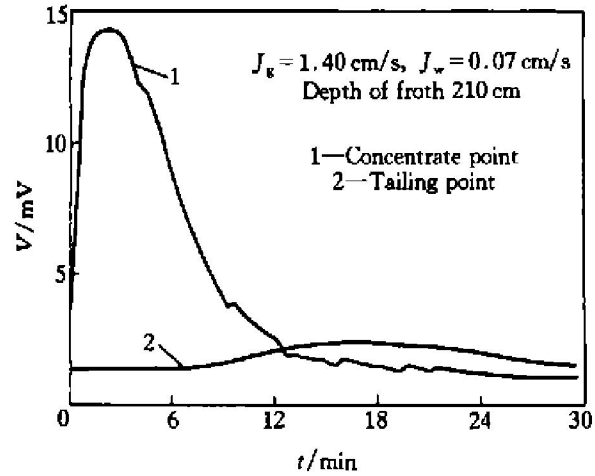

Fig. 3 Curves of voltage vs time in concentrate point and tailing point

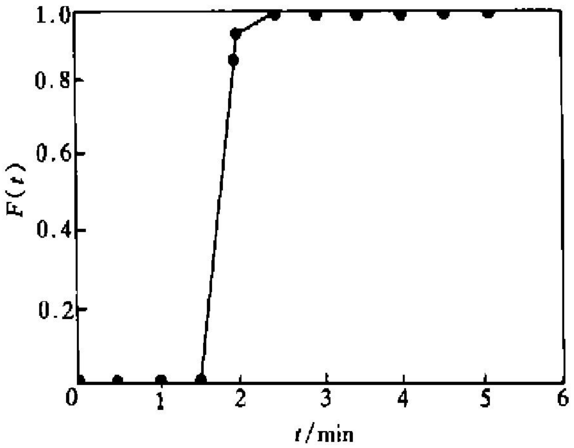

Fig. 4 RTD function $F(t)$ curve of gas in whole flotation column

3.4 Application

In experimental, phosphorous ore, which is from one of large phosphorous mine at Jingxiang ore bureau in China and is difficult to be separated and enriched, is taken as an example. Use bubble column which is packed with stainless steel ripple board with holes size of *d* 42 mm × 60 mm, cb-500.

Experimental shows that, to the original mineral of which grade of P_2O_5 is 19.7% when maintaining superficial wash water flow rate $J_w = 0.07$ cm/s, superficial air flow rate $J_g = 1.40$ cm/s and length-to-diameter ratio $H_c/D = 12.5$, the grade of P_2O_5 in fine concentrate mineral is 26.8% and correspondently the recovery of P_2O_5 reaches 85.8%.

4 SUMMARY AND CONCLUSIONS

1) In the bubbling and absorption separation process, ripple packing has a good function of mixing particle and bubble, and can stabilize the flow pattern, sustain froth and increase the flotation efficiency.

2) Residence time distribution (RTD) studies have been conducted in a laboratory packed flotation column in order to quantify the effect of gas and liquid flow rates and column geometry on mixing.

3) The degree of mixing in collection zone of the packed flotation column, which is of major importance for its performance, is clearly affected by the air flow rate and length-to-diameter among other parameters. Experiments also confirm that tanks in series model is more appropriate to describe ripple board packed column flow pattern.

4) To froth zone, mixing is determined by the well match for wash water rate and air flow rate, and it is clear that the degree of mixing affected by the relative flow rates. Simultaneously, it is also proved that wash water can improve the stability of froth and enriching of target mineral particles.

[REFERENCES]

[1] Daivd C Y. A new packed column flotation system [A]. Column Flotation' 88 [C]. Littleton: SME Inc, 1988. 257- 265.

[2] Dobby G S, Finch J A. Flotation column scale-up and modeling [J]. CIM Bull, 1986, 79: 89- 96.

[3] Goodall C M, O' Connor C T. Residence time distribution studies in a flotation column. Part 1: the modelling of residence time distributions in a laboratory column flotation cell [J]. International Journal of Mineral Processing, 1991, 31: 97- 113.

[4] Mankosa M J, Luttrell G H, Adel G T, et al. A study of axial mixing in column flotation [J]. International Journal of Mineral Processing, 1992, 35: 51- 64.

[5] Yianatos J B, Finch J A, Laplante A R. Selectivity in column flotation froths [J]. International Journal of Mineral Processing, 1988, 23: 279- 292.

[6] Levenspiel O. Chemical Reaction Engineering [M]. New York: John Wiley, 1972: 52- 315.

[7] WANG Shao-ting, CHEN Shu-zhang, LI Chun-li. The methods of estimation of parameters in the packed tower for liquid axial mixing [J]. Chemical Engineering, (in Chinese), 1988, 16(5): 46- 50.

[8] Shah Y T, Kelkar B G, Godbole S P. Design parameters estimations for bubble column reactors [J]. Ch E Journal, 1982, 28(3): 353- 379.

[9] Dobby G S, Finch J A. Mixing characteristics of industrial flotation columns [J]. Chem Eng Sci, 1985, 40: 1061- 1068.

[10] Finch J A, Dobby G S. Column Flotation [M]. Toronto: Pergamon Press, 1990. 75- 100.

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