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Vortex mechanism in hydrocyclones①

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[Abstract] On the basis of analyzing the vortex characteristics, a new mechanism of the vortex formation in hydrocyclones is developed. The main concept of the mechanism is that the vortex flow in a hydrocyclone is resulted from the overlapping of container rotation and hole leakage. The model is then used to explain the compound distribution of free vortex and forced vortex, predict the similarity of tangential velocity at different input pressures, and make count of the principle of small hydrocyclone with lower cut-size than large one. Meanwhile a new possible approach to a large hydrocyclone with lower cut-size by minimizing or eliminating the air core is discussed briefly.

[Key words] hydrocyclones; tangential velocity; vortex mechanism

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1 INTRODUCTION

As a widely used separation device, hydrocyclone is simple in structure, but rather complex in flow pattern. The most important tangential velocity is comprised by quasi-free vortex and forced vortex, the compound of tangential and axial flow results in inner vortex and out vortex, both tangential and radial movement produces the so-called "spiral flow", the relative motion between solid particles and liquid medium[1~3]. In addition, there are some other forms of flow such as short-cut flow, recycled flow and air core. For a long period, a lot of researchers have paid much attention to the flow field of hydrocyclone[4,5], however, there still are a series of problems open to question, one of them is the vortex mechanism.

In general, the liquid flow in a hydrocyclone is divided into tangential, radial and axial velocity. The distribution pattern of tangential flow reflects the basic characteristics of the vortex movement. Because of the importance of tangential velocity that is much higher than the other two velocities and produces a centrifugal force as the prerequisite for hydrocyclone operation, it is essential in both theory and practice to study the vortex flow, including its properties and formation mechanism. The basic vortexes in fluid mechanics are forced vortex and free vortex. Let an eddy element with limitless length rotate in ideal fluid, the movement formed inside and outside the eddy element is respectively the forced and free vortex. In forced vortex, the relation of tangential velocity u_θ and radius r is described by

$$u_\theta = k_1 r \tag{1}$$

in free vortex, the relation is

$$u_\theta = k_2 r^{-1} \tag{2}$$

where k_1 and k_2 are constants. The total vortex flow comprised by forced and free vortex is called as compound vortex that is a key to understand the vortex flow in hydrocyclones. In fact, the distribution of tangential velocity in radial is quite similar to the compound vortex, but with some important distinctions. In this paper, authors will investigate the formation mechanism of the vortex flow in hydrocyclones on the basis of analyzing the distinctions, then present some new ideals about the relation between the vortex and operation parameters of hydrocyclones.

2 VORTEX PROPERTIES IN HYDROCYCLONES

The vortex flow in hydrocyclones is distinguished from the compound vortex in ideal fluid by following aspects.

Firstly, in the ideal compound vortex, there is no radial and axial flow except tangential velocity. In hydrocyclones, there are three-dimensional flow, including tangential, radial and axial velocities, due to the limited flow space and the special drainage (overflow and underflow). This must result in a tangential velocity distribution different from the ideal compound vortex. Actually, it is impossible to form a ideal free vortex in the liquid area and only a quasi-free vortex observed, so the relation of tangential ve-

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locity and radius is

$$u_\theta = k_3 r^{-n} \quad (3)$$

where k_3 is a constant, n is between 0~ 1.

Secondly, there is an air core around the hydrocyclone axis. The forced vortex is mainly comprised by the core. In addition, there is a transition area between air core and quasi-free vortex[3]. Therefore, the overall distribution of tangential velocity in hydrocyclone can be illustrated as Fig. 1[6]. Although Kelsall' s early work[7] took the liquid flow around air core as forced vortex, this seems to be questionable. If the liquid around the air core rotates as a forced vortex, the light diffusion particles would have not entered the area, just as the particles can not enter air core or liquid core[8] because there is no radial flow in forced vortex. However, when the flow field in hydrocyclones is measured with LDV, the light diffusion particles can reach the interface of air-liquid. So that it is more reasonable to take the fluid flow near air core as a transition between forced vortex and quasi-free vortex rather than as a forced vortex.

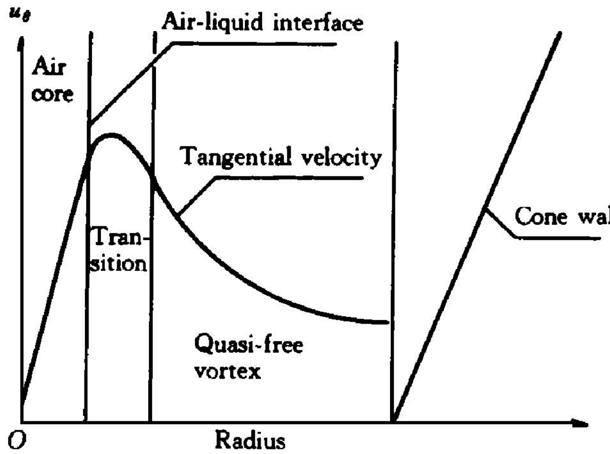

Fig. 1 Different tangential flow patterns in hydrocyclones

Thirdly, the development process of the vortex flow in hydrocyclone is different from that of the ideal free vortex. The latter is produced either by a preformed forced vortex or by a rotating solid bar with limitless length in ideal fluid. Whatever in which case mentioned, there is always a vortex center before the ideal free vortex is born. However the central vortex in hydrocyclone is not the prerequisite of the outer quasi-free vortex and is oppositely resulted from the rotating fluid entering the device. In other words, the outer quasi-free vortex in hydrocyclone appears before the inner forced vortex forms. A careful observation shows the following facts. As fed into hydrocyclone tangentially and slowly, liquid flows over the hydrocyclone wall and leaves out through the apex; with the increase of feed pressure, the rotation of liquid speeds up and a free surface looked like a funnel forms gradually; when the space is filled with liquid, a thin and short air core appears at the low end of the vortex finder, then the core grows and goes down to apex; at once the core is connected with the air outside, its diameter expands suddenly, and an apparent rotation at a high speed observed. At this moment, the flow situation in hydrocyclone tends to be stable.

In a new hydrocyclone, the designer[9] water-sealed the apex and observed a liquid core around the axis. If put the apex of a hydrocyclone with an air core into water, we can see that the original air core gradually decreases and eventually disappears, and the central liquid forced vortex is seen. When light diffusion particles are added into the hydrocyclone, the particles can not enter the liquid core, indicating that the central liquid core is a forced vortex. Obviously, the overall liquid movement in tangential is a compound vortex of forced vortex and quasi-free vortex (see Fig. 1).

The analysis above indicates that the actual vortex in hydrocyclones is different from the ideal compound vortex and also from the compound flow formed in nature such as tornado. How to explain the formation mechanism of the vortex flow in hydrocyclones is an old problem presented in 1960s[10] but still no satisfactory answer is given so far. The momentum conservation theory, i. e. $u_\theta r$ = constant, could predict the compound vortex[11], but the explanation did not take into account the special structure and operation of hydrocyclones. A new approach to the formation mechanism of the compound vortex in hydrocyclones is examined here and the new theory can account for some important phenomena and find some new applications.

3 VORTEX MECHANISM IN HYDROCYCLONES

The tangential flow in hydrocyclones may be taken as an overlap of two individual flow models. The first model is the flow pattern observed in a column container with a hole at one end, which is named here as "hole leakage model"; the second is resulted from a column container rotating around its central axis, named as "rotation model". Followings are analysis of the models in more detail.

It is well known that in a column container with a hole at its bottom end, the fluid in the container will leak out through the hole and the flow forms a free vortex approximately with a free surface of hyperboloid. If open the second hole at the other end of the container and neglect the influence of gravity, the free surface will be the overlap of two hyperboloids as shown in Fig. 2. In hydrocyclones, the apex and vortex finder are just the two holes, and the air-liquid interface is a free surface.

As for the model 2 (rotation model), the free vortex is related with the tangential feed of liquid. This feed method may be considered a column container rotating around its axis at an angular speed.

The liquid in the container forms a forced vortex and

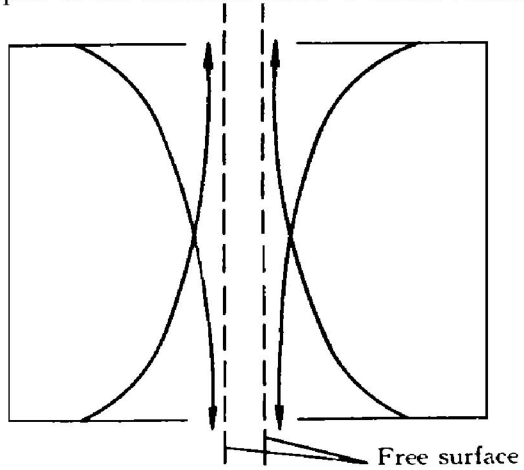

Fig. 2 Hole leakage model (Model 1) in column container with two holes at its ends

a free surface of paraboloid. Of course the free surface changes its shape with the increase of rotation speed. It is shown in Fig. 3 that there are two special cases for the free surface, i. e. a horizontal plane as angular speed $\omega = 0$ and a column as $\omega \to \infty$.

Overlaying Fig. 2 and Fig. 3, one can obtain the vortex flow in hydrocyclones (See Fig. 4), where the free surface is the air-liquid interface, the air core

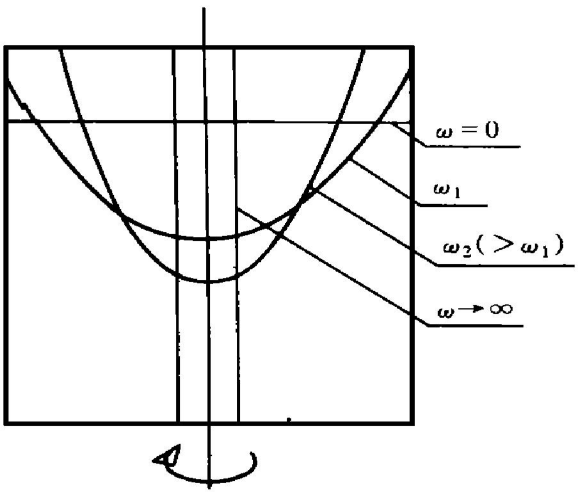

Fig. 3 Rotation model (Model 2) in column container

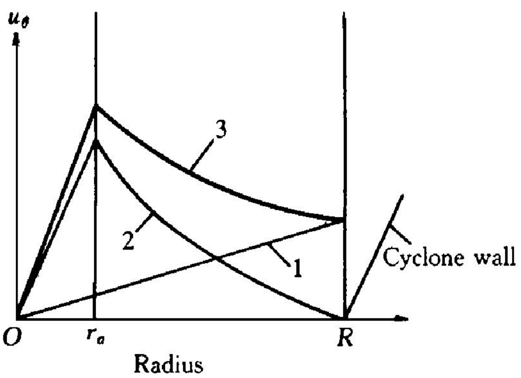

Fig. 4 Vortex flows of two models in hydrocyclones
Curve 1 —Force vortex resulted from the rotation model; Curve 2 —Quasi-free vortex and central forced vortex formed by hole leakage model; Curve 3 —Overlap of two models

moves as forced vortex, and the outside liquid movement is characterized by quasi-free vortex.

The formation mechanism of the vortex flow in hydrocyclones analyzed above, takes into account both the principles of fluid mechanics and the structure of hydrocyclones. Probably it is more useful for understanding the performance of hydrocyclones.

4 VORTEX MECHANISM AND FLOW CHARACTERISTICS

As shown above, the vortex flow in hydrocyclones is a compound of central forced vortex and outer quasi-free vortex in space, and an overlap of two flow models in formation mechanism. The mechanism can explain some important flow phenomena and provide a new reference to the selection of the operational and structural parameters of hydrocyclones.

Firstly, let us see the mechanism how to explain the similarity of tangential velocity. The tangential flow similarity is that the tangential velocity distribution pattern does not change with feed pressure, in other words, if the feed pressure increases, the tangential velocity at any given point within a hydrocyclone will go up with same amplitude. This is proven by measurements[5]. According to the new mechanism, it is easy to draw the conclusion. As shown in Fig. 5, if the feed pressure is low, the tangential velocity distribution is curve u_1 (for simplicity, the transition area is out of consideration in the figure, the velocities resulted from the rotation model and hole leakage model are represented respectively by curves 1 and $1'$); when the feed pressure increases with Δp, both the rotation and hole leakage are strengthened, then curves 1 and $1'$ becomes 2 and $2'$, the total tangential velocity rises to curve u_2. The similarity between curves u_1 and u_2 is easy to see.

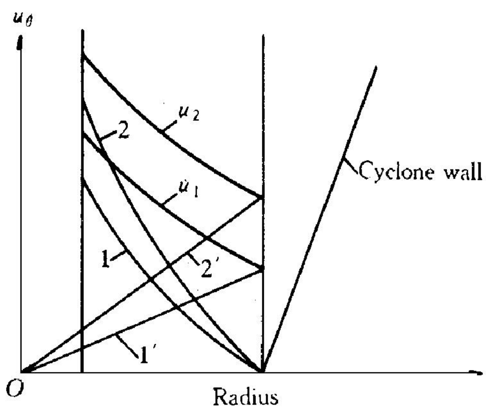

Fig. 5 Similarity of liquid tangential flow predicted by model 1 and model 2

Secondly, the new mechanism can predict the variation of air core size and shape at different feed pressure. As observed by experiments, in general, the air core is not a strict column but a long and thin funnel with a more or less larger diameter at the low end of vortex finder than that near the apex. It is easily drawn from the free surface of two flow models. In theory, only when the feed pressure is infinity, will the air core tend to be a column.

The third application of the new mechanism is as follows. In hydrocyclones with different diameters at same feed pressure, the tangential velocities are illustrated by Fig. 6. For the smaller hydrocyclone (see Fig. 6(a)), the tangential velocity predicted by rotation model is higher than that in large hydrocyclone at same radius when the rotation speed at cyclone wall is equal to each other. However, the velocity distributions resulted from the hole leakage model in large and small hydrocyclones is opposite, i. e. curve 2 should be above curve 1 if they were drawn in same coordinates. This is because of the fact that in large hydrocyclone the hole leakage is more violent than that in small hydrocyclone due to the larger apex and vortex finder. So that at the same radius, the total tangential velocity in larger hydrocyclone should be higher than that in smaller one. This may be beyond one's knowledge and needs to be verified by measurements, but it is not contradictory with the concept that smaller hydrocyclone is of lower cut-size at the same feed pressure[2]. As we know, the cut-size is not simply related to the tangential velocity, but depends on the centrifugal acceleration on the locus of zero vertical velocity (LZVV), i. e.

$$d_{50} \propto \frac{u_\theta^2}{r} \qquad (4)$$

where u_θ is the tangential velocity at radius r on

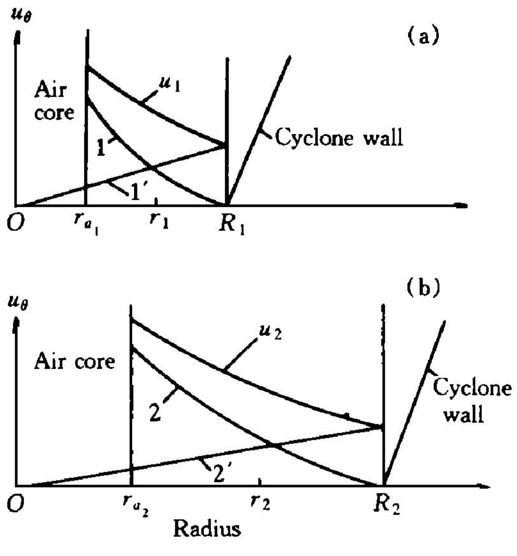

Fig. 6 Qualitative tangential velocity in hydrocyclones with different diameters, predicted by model 1 and model 2
(R_1, R_2 —Hydrocyclone radius; r_{a_1}, r_{a_2} —Air core radius)

LZVV, d_{50} is the cut-size. In the two hydrocyclones, let the average radius of LZVV be r_1 and r_2 respectively as shown in Fig. 6. It can be seen that the cut-size of small hydrocyclone is higher than that of large one due to $r_2 \gg r_1$ although the large hydrocyclone has a greater tangential velocity on LZVV. Therefore, it is probably reasonable to conclude that at the same feed pressure the lower cut-size of small hydrocyclone is owing to the smaller radius of LZVV, rather than to the tangential flow. This initiates an interesting idea, that is to move the position of LZVV inward by reducing or eliminating the air core in large hydrocyclones. As a result, the large hydrocyclones may keep a high throughout as well as a low cut-size. Authors are doing some experiments about such a hydrocyclone in a copper mine and will report the results elsewhere.

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