FLOW FIELD IN AIR-SPARGED HYDROCYCLONE①

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ABSTRACT

An experimental study on the flow pattern within a 60mm × 600mm transparent air-sparged hydrocyclone was carried out, from which it was firstly found that the liquid column at the bottom of the cyclone is one of the essential characteristics in the air-sparged hydrocyclone, and a further study was done to investigate the effect of the liquid column height on the cyclone performance. The bubble velocity in the liquid column was measured using a pickup camera. The tangential and axial velocities in the swirl-flow layer were also examined. The results are conducive to the further application study of the air-sparged hydrocyclone.

Key words: air-sparged hydrocyclone flow field froth flotation centrifuge process

1 INTRODUCTION

Air-sparged hydrocyclone (ASH) was invented by Miller[1] in the beginning of 1980s, from then it has drawn great interest all over the world[2]. To ascertain the separation behavior in ASH, some preliminary investigations have been made on the flow phenomena[3-7], and a general conclusion is that the flow field in ASH is composed of swirl layer and froth column. However, because the effects of geometry and operation parameters were hardly considered in these investigations, the research results had certain limitation to be used to further application study of ASH. In this paper, the flow field in ASH with various parameters was studied to get useful information for the application study of the cyclone.

2 EXPERIMENTAL

The ASH used is made of transparent perspex and polished. The geometry of the ASH and the selected coordinate system are shown in Fig. 1. On the wall, experimental points were arranged with axial interval of 50 mm. At each point, dyeing liquid could be injected into ASH with syinge needles and the injection position in ASH could be changed radially. Meanwhile, compressed gas could also be sparged into ASH with a series of syinge needles to form bubbles at each experimental point. The underflow pipe diameter could be changed.

In this experiment, water was fed with turpentine as frother. Firstly, the general flow pattern was observed for variable underflow pipe diameter, feed flowrate and frother dosage. Secondly, compressed gas was sparged into ASH at every experimental point and the bubble trace investigated. Finally, dyeing liquid was injected into the cyclone at every point to illustrate the trace of the liquid flow in ASH.

To study the motions of liquid and bubbles in ASH quantitatively, a pickup camera was used to measure the velocity. The method could be described as follows. Dyed liquid or compressed gas was injected at the experimental point one by one, and the motion of dyed liquid or bubbles was recorded by a pickup camera simultaneously. Then, the route of dyed liquid or bubbles within a certain time interval was analysed using a special compiling instrument. So, the average velocity of liquid

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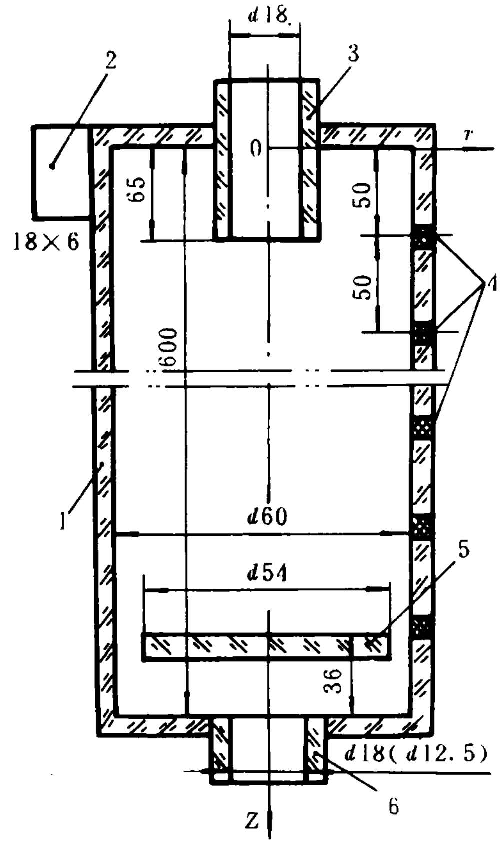

Fig. 1 Geometry of ASH and selected coordinate system

1—ASH wall; 2—inlet; 3—vortex finder wall; 4—experimental points; 5—pedestal baffle; 6—underflow pipe wall

or bubbles in ASH at different point could be calculated. To get satisfied measuring results, the feed in this study was water without frother. Firstly, keep the underflow pipe diameter (18 mm) unchanged, and measure the liquid velocity at different experimental point in swirl flow layer with different feed flowrates. Then, change the underflow pipe diameter and the feed flowrate at the same time, and measure the bubble velocity at the point of axial position $Z = 550$ mm.

3 RESULTS AND DISCUSSION

3.1 *Formation of Three Regions in ASH*

From the experimental study it was found that, when the underflow pipe diameter was fixed, the overall flow pattern varying with the feed flowrate can be described as follows. In the beginning, a thin helical belt-like layer was formed as the flowrate was small; with the increase of the flowrate, the swirl layer became wider and wider and gradually covered the internal wall surface, the layer thickness tended to be uniform with the maximum about 3 mm; then a liquid column formed at the bottom in ASH, and became larger and larger, at the same time the height of the swirl layer was shortened; finally, the space in ASH was full of liquid.

From the observation of the traces of bubbles, we found that, almost all the bubbles in ASH discharged with underflow and the froth core could not exist before the formation of liquid column, and the froth core appeared as soon as the liquid column formed. This indicates that the liquid column is essential for the formation of froth core. So, the liquid column should be one of the essential characteristics in a well operated ASH. But this was not definitely mentioned in the previous research papers because of their excessively simplified experimental apparatus, e. g. in literature[4], a main literature on the flow pattern in ASH, the experimental ASH model was a transparent round pipe with a tangent inlet and an unrestricted outlet. Therefrore, the flow field in a well operated ASH is not just composed of swirl layer and froth column as previous investigators described, but of three regions, i. e. swirl layer region, froth column region and liquid column region as shown in Fig. 2. In other words, the liquid column should be one of the essential characteristics in ASH.

3.2 *Inner and Outer Helical flows in Liquid Column*

The liquid movement in the liquid column was studied by injecting dyed liquid at different axial position Z and different radial position r. It was found that the movement of liquid in the liquid column was similar to that in a conventional hydrocyclone, and could be also divided into inner helical flow and outer helical flow as shown in Fig. 3. The flow pattern in liquid column was beneficial to the movement of bubbles from liquid column into froth core. Those bubbles which entered the centre of liquid column as the liquid transformed from outer helical flow to inner helical flow, could only stay in the centre and move upwards into froth core because of the centripetal buoyancy[8]. To compare the motion of bubbles with that of liquid in the liquid column, compressed gas and dyed liquid were injected individually at the point with $Z = 500$ mm and $r = 30$ mm. The results indicate that the bubbles move helically downwards at first, and then enter the centre and move upwards into froth core while the dyed liquid keep staying in the outer helical flow and discharge with underflow. So, the motion of bubbles and liquid are different.

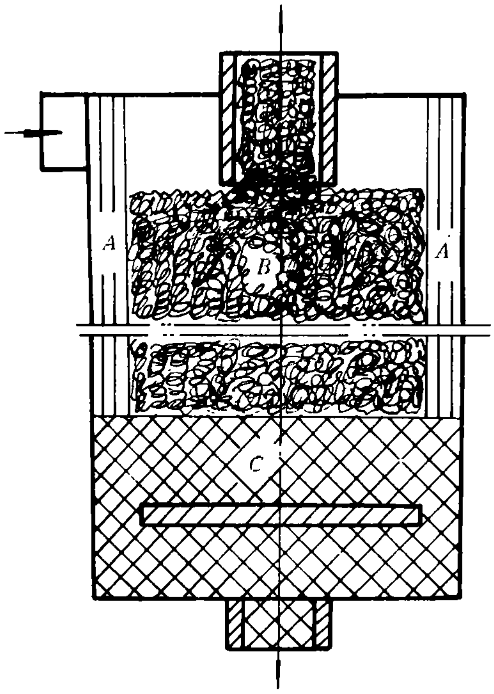

Fig. 2 Three regions in ASH
A—swirl layer region; B—froth core region; C—liquid column region

The investigation on the traces of bubbles shows that a certain part of the bubbles formed at $Z = 550$ mm could not enter the centre and directly discharged with underflow. Therefore, it is not reasonable to sparge compressed gas through the ASH wall section near the pedestal baffle, because those bubbles formed there hardly move into froth core. As a consequence, the ASH wall section near the pedestal baffle should be designed with solid wall other than porous wall.

3.3 *Liquid Column Height*

As mentioned above, the liquid column is one of the essential characteristics in a well operated ASH. But with the height of liquid column (which is defined as the length from the upper surface of pedestal baffle to the top of liquid column) increased, the height of froth core and swirl layer would decrease relevantly. If the liquid column is too high, there would be no froth core region, so no separation in ASH. On the other hand, if the liquid column is too small, the liquid column would probably disappear with the fluctuation of pump output, so the froth core region would be difficult to form. Therefore, the height of liquid column should be selected in an optimum range.

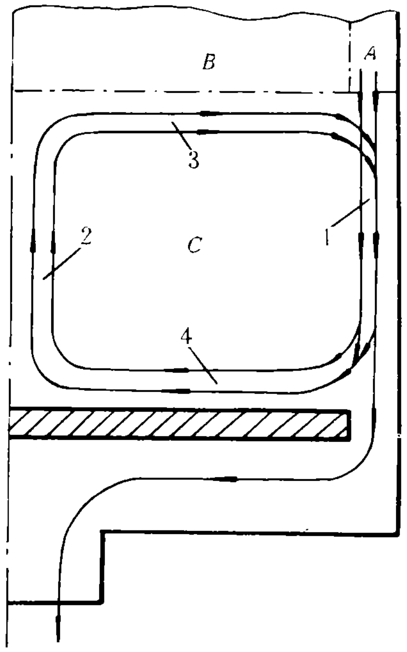

Fig. 3 Liquid movement in liquid column in ASH
A—swirl layer; B—froth core; C—liquid column; 1—outer helical flow; 2—inner helical flow; 3—transformation from inner helical flow into outer helical flow; 4—transformation from outer helical flow into inner helical flow

The effects of underflow pipe diameter and feed flowrate on the liquid column height are shown in Fig. 4. From Fig. 4 it can be seen that the underflow pipe diameter heavily affects the height of liquid column. With the underflow pipe diameter increased, the liquid column height decreases rapidly and even to zero. When the underflow pipe diameter fixed, the liquid column height increases with the feed flowrate.

It could be also pointed out in light of Fig. 4 that, frother dosage affects the liquid column height to a certain extent. When the liquid column is not too high, e. g. $H \leqslant 3D$, where H stands for the height of liquid column, and D for the diameter of ASH, the variation of the liquid column height caused by frother dosage is about less than 80 mm.

The results indicate that the height of liquid column has an optimum range, i. e. $H = (1 \sim 2)D$, in which the liquid column exists stably and leaves enough space for froth core and swirl layer regions.

3. 4 *Liquid Velocity in Swirl Layer*

Because the thickness of swirl layer is very small (about 2~3 mm), the radial velocity in it could be assumed to be zero[4]. The measured tangential and axial velocity components of the liquid in swirl layer with underflow pipe diameter of 18 mm are shown in Fig. 5. It is obvious that, tangential velocity decreases rapidly with the increase of the axial coordinate Z, while the axial velocity decreases rather slowly. This result certified what described in literature [4]. The rapid decrease of the tangential velocity component is due to the kinetic energy loss caused by friction.

Based on the analysis of the experimental results, the relationship between tangential velocity in swirl layer and axial coordinate Z could be described as:

$$V_t \cdot Z^n = C \qquad (1)$$

where V_t stands for the tangential velocity at axial coordinate Z, and n and C for constants.

Table 1 gives the values of n and C obained from linear regressions of experimental data. The interrelation coefficients exceedingly approach 1, i. e. the regression results are striking. From Table 1, it can be also found that the values of n and C vary little with the inlet velocity.

The axial velocity in swirl layer decreases slowly as the axial coordinate Z increased mainly because of the permanent gravitation. In the lower section of ASH, tangential velocity component of

Table 1 Values of n and C of Equation (1)

Inlet velocity v_e /m·s^{-1}	n	C	Interrelation coefficient $\lvert r_S \rvert$
3. 52	1. 10	176. 8	0. 9982
3. 33	1. 12	175. 1	0. 9965

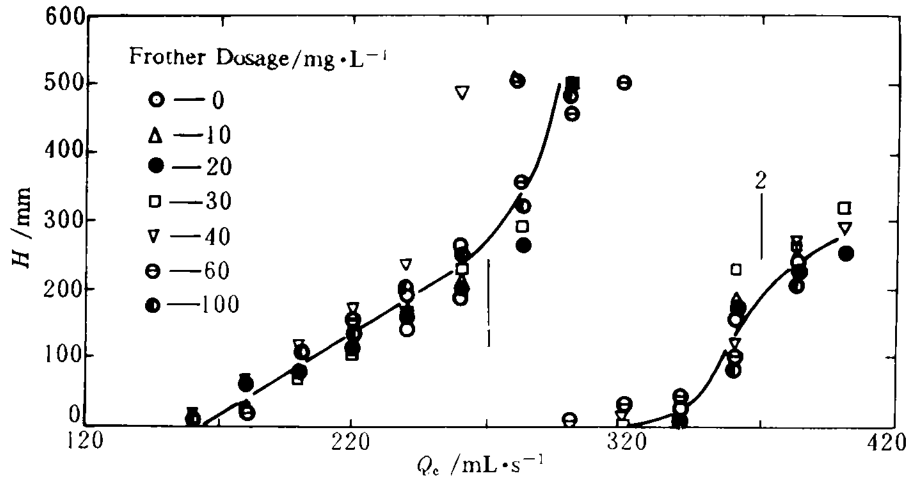

Fig. 4 **Effects of underflow pipe diameter and feed flowrate on liquid column height**

1 — $d_u = 12.5$ mm; 2 — $d_u = 18$ mm

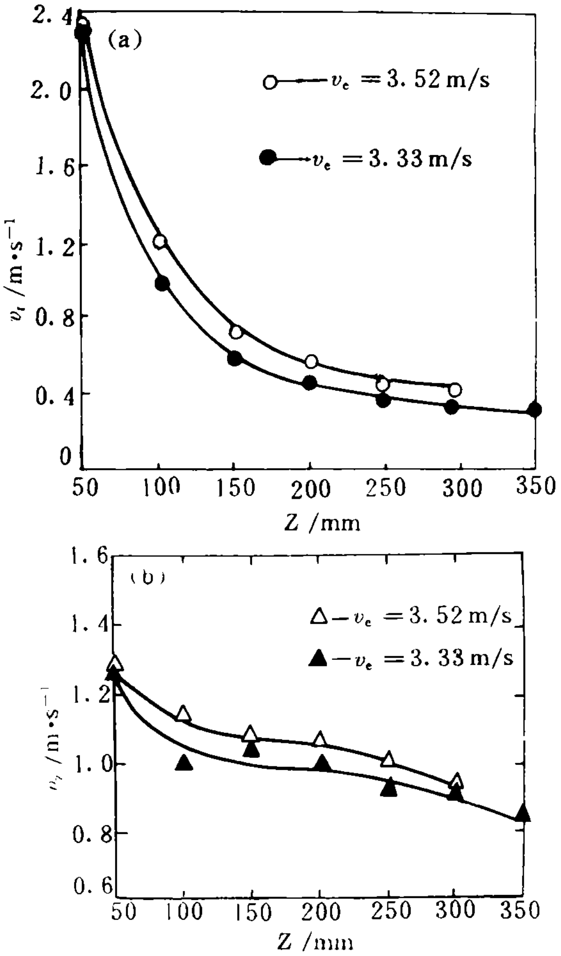

Fig. 5　Axial distribution of liquid velocity in swirl layer

(a)—tangential velocity; (b)—axial velocity

liquid is much smaller than axial velocity. This indicates that it is not proper to design an ASH with a large length/diameter ratio, because if the ASH is very long, the tangential velocity component of liquid in the lower section would be very small, so the centrifugal field would not be strong enough to intensify the flotation. And, the flotation results in series short ASHs would be better than that in a long ASH.

Fig. 6 shows the effect of inlet velocity on the liquid velocity in swirl layer with other parameters fixed. Both the total velocity and the tangential velocity component increase rapidly with the inlet velocity, while the axial velocity component increases slowly. This indicates that the inlet kinetic energy is mainly transfered into tangential kinetic energy to provide a strong centrifugal field, and the inlet velocity would be taken as a symbol of the strength of the centrifugal field in ASH.

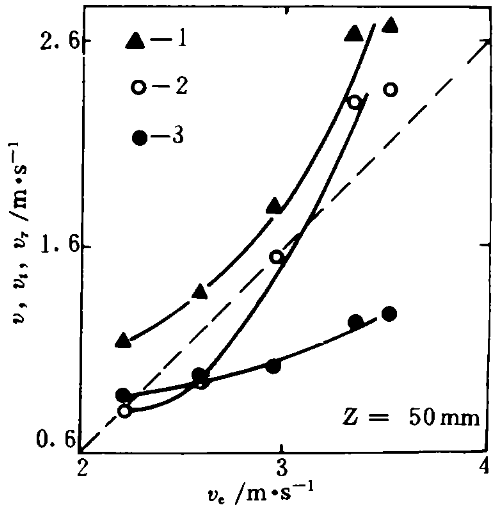

Fig. 6　Effect of inlet velocity on liquid velocity in swirl layer

1—total velocity;
2—tangential velocity component;
3—axial velocity component

3.5　*Bubble Velocity in Liquid Column*

As mentioned in section 2.2, some bubbles formed at $Z = 550$ mm directly discharged with underflow, while others might enter the centre. The velocity of the latter is shown in Table 2.

Table 2　Velocity of bubbles in liquid column formed at $Z = 550$ mm

Experimental parameters	Time for bubbles to move from ASH wall to the centre/s	Upward velocity of bubbles in the centre/cm·s^{-1}
$d_u = 18$ mm, $Q_e = 400$ mL/s	0.14	27.8
$d_u = 12.5$ mm, $Q_e = 280$ mL/s	0.16	41.7

From Table 2 it is seen that, when $Q_e = 400$ mL/s and $d_u = 18$ mm, the time for bubbles to move from ASH wall to the centre is shorter, while the upward velocity of bubbles in the centre is smaller. Because the velocity of bubbles not only affects the residence time of bubbles in ASH but also affects the collision and adherence of bubbles with particles, so in the operation of ASH, the inlet flowrate and the underflow pipe diameter should be adjusted to a comprehensive optimum range to get a satisfied separation.

4 CONCLUSSIONS

(1) Liquid column is one of the essential characteristics in a well operated ASH. The height of liquid column (H) is preferred to be $H = (1 \sim 2)D$. There exist inner helical flow and outer helical flow in liquid column.

(2) The tangential velocity component of liquid in swirl layer decreases rapidly when the axial coordinate Z increased, while the axial velocity component decreases slowly. And the tangential velocity component of liquid in swirl layer increases rapidly with the inlet velocity.

(3) It is reasonable to design an ASH with a small length/diameter ratio.

(4) It is not proper to sparge compressed gas in the section of ASH wall near the pedestal baffle, and the ASH wall near the pedestal baffle should be designed with solid wall other than porous wall.

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increasing, the Fermi level would move to the position close to ε_F of elemental Si, TM d-d interaction would become weak, and Ti-Si interaction would become strong. In addition, the bottom of valence band would shift to higher binding energy region. Thus Si s-s interaction would be intensified, and the interaction between Ti d, s, p states and Si s state would be strengthened as well.

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