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Study on the floatation mechanism and floatation performance for the floatation cyclone of natural inlet air

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Abstract

A novel structure floatation cyclone of natural inlet air has been designed, and its structural characteristics and floatation principle have been analyzed. The velocity and pressure distributions within the flow field of the floatation cyclone have been studied by Navier-Stokes equations. Based on the flow characteristics of the mixture of fine coal and water, reasonable boundary conditions are decided and the equations are modified, so that the final equations can describe the real flow state of the flow field of the floatation cyclone. The boundary surface position between float coal and tailings is determined and there is an air cylinder in the central region of the floatation cyclone. The research reveals the floatation mechanism of the floatation cyclone. The floatation results can be greatly improved by regulating the structural dimensions of cyclone. The experimental results show that the floatation cyclone is very effective for the floatation of fine coal grains.

Keywords: Natural inlet air; Floatation cyclone; Floatation mechanism; Floatation of fine coal grains

1. Introduction

The floatation of fine coals is widely used in the floatation of coal industry. In recent years, with the development of coal industry, coal fines are greatly increased due to the mechanization of coal mining. In particular, new types of equipment for fine coal separation must be developed because the development strategies of clean coal have been carried out in China. Valuable experiences have been obtained based on a great deal of research on the conventional mechanical agitating floatation machine. Also it is recognized that the floatation behavior of conventional mechanical agitating floatation machine is carried out under the gravity field. The time that coal grains and slurry remain at floatation slot affects the floatation efficiency. Fine coal grains cannot be effectively separated. Longer floatation time requires larger floatation area and therefore confines floatation production.

The floatation cyclone of natural inlet air has fractional performance during the floatation. Air is sucked into the mixing chamber spontaneously while the mixture of fine coal and water are feed into mixing chamber by a slurry pump, and the cyclone has floatation performance also. Therefore the floatation cyclone of natural inlet air is the combination of both fraction and floatation. At first, the cyclone being put forward had fatal drawback [1], that is, air is forced into the mixture of fine coal and water and larger air bubbles were produced due to high pressure. They were not stable, so that normal separation flow field was seriously broken. But fine and stable bubbles play an important role in floatation and separation. It is impossible that the floatation is carried out with forcing air into the mixture of fine coal and water.

In recent years, researchers at home and abroad are studying coal floatation performance under centrifugal field, which is just investigated from processing technology [2]. But the authors have put forward a novel structure floatation cyclone of natural inlet air based on other researchers' investigations. Centrifugal force field is used for strengthening the process of the floatation. Great progress has been

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Nomenclature

r, θ, z	coordinates in r-direction, θ-direction and z-direction, respectively (m)	p	pressure of a certain point in the flow field (Pa)
u_r, u_θ, u_z	velocities in r-direction, θ-direction and z-direction respectively (m/s)	n	coefficient
F_r, F_θ, F_z	unit mass force in r-direction, θ-direction and z-direction respectively (N/kg)	R_0	inner radius of floatation cyclone (m)
ρ	density of mixture of fine coals and water (kg/m^3)	R_1	radius of forced vortex (m)
μ	dynamic viscosity of mixture of fine coals and water, (Pa s)	u_k	axial velocity of forced vortex (m/s)
		p_0	the pressure of feed mixture at inlet area of floatation cyclone (Pa)
		u_0	initial velocity of the feed mixture of fine coals and water (m/s)
		r_0	radius of boundary surface position (m)

made in the floatation of coal slurry. Compressor device is not used in the cyclone and the results of the floatation are good. The paper studies the velocity and pressure distributions within the floatation cyclone of inlet air by Navier-Stokes equations. The floatation results are greatly improved by regulating structural dimensions of cyclone. The achievement provides theoretical basis for the design of cyclone. The experimental results show that the cyclone is the effective equipment for the floatation of fine coal grains.

2. Analysis of the cyclone structure

2.1. Structure of the cyclone

As shown in Fig. 1, the mixture of fine coal and slurry under a certain pressure passes through the nozzle 2 and static pressure of the mixture is transformed into kinetic pressure. Vacuum is gained in the outlet area of the nozzle, air is inhaled into mixing chamber 5 by pipe of air inlet, and both air and mixtures are fully mixed. Outlet pipe 7 of float coal is an important component and the float coal is

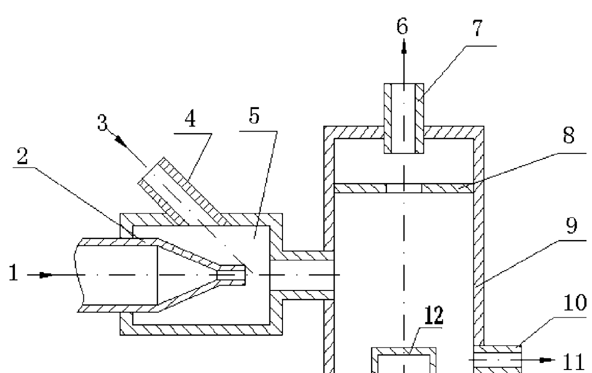

Fig. 1. Structure of floatation cyclone. 1, Inlet of mixtures; 2, Nozzle; 3, Air inlet; 4, Pipe of air inlet; 5, Mixing chamber; 6, Outlet of float coal; 7, Outlet pipe of float coal; 8, Damping plate; 9, Body of the floatation cyclone; 10, Outlet pipe of tailings; 11, Outlet of tailings; 12, Supporting plate.

overflowed from it. Damping plate 8 prevents higher ash coal from overflowing from outlet of float coal. The whole process of floatation is carried out in the body of the floatation cyclone 9. The purpose of supporting plate 12 is to make big coal grains of lower ash coal to the foam cylinder to overflow from the outlet of float coal, so that the float coals are obtained and the ash of tailings is increased. The tailings overflow from the outlet pipe of tailings.

2.2. Principle of the floatation

Floatation cyclone of natural inlet air mainly consists of air inlet pipe and body of the floatation cyclone. Natural inlet air is changed into air bubbles while coal slurry is feed into mixing chamber. The shape of the floatation cyclone body is cylindrical, in which damping plate and supporting plate are installed. Inlet of the mixture of coal and water is located in the middle-up of the cyclone and is tangential to the cylinder. Outlet pipe of tailing is located in the bottom of the cyclone and is tangential to the cylinder. The mixture of bubbles and coal slurry enter the cyclone along the tangent of cylinder at high-speed, and rotate in the side of the cyclone. The function of bubbles and hydrophobic fine coals makes the bubbles mineralize and produces the results of low density of hydrophobic fine coals, but hydrophilic dirt fine coals can not attach to the bubbles because density of hydrophobic fine coals is great different from that of hydrophilic dirt fine coals. According to the separation principle of cyclone, the mineralization bubbles flow into the center of the cyclone alone the radial direction of the cyclone to form foam cylinder, and finally discharge from outlet of float coal. But hydrophilic dirt fine coals flow into the bottom of the cyclone alone the inner surface of the cyclone and discharge from outlet pipe of tailing at last. That is the working principle of the cyclone. The supporting plate prevents foam cylinder from moving up in the vertical direction of the cyclone. The damping plate confines the velocity of foam cylinder, so that a stable foam layer is formed in the upper of the cyclone [3].

3. Theoretical research of the cyclone

In previous studies of the cyclone at home and abroad [4], most researchers did not study the flow field of the cyclone by Navier-Stokes' equations. The paper deals with the flow field of the cyclone by Navier-Stokes' equations and reveals the floatation mechanism of the cyclone.

From the flow phenomenon of the cyclone, the flow is three-phase (liquid–solid–gas). If the flow field of the cyclone is calculated according to the equation of three-phase, it is too difficulty to be solved. This paper is trying to analyze the flow field of the cyclone in a simple way, in which, first of all, the flow of the cyclone is assumed to be single-phase only and calculated, then the results of the calculation are modified according to the flow characteristics of two-phase (the influence of gas is ignored, because of little gas). And finally, the correctness of the results of the flow field will be verified by experiment.

3.1. Navier-Stokes' equations

In order to analyze the flow field of the cyclone, first of all, flow equations are introduced and simplified reasonably. Navier-Stokes' equations [5] for cylindrical coordinates are equation in r-direction:

$$\rho\left(\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}+u_z\frac{\partial u_r}{\partial z}-\frac{u_\theta^2}{r}\right) = \rho F_r-\frac{\partial p}{\partial r} + \mu\left(\frac{\partial^2 u_r}{\partial r^2}+\frac{1}{r}\frac{\partial u_r}{\partial r}+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial \theta^2}+\frac{\partial^2 u_r}{\partial z^2}-\frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}-\frac{u_r}{r^2}\right) \quad (1)$$

Equation in θ-direction:

$$\rho\left(\frac{\partial u_\theta}{\partial t}+u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}+u_z\frac{\partial u_\theta}{\partial z}+\frac{u_r u_\theta}{r}\right) = \rho F_\theta-\frac{1}{r}\frac{\partial p}{\partial \theta} + \mu\left(\frac{\partial^2 u_\theta}{\partial r^2}+\frac{1}{r}\frac{\partial u_\theta}{\partial r}+\frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2}+\frac{\partial^2 u_\theta}{\partial z^2}-\frac{2}{r^2}\frac{\partial u_r}{\partial \theta}-\frac{u_\theta}{r^2}\right) \quad (2)$$

Equation in z-direction:

$$\rho\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial \theta}+u_z\frac{\partial u_z}{\partial z}\right) = \rho F_z-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 u_z}{\partial r^2}+\frac{1}{r}\frac{\partial u_z}{\partial r}+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial \theta^2}+\frac{\partial^2 u_z}{\partial z^2}\right) \quad (3)$$

As shown in Fig. 2, there are flow of semi-free vortex and flow of forced vortex.

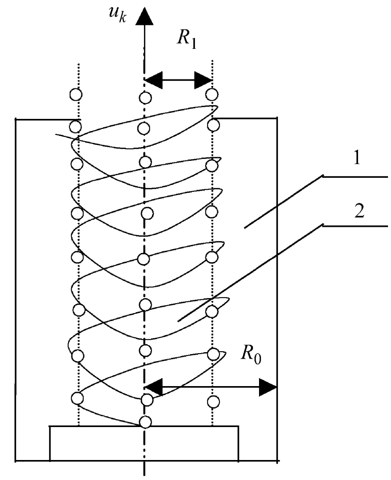

Fig. 2. Flow field region of floatation cyclone. 1, Flow of semi-free vortex; 2, Flow of forced vortex.

Since the flow state of the mixture is not related to the flow time, we have

$$\frac{\partial u_r}{\partial t}=\frac{\partial u_\theta}{\partial t}=\frac{\partial u_z}{\partial t}=0$$

Values F_θ and F_z are neglected, that is

$$F_\theta=F_z=0$$

Furthermore, $u_\theta r^n=C$ (Constant), $n=0.5$–0.9 [6], we obtain

$$\frac{\partial u_\theta}{\partial \theta}=\frac{\partial u_\theta}{\partial z}=0$$

Because of $p=p_{(r)}$, $u_z=u_{(r)}$, $u_r=u_{(r)}$, we obtain

$$\frac{\partial u_z}{\partial r}=\frac{\partial u_z}{\partial \theta}=0, \quad \frac{\partial u_r}{\partial \theta}=\frac{\partial u_r}{\partial z}=0$$

According to the above expressions, Eqs. (1)–(3) are converted into Eqs. (4)–(6) 'respectively' as below

$$\rho\left(u_r\frac{\partial u_r}{\partial r}-\frac{u_\theta^2}{r}\right)=\rho F_r-\frac{\partial p}{\partial r}+\mu\left(\frac{\partial^2 u_r}{\partial r^2}+\frac{1}{r}\frac{\partial u_r}{\partial r}-\frac{u_r}{r^2}\right) \quad (4)$$

$$\rho\left(u_r\frac{\partial u_\theta}{\partial r}+\frac{u_r u_\theta}{r}\right)=\mu\left(\frac{\partial^2 u_\theta}{\partial r^2}+\frac{1}{r}\frac{\partial u_\theta}{\partial r}-\frac{u_\theta}{r^2}\right) \quad (5)$$

$$\rho u_r\frac{\partial u_z}{\partial r}=\mu\left(\frac{\partial^2 u_z}{\partial r^2}+\frac{1}{r}\frac{\partial u_z}{\partial r}\right) \quad (6)$$

3.2. Analytic solutions of Navier-Stokes equations

First of all, the boundary conditions are discussed. When the mixture of fine coal grains and water just enter the cyclone along the tangent of the cyclone, only the tangential velocity is not zero, in other words, the velocities are equal to zero in z-direction and r-direction. The boundary conditions are specified as:

$$r = R_0,\ u_z = 0,\ p = p_0,\ u_\theta = u_0$$

$$r = R_1,\ u_z = u_k,$$

on the other hand

$$F_r = \frac{C^2}{r^{(2n+1)}}.$$

By integrating Eqs. (4)–(6), we have

$$p = -\frac{\mu^2(n+1)^2}{2\rho}\frac{1}{r^2} - \frac{\rho u_0^2 R_0^{2n}}{n r^{2n}} + \frac{\mu^2(n+1)^2}{2\rho}\frac{1}{R_0^2} + \frac{\rho u_0^2}{n} + p_0 \tag{7}$$

$$u_r = \frac{\mu}{\rho}\frac{(n+1)}{r} \tag{8}$$

$$u_z = \frac{u_k}{[R_1^{-(n+1)} - R_0^{-(n+1)}]r^{(n+1)}} - \frac{u_k}{[R_1^{-(n+1)} - R_0^{-(n+1)}]R_0^{(n+1)}} \tag{9}$$

As to Eq. (7), let $p=0$, we obtain $r=r_0$.

Eq. (8) is modified, given

$$u_r = \frac{\mu}{\rho}\frac{(n+1)}{r} + C_1,$$

and the boundary conditions are specified as: $r=r_0$, $u_r=0$, we obtain

$$u_r = \frac{\mu}{\rho}\frac{(n+1)}{r_0} - \frac{\mu}{\rho}\frac{(n+1)}{r} \tag{10}$$

Eq. (9) is modified, given

$$u_z = \frac{u_k}{[R_1^{-(n+1)} - R_0^{-(n+1)}]r^{(n+1)}} - \frac{u_k}{[R_1^{-(n+1)} - R_0^{-(n+1)}]R_0^{(n+1)}} + C_2,$$

and the boundary conditions are specified as: $r=r_0$, $u_z=0$, we obtain

$$u_z = \frac{u_k}{[R_1^{-(n+1)} - R_0^{-(n+1)}]r^{(n+1)}} - \frac{u_k}{[R_1^{-(n+1)} - R_0^{-(n+1)}]r_0^{(n+1)}} \tag{11}$$

Parameter p, u_r and u_z are functions of parameter r respectively.

3.3. The results of calculations

Parameters p, u_r and u_z are calculated by computer, and we obtain the curves for velocity and pressure distributions for the diameters 100 and 200 mm of floatation cyclone.

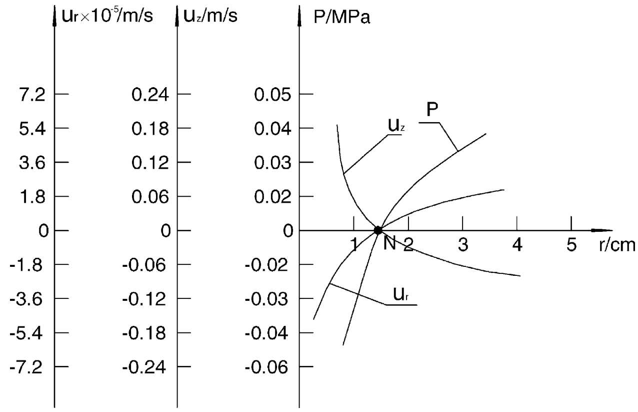

Fig. 3. Velocity and pressure distributions for the diameter 100 mm of floatation cyclone.

3.3.1. Distributions of radial velocities

As shown in Figs. 3 and 4, radial velocity u_r at a certain point (point N) is equal to zero in the cyclone, and the point N is the boundary point. As to cylindrical cyclone, cylindrical surface formed by boundary points is called the boundary surface. In the cyclone, radial velocities include inward and outward flow velocities. As for the diameter 100 mm of floatation cyclone, the direction of radial velocities ($r>15.75$ mm) is in the direction of outward flow, but the direction of radial velocities ($r<15.75$ mm) is in the direction of inward flow. As for the diameter 200 mm of floatation cyclone, the direction of radial velocities ($r>34.75$ mm) is in the direction of outward flow, but the direction of radial velocities ($r<34.75$ mm) is in the direction of inward flow.

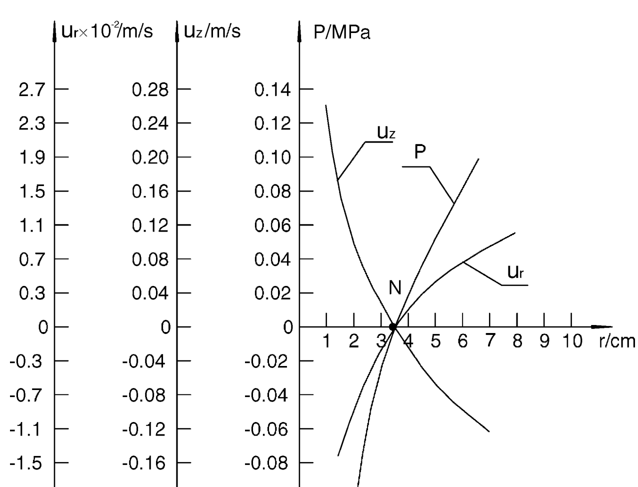

Fig. 4. Velocity and pressure distributions for the diameter 200 mm of floatation cyclone.

3.3.2. Distributions of axial velocities

As shown in Figs. 3 and 4, the axial velocities decrease with the increment of the radius of the cyclone. As for the diameter 100 mm of floatation cyclone, the direction of axial velocities ($r > 15.75$ mm) is in the direction of downward flow, but the direction of axial velocities ($r < 15.75$ mm) is in the direction of upward flow. As for the diameter 200 mm of floatation cyclone, the direction of axial velocities ($r > 34.75$ mm) is in the direction of downward flow, but the direction of axial velocities ($r < 34.75$ mm) is in the direction of upward flow. The boundary surface position between float coal and tailings mainly depends on outlet pipe of float coals, initial velocity and the pressure of the feed mixture of fine coals and water. Furthermore, the initial velocity of the feed mixture is a key factor.

3.3.3. Distributions of pressure

As shown in Figs. 3 and 4, the pressure in the flow region of semi-free vortex increases with the increment of radius, but the pressure in the flow region of forced vortex decreases with the decrement of radius. A certain point (point N, $p = 0$) is called boundary point or boundary surface. The phenomenon shows that negative pressure and an air cylinder exist in the flow region of forced vortex. Diameter of an air cylinder depends on pipe diameter of float coals, initial velocity and the pressure of the feed mixture of fine coals and water, and it plays a most important role in the fractional performance.

3.4. Explanation of theoretical calculations

According to the research results of floatation cyclone at home and abroad, there is not any researchers to study the flow field of floatation cyclone by Navier-Stokes' equations. Of course, authors also derived analytic solutions of Navier-Stokes' equations under many assumptions, and the results of calculations coincide with the practical flow field and reveal the floatation mechanism of the floatation cyclone. The results of calculations have some errors and should be improved. Although authors try to study the floatation cyclone in theory, there are certain shortages, and we would be very glad to give us some suggestions from researchers on the floatation cyclone.

4. Experimental research of the floatation cyclone

In order to examine the velocity and pressure distributions of the flow field of the cyclone, experimental research is carried out. As shown in Fig. 1, it is very difficult that the velocity and pressure distributions of the flow field of the cyclone are measured directly, that is, the velocity and pressure transducers are laid in the inside of body of the floatation cyclone. The external shape of the transducers themselves will disturb the velocity and pressure distributions of the flow field of the cyclone. Even if the velocity and pressure of some points of the cyclone could be measured, they could not show the real flow state of the flow field of the floatation cyclone either. So the correctness of the results of the flow field can be only verified indirectly, that is, ash of float coal and ash of tailings measured by experiment can prove the correctness of the results of the flow field

Many factors greatly affect the floatation performance of floatation cyclone, and the Ref. [3] has dealt with jet nozzle in details. The nozzle is the key component that influences the floatation performance of floatation cyclone. Here, experimental researches are carried for outlet pipe diameter of tailings and outlet pipe diameter of float coal influencing on floatation performance. In Fig. 1, component 10 is outlet pipe of tailings, from which tailings overflow, and component 7 is outlet pipe of float coal, from which the float coals overflow. The position of the outlet pipe of tailings, and the outlet pipe diameter of tailings and the outlet pipe diameter of float coal determine the quality of floatation. Table 1 (outlet pipe diameter of float coal = 34 mm) and Table 2 (outlet pipe diameter of float coal = 72 mm) are experimental data from a certain floatation plant. Through changing outlet pipe diameter of tailings and pressure of feed mixture, different ash of float coal and ash of tailings are obtained. Table 1 is the experimental data for the diameter 100 mm of floatation cyclone and Table 2 is the experimental data

Table 1
Comparison data for the diameter 100 mm of floatation cyclone (Outlet pipe diameter of float coal = 34 mm)

Outlet pipe diameter of tailings (mm)	Pressure of feed mixture (MPa)	Ash of float coal (%)	Ash of tailings (%)
19	0.05	12.29	26.50
19	0.04	11.99	26.78
17	0.04	10.22	27.55
16	0.04	14.81	27.65
14.5	0.04	14.13	28.57
14.5	0.03	14.50	30.16

Table 2
Comparison data for the diameter 200 mm of floatation cyclone (Outlet pipe diameter of float coal = 72 mm)

Outlet pipe diameter of tailings (mm)	Pressure of feed mixture (MPa)	Ash of float coal (%)	Ash of tailings (%)
30	0.08	10.06	31.72
30	0.12	8.68	25.56
32	0.08	8.60	32.40
32	0.11	8.30	36.36
35	0.09	11.84	34.36
35	0.12	10.70	35.74

Table 3
Comparison data for the diameter 100 mm of floatation cyclone (Outlet pipe diameter of tailings = 17 mm)

Outlet pipe diameter of float coal (mm)	Pressure of feed mixture (MPa)	Ash of float coal (%)	Ash of tailings (%)
30	0.05	12.50	28.23
30	0.04	10.23	26.73
34	0.04	9.80	29.12
34	0.04	13.52	27.35
36	0.04	14.16	28.08
36	0.03	15.08	32.34

for the diameter 200 mm of floatation cyclone. Table 3 (outlet pipe diameter of tailings = 17 mm) and Table 4 (outlet pipe diameter of tailings = 32 mm) are experimental data from the same floatation plant. Through changing outlet pipe diameter of float coal and pressure of feed mixture, different ash of float coal and ash of tailings are obtained. Table 3 is the experimental data for the diameter 100 mm of floatation cyclone and Table 4 is the experimental data for the diameter 200 mm of floatation cyclone.

The experimental results show that when the outlet pipe diameter of tailings is decreased, practical separation density can be increased, but if the outlet pipe diameter of tailings is too small, the extrusion of coals may be caused in the outlet area of tailings. As to floatation, dirt coals are easily mixed with float coals, and the outlet area of tailings is also jammed. But if the outlet pipe diameter of tailings is too large, lower recoveries of float coal are obtained. When outlet pipe diameter of float coal is decreased (the outlet pipe diameter of float coal is smaller than 31.5 mm for the diameter 100 mm of floatation cyclone, and the outlet pipe diameter of float coal is smaller than 69.5 mm for the diameter 200 mm of floatation cyclone), floatation of coals is not fully obtained, and that is, some float coals are discharged from the outlet pipe of tailings. But if the outlet pipe diameter of float coal is increased (the outlet pipe diameter of tailings is far larger than 31.5 mm for the diameter 100 mm of floatation cyclone, and the outlet pipe diameter of tailings is far larger than 69.5 mm for the diameter 200 mm of floatation cyclone), dirt coals are easily mixed with float coals, and some dirt coals are discharged from the outlet pipe of float coal, so that ash of float coal is increased and floatation performance is also reduced.

Table 4
Comparison data for the diameter 200 mm of floatation cyclone (Outlet pipe diameter of tailings = 32 mm)

Outlet pipe diameter of float coal (mm)	Pressure of feed mixture (MPa)	Ash of float coal (%)	Ash of tailings (%)
70	0.08	11.05	32.56
70	0.12	9.66	30.58
72	0.08	8.75	33.14
72	0.11	8.30	37.25
74	0.09	10.86	36.53
74	0.12	10.93	35.74

From the results of calculations, the outlet pipe diameter of float coal is decided by the position of boundary surface, so that firstly the position of boundary surface is determined through the theoretical calculations before the outlet pipe diameter of float coal is designed, then the outlet pipe diameter of float coal (the outlet pipe diameter of float coal is slightly larger than the diameter of the position of boundary surface) is chosen near boundary surface. As shown in Fig. 3, the diameter of the position of boundary surface is equal to 31.5 mm, so the outlet pipe diameter of float coal is chosen for 34 mm. As shown in Fig. 4, the diameter of the position of boundary surface is equal to 69.5 mm, so the outlet pipe diameter of float coal is chosen for 72 mm. A theoretical basis is provided for designing the floatation cyclone.

From experiments, under the pressure of 0.04 MPa, floatation cyclone for the diameter 100 mm works well in floatation performance with the outlet pipe diameter 17 mm of tailings and the outlet pipe diameter 34 mm of float coal. Under the pressure of 0.11 MPa, floatation cyclone for the diameter 200 mm works well in floatation performance with the outlet pipe diameter 32 mm of tailings and the outlet pipe diameter 72 mm of float coal. But the optimum of outlet pipe diameter of tailings can be determined only through a lot of experiments.

5. Conclusions

1. The newer structure floatation cyclone of natural inlet air has been put forward. And flow field of floatation cyclone is calculated by using a simple and new kind of method, and the method is feasible from the experiments.
2. From theoretical calculations, the velocity and pressure distributions are determined by Navier-Stokes' equations for the floatation cyclone of natural inlet air.
3. The boundary surface position between float coal and tailings is determined. An air cylinder exists in the flow region of forced vortex. Diameter of an air cylinder depends on pipe diameter of float coals, initial velocity and the pressure of the feed mixture of fine coals and water, and it plays a most important role in the fractional performance. The research reveals the floatation mechanism of the floatation cyclone.
4. The experimental results show that the diameter of outlet pipe diameter of tailings and the outlet pipe diameter of

float coal influence the floatation performance, and the optimum diameter of outlet pipe of tailings is determined by a lot of experiments.

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