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Research Article

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Impacts of upwelling speed and height-diameter ratio on separation action of coarse coal slime in teetered bed separator

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ABSTRACT

Ateetered bed separator (TBS)was improved based on the predecessors' models, andan experiment system was built.A mass of researches on narrow and mixture sizes fraction of coarse coal slime with subtle partition were conducted, a series behavioral parameter values of coarse coal slime's separation in TBSwere summarized. The results showed that good separation effect can be obtained both at low and high separation density in TBS for coarse coal slime whose size range is 3 to 0.5 mm; the best height-diameter ratio of TBS for this coarse coal slime sample is 3:1; upwelling speed should increase as size's increasing for narrow size fraction; the smaller the size range of particles is, the better the separation effect is.

Key words: teetered bed separator, coarse coal slime, separation action, hindered settling, upwelling speed

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INTRODUCTION

With the development of society, stricter requirement that separating with higher precision is put forward for various full-size-range mineral. At present, most of the coal preparation plants adopt the process which combines the gravity separation and flotation, while 0.5 mm is generally the cut-off point for them[1-3]. However, for gravity separation, separation efficiency falls sharply with the decrease of the particle size,thus no matter for the jig or cyclone (especially for large diameter cyclone),the separation efficiency of material near1.5 mm and below is very poor[4,5].According to statistics, the lower limit of effective separation size of most dense medium cyclones, whose diameters are bigger than 1m, is bigger than 1.5 mm, while the most congenial jig separating granularity limit is 1-3 mm.In terms of flotation, due to the limited bubble adhesion strength, its efficiency decreases with the increase of particle size and itssize limit cannot be too big. The generally accepted effective flotation maximum particle size is 0.5 mm[6]. Therefore a portion of the material (mainly 1.5-0.5 mm) between the dense medium separation lower limit and flotation upper limit cannot be separated effectively.

At present, many developed countries have applied TBS to replace spiral separator to deal withcoarse coal slime or the cleaned coal of spiral separator in coal preparation plants, and the results show that it has more advantages than spiral separators. According to related data, TBS can also be used for the heavy metal separating, such aszircon, quartz, phosphate rock and so on.Due to the great advantages such as simple construction, high segregation precision, easy control, low cost, and convenient for maintenance, TBS receives the industry's favor more and more[7]. For the separation of coarse coal slime, the lower limit can be 0.15 mm and the upper can be 2-3 mm. According to the application practice of Australia's fourth generation TBS, the separation density is less than 1.50 g/cm^3,meanwhile the ash content of product can be below 10%[8].

EXPERIMENTAL SECTION

Apparatus and materials:
Narrow fraction of coarse coal slime, particle size, respectively for 3-2 mm, 2-1.5 mm, 1.5-1.25 mm, 1.25-1 mm, 1-0.5 mm; wide and graded coarse coal slime, particle size, respectively for 3-1.5 mm, 1.5 -1 mm, 1.5-0.8 mm,3-0.5 mm, etc.

Phi 200 mmTBS model (homemade), muffle furnace, blast drying oven, electronic balance, sampling machine, domestic standard sieves, mixing barrel, crusher, densimeter, rotameter, floating barrels, pots and plates.

Characteristic analysis
According to the China Standards GB/T478-2008*Method for float-and-sink analysis of coal*to test every size range and draw out the washability curvesfor thesample coarse coal slime, as shown below.

Table 1:density distribution analysis of 3-2 mm sample

Density Fractions ($G\cdot L^{-1}$)	Yield (%)	Ash (%)	Cumulative Floats		Cumulative Sinks	
			Yield (%)	Ash (%)	Yield (%)	Ash (%)
<1.3	11.34	3.61	11.34	3.61	100	17.85
1.3-1.4	65.65	7.30	76.98	6.76	88.66	19.67
1.4-1.5	6.35	14.04	83.33	7.31	23.02	54.95
1.5-1.6	1.81	24.65	85.15	7.68	16.67	70.53
1.6-1.8	1.25	58.83	86.39	8.42	14.85	76.13
>1.8	13.61	77.72	100	17.85	13.61	77.72
Total	100	17.85				

Table 2:density distribution analysis of 2-1.5 mm sample

Density Fractions ($G\cdot L^{-1}$)	Yield (%)	Ash (%)	Cumulative Floats		Cumulative Sinks	
			Yield (%)	Ash (%)	Yield (%)	Ash (%)
<1.3	10.43	3.46	10.43	3.46	100	17.13
1.3-1.4	64.74	9.52	75.17	8.68	89.57	18.72
1.4-1.5	7.82	12.77	82.99	9.06	24.83	42.72
1.5-1.6	5.10	17.67	88.10	9.56	17.01	56.49
1.6-1.8	1.70	52.66	89.80	10.38	11.90	73.13
>1.8	10.20	76.54	100	17.13	10.20	76.54
Total	100	17.13				

Table 3:density distribution analysis of 1.5-1.25 mm sample

Density Fractions($G\cdot L^{-1}$)	Yield (%)	Ash (%)	Cumulative Floats		Cumulative Sinks	
			Yield (%)	Ash (%)	Yield (%)	Ash (%)
<1.3	11.68	3.60	11.68	3.60	100	17.40
1.3-1.4	64.37	7.91	76.05	7.25	88.32	19.22
1.4-1.5	7.01	14.34	83.06	7.85	23.95	49.62
1.5-1.6	2.45	31.98	85.51	8.54	16.94	64.22
1.6-1.8	2.22	40.15	87.73	9.34	14.49	69.69
>1.8	12.27	75.03	100	17.40	12.27	75.03
Total	100	17.40				

Table 4:density distribution analysis of 1.25-1 mm sample

Density Fractions ($G\cdot L^{-1}$)	Yield (%)	Ash (%)	Cumulative Floats		Cumulative Sinks	
			Yield (%)	Ash (%)	Yield (%)	Ash (%)
<1.3	32.98	3.89	32.98	3.89	100	16.95
1.3-1.4	43.15	8.74	76.12	6.64	67.02	23.38
1.4-1.5	7.82	13.81	83.94	7.31	23.88	49.84
1.5-1.6	2.14	27.26	86.08	7.80	16.06	67.38
1.6-1.8	2.68	55.35	88.76	9.24	13.92	73.55
>1.8	11.24	77.88	100	16.95	11.24	77.88
Total	100	16.95				

Table 5:density distribution analysis of 1-0.5 mm sample

Density Fractions (G·L^{-1})	Yield (%)	Ash (%)	Cumulative Floats		Cumulative Sinks	
			Yield (%)	Ash (%)	Yield (%)	Ash (%)
<1.3	5.04	3.52	5.04	3.52	100	9.85
1.3-1.4	78.86	7.21	83.90	6.99	94.96	10.18
1.4-1.5	9.42	12.32	93.32	7.53	16.10	24.74
1.5-1.6	2.74	15.47	96.06	7.75	6.68	42.25
1.6-1.8	1.10	35.66	97.15	8.07	3.94	60.85
>1.8	2.85	70.54	100	9.85	2.85	70.54
Total	100	9.85				

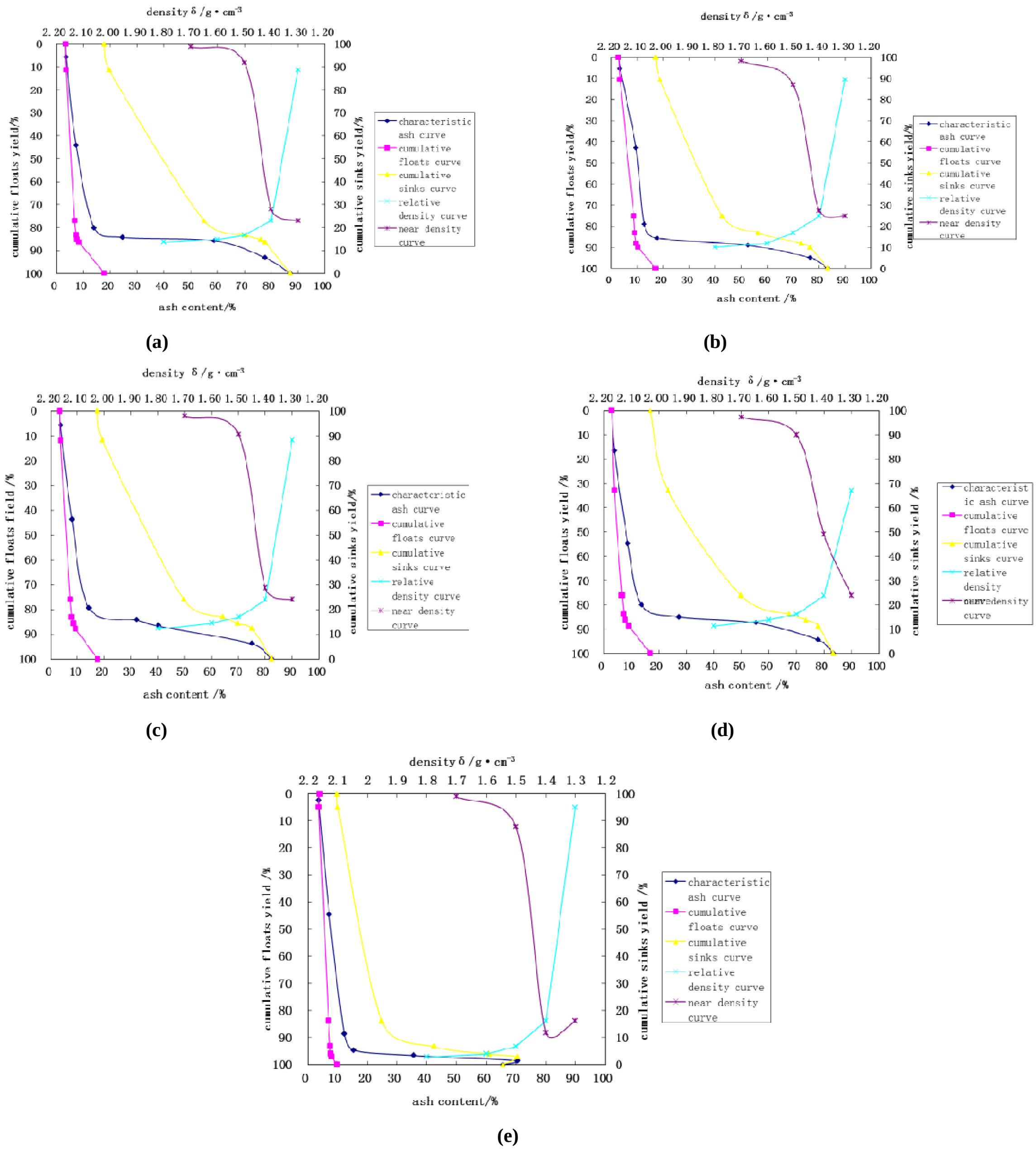

Fig. 1:Washability curves of different narrow size fractions coarse coal slime sample
(a) 3.00-2.00 mm; (b) 2.0-1.5 mm; (c) 1.5-1.25 mm; (d) 1.25-1.0 mm; (e) 1.00-0.5 mm

Force analysis of particles in teetered bed

TBS makesparticles be fluidized by a rising flow toform a fluidized bed at a certain density which is similar to suspension. As other gravity separation methods, TBSneeds a good stratification and separation effect to obtain good separation indexes.The mechanism and regularity that particles get be layered and separated according to density as the main characteristic (also test the effect of size and shape) in the fluidized separation environment should be explained by liquid-solid fluidization theory. In this regard, the theoretical basis of liquid-solid fluidized separation should include two aspects: the first is the interference subsidence theory in the upwelling environment, it mainly considers the process of stratification and separation from the single particle angle; the other is liquid-solid fluidization technology which is similar to heavy medium suspending liquid separation to investigate separation process from the angle of macro perspective or the separation environment. Therefore, the interference stress of the particles in the bed was analyzed.

The motion law of an object in fluid is a basic problem in the process of numerous mineral separation, the different trajectories of mineral particles with different natures in fluid determine the results of size-dominant or density-dominant separation. Actually,mineral processing is a process that using the properties of fluid and flow field reasonably to increase the track gap of mineral particles with different physical properties and separate them.

Particle force analysis is the core problem of solid particles motion in the liquid-solid two phase flow. Basset (1885), Boussineaq (1885), Oseen (1927) studied the linear motion of single ball with accelerated motion in the viscous fluids, and pointed out that the force of sphere depends not only on sphere's instantaneous speed and acceleration, but also the history of accelerated motion which the ball does, then the famous B.B.O. equation was obtained. Later generations modified the B.B.O. equation, and added the relevant particle interactions to it [9-11]. The improved particle motion equation in the two phase flow is:

$$\frac{1}{6}\pi d^3\rho_\rho\left(\frac{du_\rho}{dt}\right)=F_g+F_p+F_a+F_B+F_m+F_l+F_r+F_{IP}+F_s \tag{1}$$

Where d is the particle size, u_ρ is the movement speed of particle, ρ_ρ is the density of particle, t is time, F_g is the gravity, F_p is pressure, F_a is the additional mass force, F_B is Basset force, F_m is Maguns force, F_s is Saffman force, F_l is the buoyancy force of particle, F_{IP} is the resistance between phase, F_r is the force between particles.

For single particle in liquid-solid fluidized bed separation system, most of them are surrounded by other particles except the few near the wall. As a result, the resultant force of a single particle in the horizontal direction is zero. For separating, what should be mainly taken into consideration and cared about is the stress in the vertical direction. So, particles' rotation movement, lateral movement, buoyancy, Maguns and Saffman force could be ignored [12-15]. The equation is simplified as:

$$\frac{1}{6}\pi d^3\rho_\rho\left(\frac{du_\rho}{dt}\right)=F_g+F_p+F_a+F_B+F_r+F_{IP} \tag{2}$$

The separation of coarse coal slime in TBS is actually a process that coal particles move in autogenous medium and get be layered and separated. The generation of the additional mass force due to the accelerated movement of the mediumwho driven together by the particles that do relative accelerated movement in the bed medium.Andthe additional mass force is directly proportional to the speed difference between the particle and the medium. While the speed difference is nearly zero in the liquid-solid fluidized bed separation system, so the force can be completely ignored. Because of the existence of sticky, there is an accelerate process before particles getting into bed, and the flow field around can't achieve stability immediately. The force which particle obtains from the flow field in bed depends not only on the relative speed of the particles, also depends on the previous acceleration, this component is Basset force, which is significant only in the early stage of accelerated motion. The time one particle spends to reach at the end of the sedimentation rate of acceleration is very short, the action time of Basset force is short, too. But what exerts a tremendous influence actually in the separation is the movement after achieving the terminal velocity, so the Basset force can be ignored also [16, 17].

The above equation is simplified to:

$$\frac{1}{6}\pi d^3\rho_\rho\left(\frac{du_\rho}{dt}\right)=F_g+F_p+F_r+F_{IP} \tag{3}$$

The gravity F_g on the particle is

$$F_g = \frac{1}{6}\pi d^3 \rho_p g \tag{4}$$

（2）the buoyancy F_p on the particle is

$$F_p = \frac{1}{6}\pi d^3 \rho_l g \tag{5}$$

The resistance between phases F_{IP}

$$F_{IP} = \frac{\pi}{8} C'_R \rho_l (v_l - v_p)|v_l - v_p| \tag{6}$$

From the above, the resultant force acts on the particle in liquid-solid fluidized bed is

$$\frac{1}{6}\pi d^3 \rho_\rho \left(\frac{du_\rho}{dt}\right) = \frac{1}{6}\pi d^3 (\rho_p - \rho_l) g + \frac{\pi}{8} C'_R \rho_l (v_l - v_p)|v_l - v_p| + F_r \tag{7}$$

After filling into the bed, no matter whether the v_p is equal to zero, before reaching at the end of the sedimentation velocity, $v_l \neq 0$, $v_l - v_p \neq 0$, so $\frac{\pi}{8} C'_R \rho_l (v_l - v_p)|v_l - v_p| \neq 0$ .The smaller the feed particle size is, the more important the resistance of particle in the resultant force is. Therefore, F_{IP} can't be ignored. Because the particle size is almost as big as the medium particle size in autogenous liquid-solid fluidized bed, the force generated by the continuous collision from the medium particlethat acting on feed particle also cannot be ignored, which directly influences the movement direction of particle, so $F_r \neq 0$. The unbalance forces which drive the particles in bed to move include not only the net buoyancy, but the fluid resistance F_{IP} and the resultant force of medium particles. Therefore, theups and downs ofparticle depends not only on the direction of net buoyancy, but also the size and direction of F_{IP} and F_r . As a result, the delamination of materials group is driven priority by density difference, meanwhile is influenced by other factors, especially for fine particle.

RESULTS AND DISCUSSION

Narrow size fraction

Impacts of the upwelling speed on the separation result

The rising flow provides power and layered conditions for coarse coal slime, so its size and uniformity will have an important influence on separation effect. In all tests, the amount of materials given in the separator is same. Sampling and analysis after same timeoperation at different upwelling speeds then draw up the separation effect graphs.

According to the separation results in different conditions and the theoretical yields from Fig. 1, the quantity efficiency were calculated. Fig. 2is the quantity efficiency and Fig. 3 is the combustible recovery.

As Fig. 2 and Fig. 3show, when the upwelling speed is small, both the quantity efficiency and combustible recovery rate are low; when the upwelling speed is large, both the quantity efficiency and combustible recovery rate are high. They rapidly increase as straight line in initial stage, afterreachingat about 90%, increasing trend is reduced.Different size fractionshave different critical values, but mainly bigger the size is the smaller the critical value is, but all the values reach the maximum when the upwelling speed is about 9 m^3/h. So, 9 m^3/h was used as the best speed in the later study. This proves thatupwelling speed has a significant impact on the quality and quantity of clean coal product.

Impacts of the height-diameter ratio on the separation result

For capacity, themost important factoris bed diameterand associates with the upwelling velocity of bed. For a certain diameter and upwelling velocity, feed amount can be worked out according to the production,and then the static bed height can be got from the required residence time of feed in the fluidized bed. While real bed heightcan be got according to the expansion ratio and porosity.

In order to get a suitable height-diameter ratio, a TBS was designed with five detachable 200 mm connection cylinder structures, so a systematic separationeffecttestswith four height-diameter ratios (5:1、4:1、3:1、2:1) were conducted.

The calculation predictsthe quantity efficiency and combustible recovery rate on 2.0-1.5 mm size range and 9 m^3/h upwelling speed, as illustrated in thesetables.

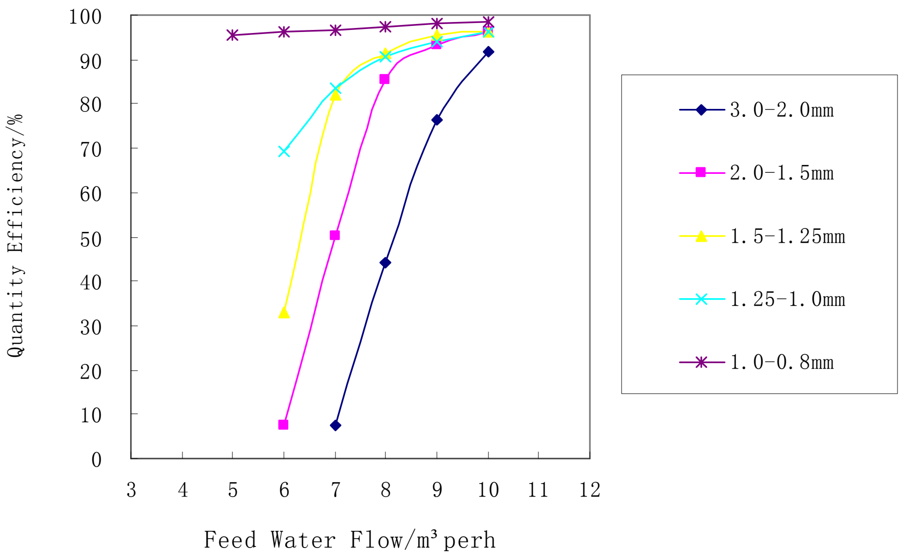

Fig. 2:Quantity efficiency curves of various narrow size fractions with4:1 height-diameter

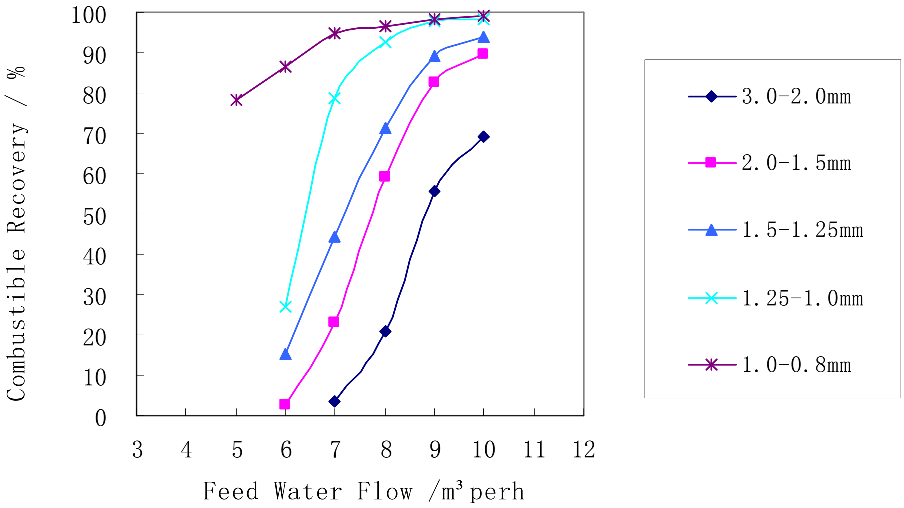

Fig. 3:Combustible recovery curves of various narrow size fractionswith4:1 height-diameter

Table 6:quantity efficiency for 2.0-1.5 mmcoarse coal slime with 4:1height-diameter ratio

Height-diameter Ratio	5:1	4:1	3:1	2:1
Quantity Efficiency (%)	72.03	92.09	94.32	92.74

Table 7:combustible recovery for 2.0-1.5 mmcoarse coal slime with 4:1 height-diameter ratio

Height-diameter Ratio	5:1	4:1	3:1	2:1
Combustible Recovery (%)	76.76	82.44	86.86	84.02

Table 6 and Table 7 demonstrate that height-diameter ratio has a major impact on TBS'separation and is one of the most important structure parameters. In the beginning of height-diameter ratiochanges from larger value to small, both quantity efficiency and combustible recovery rate increase. The best height-diameter ratio is about 3:1.When the height-diameter ratio is 3:1, both quantity efficiency and combustible recovery rate reached the maximum. After the maximum, both of themdeclined in different degrees.

Wide size fraction

Impacts of the upwelling speed on the separation result

The quantity efficiency and combustible recoveryof mixed size fraction with3:1height-diameter ratio are shownin the following tables.

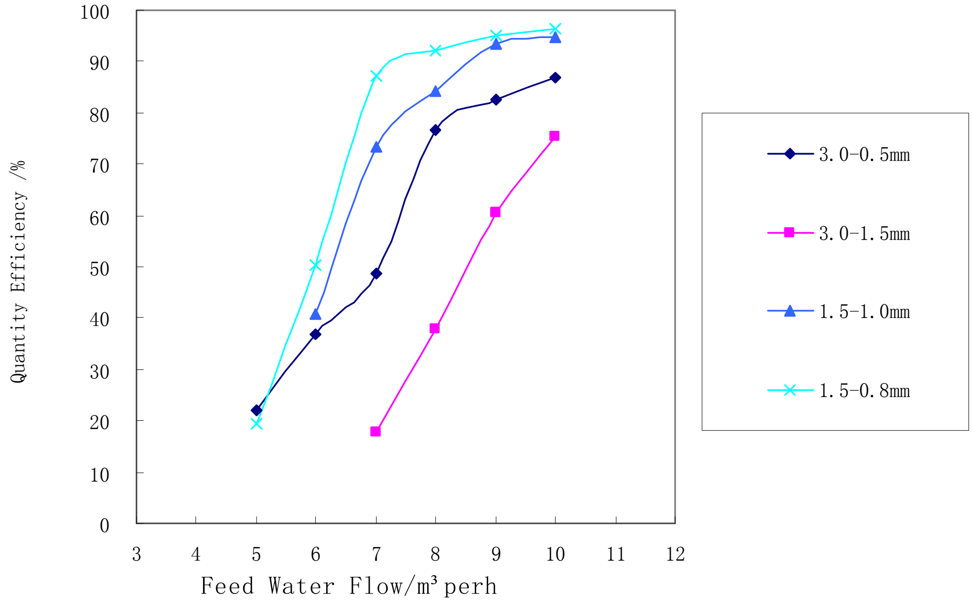

Fig. 4:Quantity efficiency curves of various mixed size fractions with3:1 height-diameter

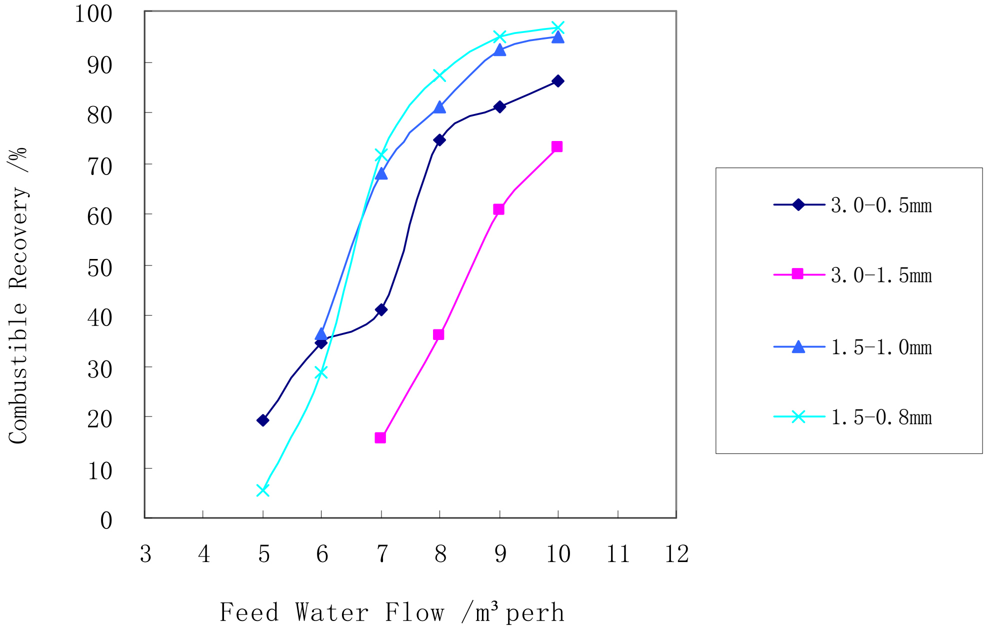

Fig. 5:Combustible recovery curves of various mixed size fractions with3:1 height-diameter

As shown in Fig. 4 and Fig. 5, the separation of mixed and narrow size fraction in TBS have the same tendency roughly, when upwelling speed is small, cleans ash, quantity efficiency and combustible recovery rate are low; when the upwelling speed is large, cleans ash, quantity efficiency and combustible recovery rate are high.So upwelling speed has a significant impact on the quantity efficiency and combustible recovery ratefor various size fraction.

Bothquantity efficiency and combustible recovery rate increase with the increasing of upwelling speed, and they generally reach at their maximumsat 9 m^3/h, then their increasing trend are flat gradually.But, bothof them are smaller than narrow size fraction.

Impacts of the height-diameter ratio on the separation result

Quantity efficiency and combustible recovery rate of 3-0.5 mmsize fraction at 9 m^3/h upwelling speed can be got from a great number of experiment data, as follows.

Table 8: quantity efficiency for 3-0.5 mm coarse coal slime with 9 m^3/h feed water

Height-diameter Ratio	5:1	4:1	3:1	2:1
Quantity Efficiency (%)	60.77	83.91	85.84	84.85

Table 9:combustible recovery for 3-0.5 mm coarse coal slime with 9 m^3/h feed water

Height-diameter Ratio	5:1	4:1	3:1	2:1
Combustible Recovery (%)	74.43	80.93	83.98	81.04

Table 8 and table 9 suggest that for the separation of 3-0.5 mm coarse coal slime with 9 m^3/h feed water, quantity efficiency and combustible recovery have similar variation tendencies,theyincrease rapidly in the early, while go down gently after reaching their maximums at approximately 3:1 height-diameter ratio.

CONCLUSION

In summary,upwelling speed and height-diameter ratio aresignificant factors for the separation of narrow and wide size fractions coarse coal slime in TBS, the best upwelling speed which got from this study is 4.8m/min(as 9 m^3/h feed water) and the best height-diameter ratio is approximately 3:1.

The separation effect for narrow size fraction is better than wide fraction, this can be explained by the interference settling theory as the equal settling ratio of wide size fraction comes close to or bigger than the hindered settling's. Therefore, the feed of TBS should have a narrow size range.

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