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An Applied Model of Minimum Rotating Speed for Drum Shearer to Avoid Drum Clogging

Kuidong Gao, Xin Zhang*, Kao Jiang, Yang Yang, Guangjun Yin and Bing Liu

College of Mechanical & Electrical Engineering, Shandong University of Science & Technology, Qingdao 266590, Shandong, China
**Corresponding Author: zhangxinmt@163.com*

ABSTRACT

Shearer drum of thin coal seam is prone to clogging. In response to this phenomenon, this paper carries out a study on the minimum rotating speed of shearer drum. Firstly, it establishes a space capacity model of shearer drum with clearance ring taken into consideration. Next, it establishes a mathematical model for the restrictive effect of drum capacity on rotating speed according to operation features of shearer drum and features of excavated coal. Finally, it verifies the accuracy and effectiveness of the mathematical model through modeling test. The results show that the mathematical model can serve as determining the minimum rotating speed, which will not clog the shearer drum. When rotating speed is much larger than that minimum rotating speed, the drum space capacity will be greatly influenced by centrifugal force. Under the same structural and operation parameters, the sectional area utilization coefficient of shearer drum's discharge section is larger when it is in drum up cutting mode compared with drum down cutting mode.

Keywords: Coal loading rate; Drum space capacity; Mathematical model; Rotating speed; Shearer.

INTRODUCTION

Shearer is the most common mining equipment on fully mechanized mining face. The efficiency and reliability of shearers greatly rely on the performance of their drums. Shen, LIU Songyong, LIU Xiaohui and others (Shen et al., 1997; LIU et al., 2009a; LIU et al., 2015) studied the lump coal cutting efficiency of shearer drum through theoretical analysis and experiments, and the influence of drum structure parameters and operation parameters was pointed out. Those achievements would give more guidance on shearer drum design to improve lump coal rate. Achanti (1998), Muralidharan (2003) and Rizwan (2003) studied the relationship between respirable dust generation and drum parameters, pick parameters through experiments, and respirable dust reduction was promoted in coal mining. Hekimoglu and Ozdemir (2004), Eyyuboglu and Bolukbasi (2005), Bo Yu(2005), Liu et al. (2009,b,c) and Liu et al. (2014) studied the respective relations between cutting torque and drum structure, pick parameters and cutting parameters, and their suggestions are very helpful in improving drums cutting capacity and reducing drums stress or abrasion. The above researches have played very important roles in improving shearer drums cutting efficiency and increasing their service life. Nevertheless, as the shearer is working, the performance of the shearer drum not only depends on cutting performance, but also depends on its coal loading performance.

In 1980s and 1990s, some British scholars discussed and studied the key factors influencing the loading performance of shearer drum in medium coal seam mining. Their suggestions on the drum structure design and working parameter selection have done great help in improving the mining efficiency in medium coal seam (Morris 1980; Hurt and Mcstravick 1979; Ludlow and Jankowski 1984). In 1984, Peng and Chiang briefed us on the factors that would affect drum coal loading performance, but gave no details (Peng and Chiang, 1984). In 1994, Ayhan (1994) analyzed the cutting and loading performance of drum shearers in Orta Anadolu Linyitleri (OAL) Mine in his master's thesis and mentioned that the distance between the coal wall and armored face conveyor (AFC) had a great influence on coal loading performance. In 2006, a kind of shearer drum with conical drum hub was tested by Ayhan and Eyyuboglu, and its advantage over the shearer drum with cylindrical drum hub in terms of coal loading efficiency was verified (Ayhan and Eyyuboglu 2006). Bołoz Ł (2013) developed a new longwall shearer, which had been used in thin hard coal seams mining; and this shearer and its operation technology could help the coal mine acquire very good daily output achievement. From the above researches, it can be concluded that foreign researchers mainly focus on study on that of medium and thick coal seam shearer; very less attention had been paid to thin seam shearer research. In China, as medium and thick coal seams are decreasing, mining of thin seam has attracted great attention of domestic mining industry, increasing investment from Chinese major coal mine enterprises. Chinese mining equipment researchers have been focusing on the performance of thin seam shearers. Even, the achievements obtained from medium shearer technology research can give help in drum and shearer design, but the help is very little and insignificance. Owing to the mining thickness limit, the drum diameter of thin seam shearer is much smaller than medium thick seam shearer, and the shearer drum working condition and performance also have much difference, which have been paid attention to by Chinese researchers. Orthogonal model test method was used by S.Y. Liu, et al. (2011) to study the effect condition of the vane angle, rotating speed and hauling speed on coal loading rate in drum down cutting mode. Model test was used to ensure the best vane angle, and discrete element method (DEM) was used to research the influence of mining face angle, drum position parameters and ranging arm thickness on coal loading performance, from which some useful conclusions have been reached (Gao et al., 2012, 2014 a b).

Even vast researches on thin coal seam shearer have been carried out by Chinese scholars, but this still cannot satisfy the manufacture need. For example, the appearance of shearer drum clogging frequently arises in thin coal seam mining on account of improper drum structure or improper shearer operation. Because the vane depth of thin coal seam shearer drum is small, the space in drum is very tight, and the drum will be easily clogged when the operation parameters mismatch the drum structure parameters. Shearer drum clogging not only affects the movement of coal, but also increases the load of shearer driver, which will hinder the drum cutting and shearer haulage. In response to it, based on the structural and operation features of shearer drum and the features of excavated coal analysis, a mathematical model for the restrictive effect of shearer drum space capacity on rotating speed was established and verified.

MODEL ESTABLISHMENT

Figure 1 shows the structure of shearer drum, from which it can be seen that shearer drum mainly consists of conical pick, pick holder, drum hub, clearance ring and helix vane. The shearer drum's capacity to hold coal depends on the diameter of clearance ring, helix vane and drum hub. Figure 2 shows the working situation of the shearer drum. From Figure 2, with the spiral effect of the helix vane, some of the excavated coal are conveyed to AFC; Also, some are thrown to the back of the shearer drum and become float coal in the track. When the excavated coal are moving from clearance ring to goaf side of drum, the amount of coal will increase along the motion path. If the amount of coal is larger than the space capacity in any place of the drum, drum clogging will happen at that place. The shearer drum clogging, on one hand, may hinder the rotating of drum, which will lead to abrupt change load of the cutting unit, posing threat to the shearer normal operation; on the other hand, drum clogging will severely clog the carrier route of the coal, which drastically lowers the coal loading efficiency.

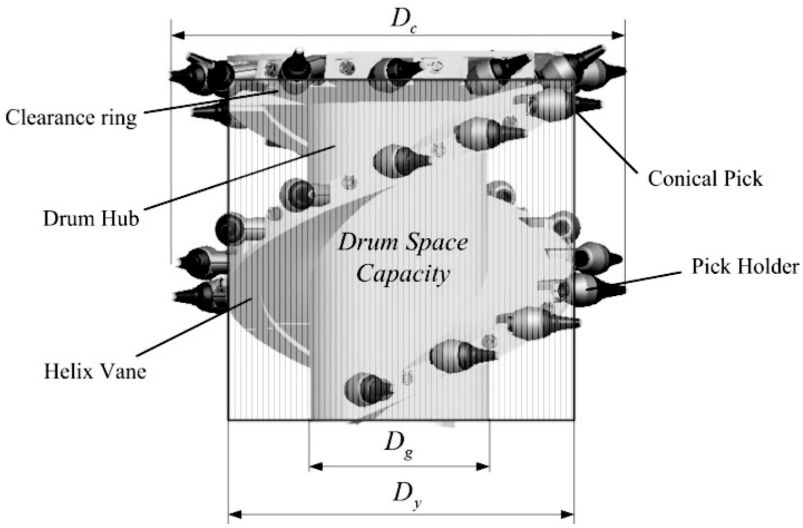

Fig. 1. Structure of shearer drum.

To avoid drum clogging, firstly, in terms of the structural design and operation parameters of the shearer drum, the capacity restriction should be taken into consideration. Thus, this section gives account to the derivation process of the capacity mathematical expression, and the restricted condition of rotating speed and hauling speed is discussed.

The calculated method of drum loading capacity was proposed by Peng and Chiang in 1984, which was based on drum expansion scheme, ignoring the influence of enveloping space changing on drum loading capacity when helix vanes were expanded, while in fact the clearance ring occupies a part of the shearer drum, and they also did not consider this. Thus, based on previous research, the mathematical expression is further derived, taking clearance ring into consideration. We take the centre of the unload section of the shearer drum as the origin and establish coordinate, as shown in Figure 3.

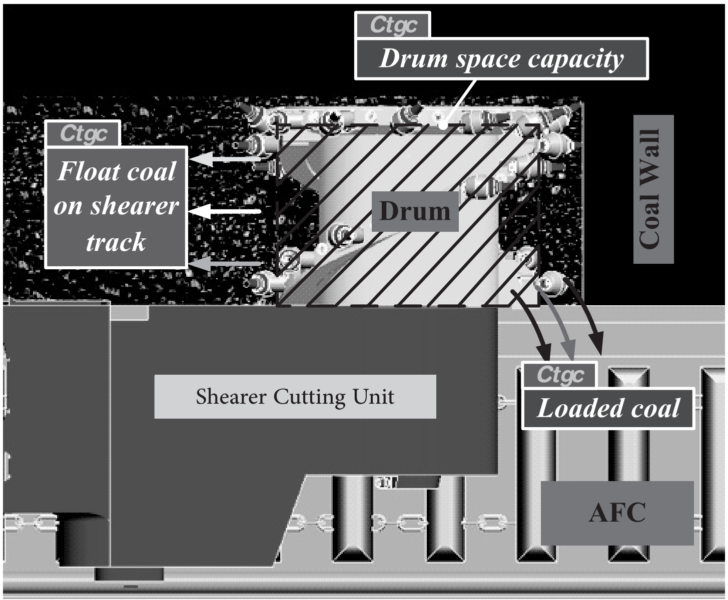

Fig. 2. Work condition of shearer drum.

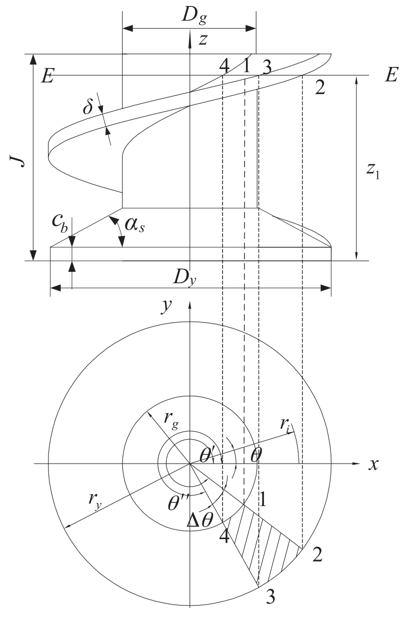

Fig. 3. Section of single helix vane drum.

The helix vane in Figure 3 can be regarded as the spirochete formed by the screw motion of the rectangular surface along the axis of drum hub. Its helicoid is the space curved face formed by numerous helixes with the same pitch, whose radius r ranges in $r_g \sim r_y$. The rectangular equation of the helix is

$$\begin{cases} x = r\cos\theta \\ y = r\sin\theta \\ z = r\theta\tan\alpha \end{cases} \tag{1}$$

where r is radius of any point in helix vane, m; r_g is radius of drum hub, m; r_y is radius of helix vane, m; θ is surrounding angle of the helix vane, rad; α is angle of the helix vane at diameter, rad.

And because

$$\tan\alpha_g = \frac{J}{2\pi r_g} \tag{2}$$

$$\tan\alpha_i = \frac{J}{2\pi r} \tag{3}$$

where J is web depth, m; α_g is start angle of the helix vane at diameter, rad; α_i is lead angle of the helix vane at diameter, rad.

Hence,

$$r\theta\tan\alpha_i = r_g\theta\tan\alpha_g \tag{4}$$

Considering helix vane thickness, the equation of the other helicoids is

$$\begin{cases} x = r\cos\theta \\ y = r\sin\theta \\ z = r\theta\tan\alpha + \delta/\cos\alpha_i \end{cases} \tag{5}$$

where δ is thickness of the helix vane, m.

Assume that the helix vane is cut by a plane, which is perpendicular to the direction of z and crosses the point 'z_1'. The plane intersects helix vane at point 1, 2, 3, 4. The cross-sectional area of the shearer drum is

$$S_{1234} = \frac{1}{2}\Delta\theta r_y^2 - \frac{1}{2}\Delta\theta r_g^2 \tag{6}$$

From Equation (1) and Equation (5), the rotating angle of $\overline{12}$ is

$$\theta' = \frac{z_1}{r_{cp}\tan\alpha_{cp}} \tag{7}$$

where r_{cp} is average radius of helix vane, and $r_{cp} = (r_g + r_y)/2$, m; α_{cp} is average angle of helix vane, rad; z_1 is the distance from the plane z to the goaf side of drum.

The rotating angle of $\overline{34}$ is

$$\theta'' = \frac{z_1 - \delta/\cos\alpha_{cp}}{r_{cp}\tan\alpha_{cp}} \tag{8}$$

The angle between $\overline{12}$ and $\overline{34}$ is

$$\Delta\theta = \theta' - \theta'' = \frac{\delta}{r_{cp}\sin\alpha_{cp}} \tag{9}$$

Bringing Equation (9) into Equation (6),

$$S_{1234} = \frac{\pi}{4}(D_y^2 - D_g^2)\frac{\delta}{J\cos\alpha_{cp}} \tag{10}$$

where D_y is drum helix vane diameter, m; D_g is drum hub diameter, m.

For the single helix vane shown in Figure 3, the maximum sectional area for coal loading F_{max} is

$$F_{\max} = \frac{\pi}{4}(D_y^2 - D_g^2)(1 - \frac{\delta}{J\cos\alpha_{cp}}) \tag{11}$$

For the multi helix vanes, the maximum sectional area for coal loading is

$$F_{\max} = \frac{\pi}{4}(D_y^2 - D_g^2)(1 - \frac{Z\delta}{J\cos\alpha_{cp}}) \tag{12}$$

where Z is helix vane number.

Without considering the clearance ring, the drum space capacity is

$$Q_F = F_{\max}J = \frac{\pi}{4}(D_y^2 - D_g^2)(1 - \frac{Z\delta}{J\cos\alpha_{cp}})J \tag{13}$$

Considering the clearance ring, the overlap amount of the clearance ring and the vane is

$$Q_{cd} = \frac{\pi Z\delta(D_y^2 - D_g^2)}{4J\cos\alpha_{cp}}[\frac{(D_y - D_g)\tan\alpha_s}{4} + c_b] \tag{14}$$

where c_b is column width of the clearance ring, m; α_s is taper angle of the clearance ring, rad.

The space occupied by the clearance ring in the shearer drum is

$$Q_D = \frac{\pi(D_y - D_g)^2\tan\alpha_s}{24}(D_y + 2D_g) + \frac{\pi(D_y^2 - D_g^2)c_b}{4} \tag{15}$$

Because of $Q_r = Q_F - Q_D + Q_{cd}$, the actual space capacity of the shearer drum is

$$\begin{aligned} Q_r = {} & \frac{\pi(D_y^2 - D_g^2)(J - c_b)}{4} - \frac{\pi(D_y - D_g)^2\tan\alpha_s}{24}(D_y + 2D_g) + \\ & \frac{\pi Z\delta(D_y^2 - D_g^2)}{4J\cos\alpha_{cp}}[\frac{(D_y - D_g)\tan\alpha_s}{4} + c_b - J] \end{aligned} \tag{16}$$

Considering the clearance ring, the average sectional area of the shearer drum for coal loading is

$$\begin{aligned} F_{av} = \frac{Q_r}{J} = {} & \frac{\pi(D_y^2 - D_g^2)(J - c_b)}{4J} - \frac{\pi(D_y - D_g)^2\tan\alpha_s}{24J}(D_y + 2D_g) + \\ & \frac{\pi Z\delta(D_y^2 - D_g^2)}{4J^2\cos\alpha_{cp}}[\frac{(D_y - D_g)\tan\alpha_s}{4} + c_b - J] \end{aligned} \tag{17}$$

When the shearer drum cutting the coal seam, the amount of the excavated coal on the web depth direction is roughly equal, and the move of the excavated coal in the vane is relatively even, too. The amount of the excavated coal is increasing from the clearance ring to goaf side of drum and presents a linear relationship. To ensure the shearer drum can convey the excavated coal well, the sectional area of coal flow at goaf side of drum cannot not exceed the maximum sectional area F_{max}. So, the true average sectional area F_{true} should be much smaller than F_{av}. To simplify the calculation, the actual sectional area F_{true} is set as

$$F_{true} = \psi_z F_{av} \tag{18}$$

where ψ_z is sectional area utilization coefficient.

The axial speed of the excavated coal in the shearer drum is

$$V_p = \frac{\pi n D_{cp} \sin\alpha_{cp} \cos(\alpha_{cp} + \rho_m)}{\cos\rho_m} \tag{19}$$

where n is drum rotating speed, r/min; D_{cp} is mean diameter of drum helix vane, $D_{cp} = \left(D_y + D_g\right)/2$, m; V_p is axial velocity of coal flow, m/min; ρ_m is frictional angle between coal and helix vane, rad.

So with the clearance ring being taken into consideration, the theoretical capacity for coal Q_z is

$$\begin{aligned} Q_z = F_{true} V_p = &\left\{\frac{\pi}{4}(D_y^2 - D_g^2)(J - c_b) + \frac{\pi Z\delta\left(D_y^2 - D_g^2\right)}{4J\cos\alpha_{cp}}\left[\frac{\left(D_y - D_g\right)\tan\alpha_s}{4} + c_b - J\right] - \right. \\ &\left. \frac{\pi\left(D_y - D_g\right)^2 \tan\alpha_s}{24}\left(D_y + 2D_g\right)\right\} \frac{\pi n \Psi_z D_{cp} \sin\alpha_{cp} \cos\left(\alpha_{cp} + \rho_m\right)}{J\cos\rho_m} \end{aligned} \tag{20}$$

where Q_z is amount of the loaded coal, m^3/min.

To avoid the coal clogging, the coal loading rate must be larger than the excavated coal rate. When the hauling speed is fixed, the requirement ensuring there is no coal clogging is

$$Q_z \geq Q_t \tag{21}$$

where Q_t is the amount of the excavated coal, m^3/min.

The amount of the excavated coal Q_t is

$$Q_t = J v_q D_c \lambda k \tag{22}$$

where λ is coefficient of volumetric expansion of the coal; k is supposed coefficient of the amount of the loaded coal, $k = 1 - \frac{\left(D_c - D_y\right)}{D_c\lambda}$; D_c is drum diameter, m; v_q is hauling speed, m/min.

Combined with Equation (20), the requirement of the rotating speed should be fulfilled in order not to clog the shearer drum; namely, the mathematical model for the restrictive effect of drum capacity on rotating speed is

$$\begin{aligned} n \geq &\frac{J^2 v_q D_c \lambda k \cos\rho_m}{\pi\psi_z D_{cp} \sin\alpha_{cp} \cos\left(\alpha_{cp} + \rho_m\right)} \Bigg/ \left\{\frac{\pi Z\delta\left(D_y^2 - D_g^2\right)}{4J\cos\alpha_{cp}}\left[\frac{\left(D_y - D_g\right)\tan\alpha_s}{4} + c_b - J\right]\right. \\ &\left. - \frac{\pi\left(D_y - D_g\right)^2 \tan\alpha_s}{24}\left(D_y + 2D_g\right) + \frac{\pi\left(D_y^2 - D_g^2\right)\left(J - c_b\right)}{4}\right\} \end{aligned} \tag{23}$$

Taking the shearer drum with D_c=1050mm as an example, according to Equation (23), the relation among the minimum rotating speed, hauling speed, web depth, helix angle of the vane, and drum hub is shown in Figure 4-Figure 7. It can be seen that when other parameters are the same, the minimum rotating speed of shearer drum decreases with the helix angle of the vane and increases with the drum hub diameter and the web depth. The hauling speed has the greatest influence on the minimum rotating speed. The influence of the drum hub diameter and the web depth on the minimum rotating speed increases with the hauling speed.

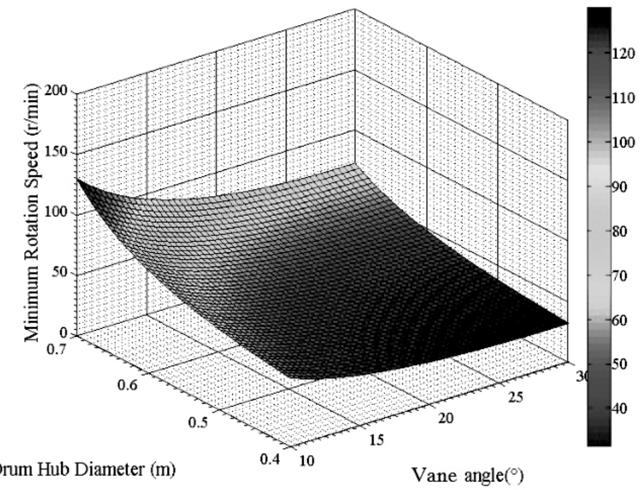

Fig. 4. Relationship of minimum rotating speed with vane angle and drum hub diameter.

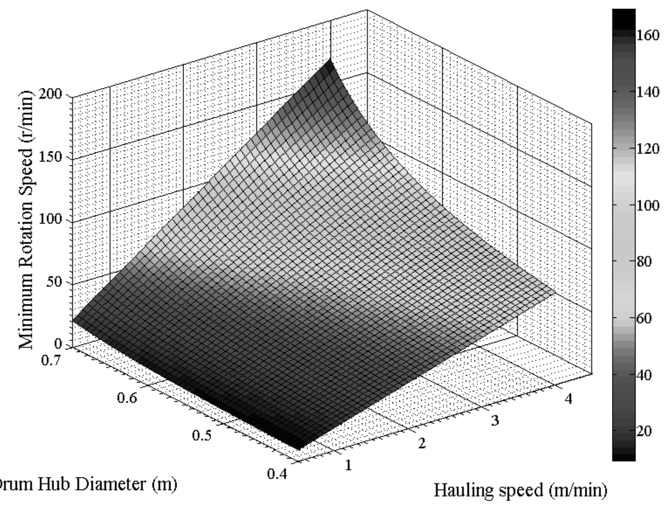

Fig. 5. Relationship of minimum rotating speed with drum hauling speed and drum hub diameter.

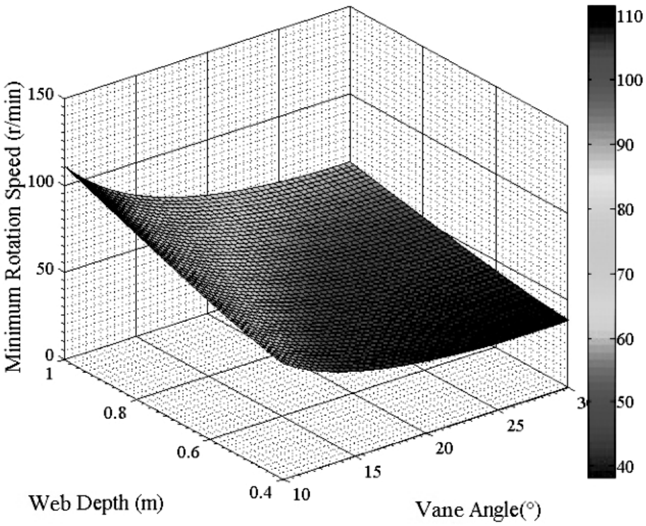

Fig. 6. Relationship of minimum rotating speed with vane angle and web depth.

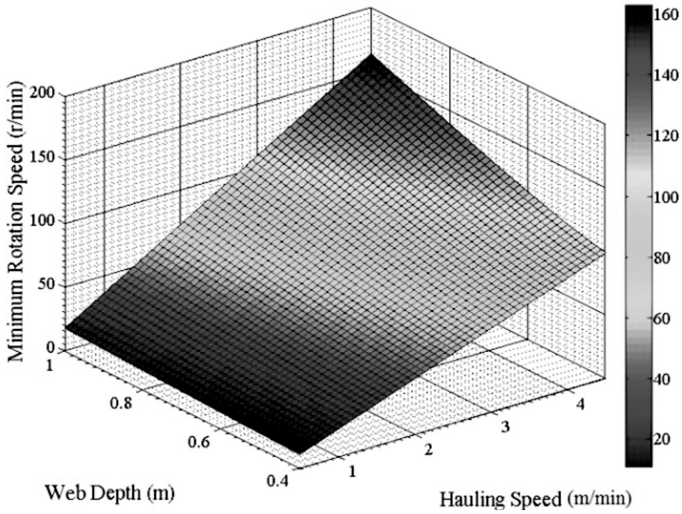

Fig. 7. Relationship of minimum rotating speed with drum hauling speed and web depth.

From Figure 3 we can imagine that if the parameters of clearance ring are fixed, the minimum rotating speed will be influenced more obviously by clearance ring with web depth decreasing. The influence of clearance ring taper angle a_s on minimum rotating speed was shown in Figure 8. From this figure we can find that the influence of clearance ring taper angle a_s on minimum rotating speed is increasingly apparent with its increase. Equation (23) can be used to calculate the minimum rotating speed.

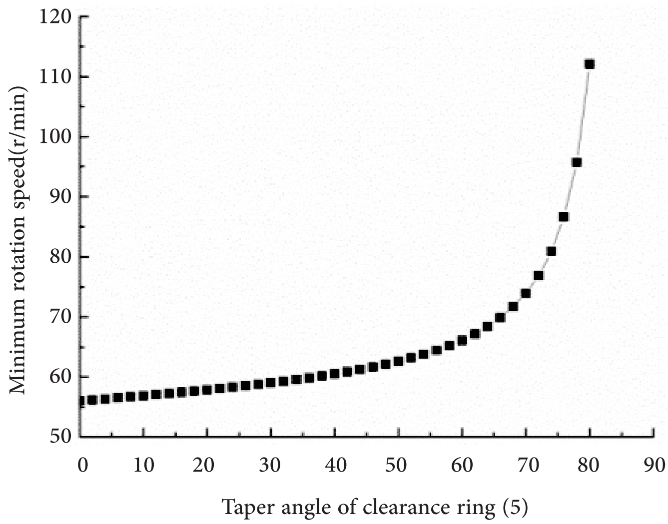

Fig. 8. Influence of clearance ring taper angle on drum minimum rotating speed.

MODEL VERIFICATION AND ANALYSIS BY EXPERIMENT

To verify the effectiveness of the model, validation experiment is conducted on the cutting test bed (Liu et al., 2009 a b), shown in Figure 9. The available coal loading zone is shown in Figure 10. Both drum up cutting mode and drum down cutting mode were adopted in the experiment to load the coal, shown in Figure 11. Figure 12 shows the model test drums, which are designed and manufactured at a similarity ratio of 1:2 to the actual sheared drum according to similar theory. Its detailed structural parameters are shown in Table 1.

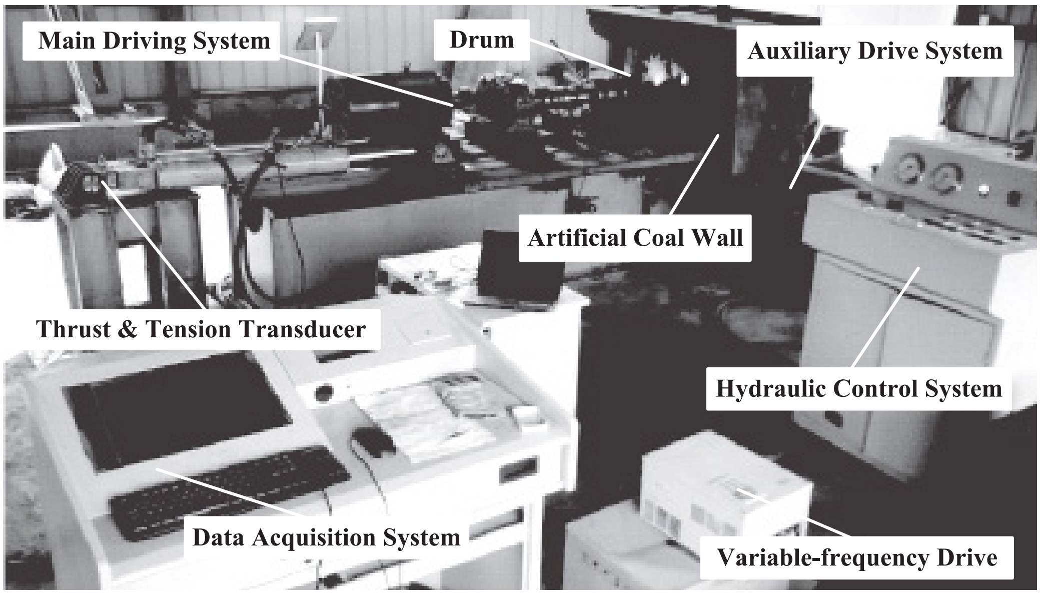

Fig.9. Cutting test bed.

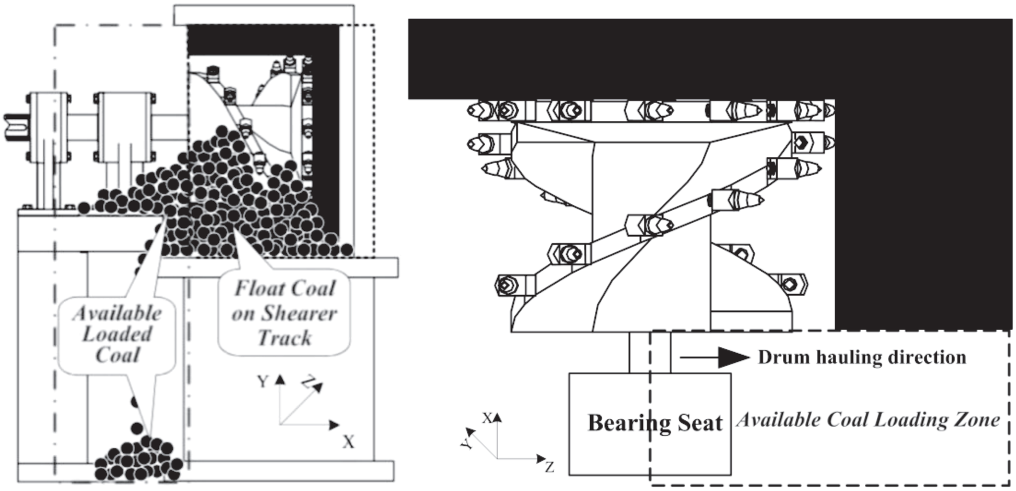

Fig. 10. Scheme of available coal loading zone.

Coal loading experiments in drum up cutting mode and down cutting mode were carried out using these four shearer drums with the rotating speed 45 r/min, web depth 0.45 m, compression strength of the artificial coal wall 1.06 MPa. The drum torques were obtained by torque sensor and data acquisition system, shown in Figure 13. Test results of coal loading in drum up cutting mode by four different hub diameter drums are presented in Table 2, where K is the ratio of real mean hauling speed to the default (1 m/min).

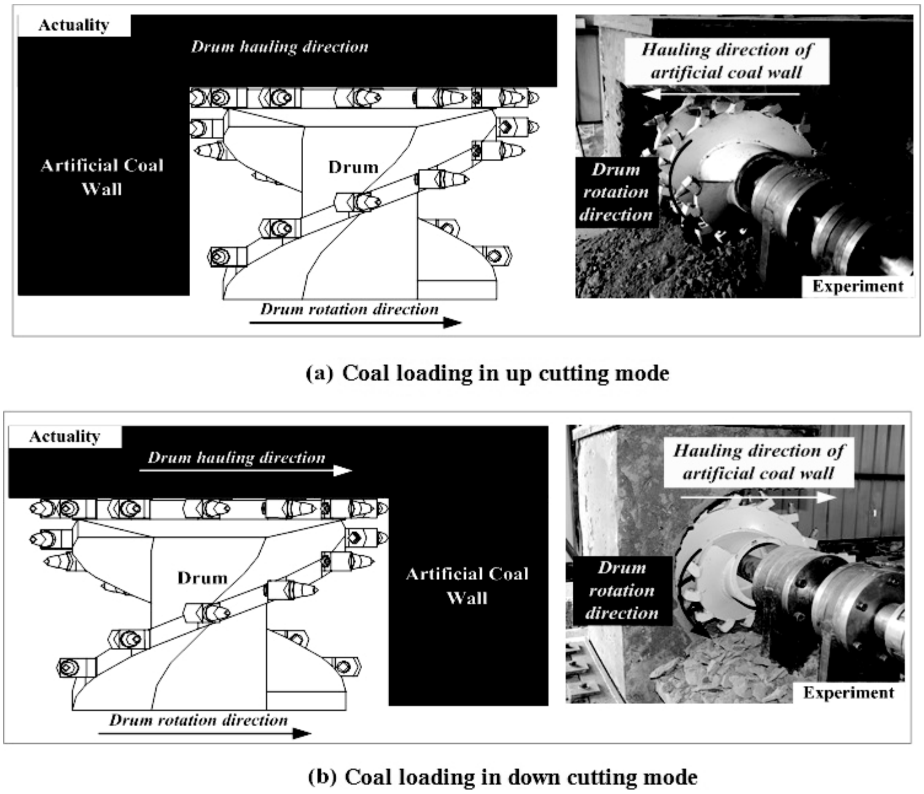

Fig. 11. Two modes of coal loading.

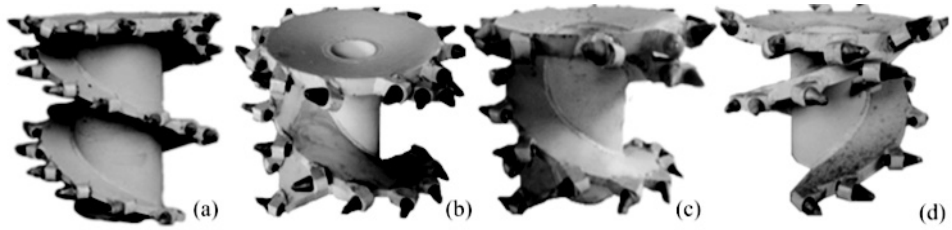

Fig. 12. Four different hub diameter drums.

Table 1. Structure parameters of the four different hub diameter drums.

No.	Vane angle (°)	Line spacing (mm)	Drum length (mm)	Drum hub diameter (mm)	Drum diameter (mm)	Vane Diameter (mm)
(a)	21	40	650	240	530	420
(b)	21	40	450	150	530	420
(c)	21	40	450	180	530	420
(d)	21	40	450	210	530	420

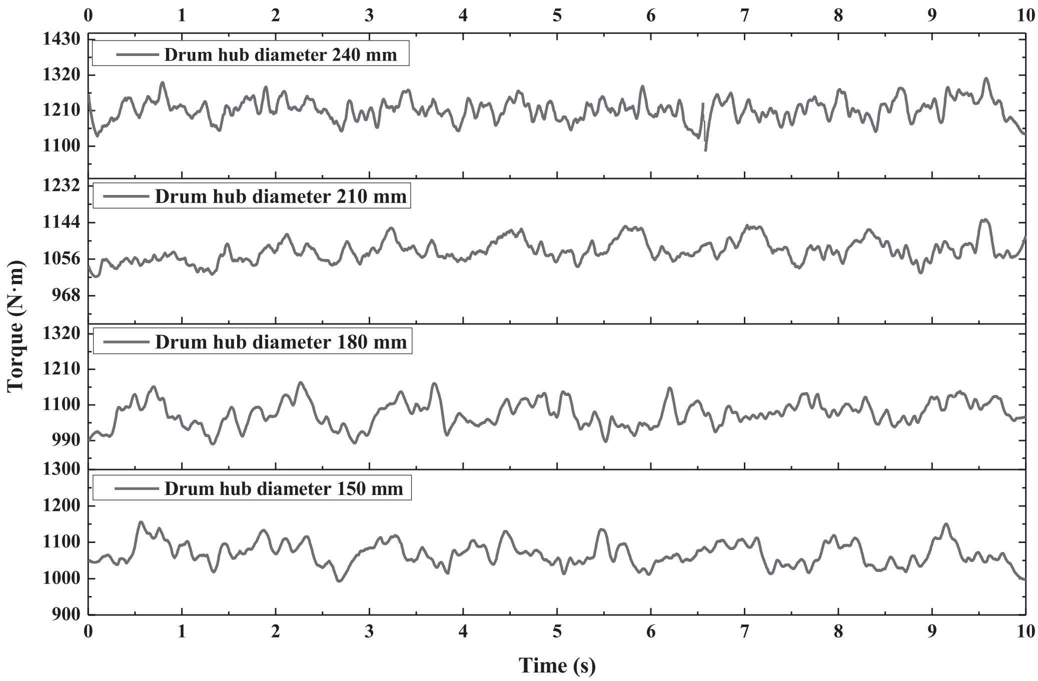

Fig. 13. Torques of four different hub diameter drums (coal loading in drum up cutting mode).

Table 2. Test results of coal loading in drum up cutting mode by four different hub diameter drums.

Coal loading mode	Drum hub diameter (mm)	Effective loaded coal (kg)	Ttal mass (kg)	Coal loaing rate (%)	Mean torque (Nžm)	Mean hauling speed (m/min)	K
Up cutting mode	150	45.64	75.32	60.6	1068.19	1.01	1.01
	180	47.43	69.24	68.5	1073.39	1	1
	210	66.61	89.64	74.3	1075.88	0.99	0.99
	240	52.32	85.49	61.2	1213.85	1.07	1.07

The loading rate and torque of the shearer drum change with the drum hub diameter, shown in Figure 14. It can be seen that the loading rate increases first and decreases later with the drum hub diameter, while the torque increases with the diameter. From Equation (23), apart from the drum structure parameters and the hauling speed, the sectional area utilization coefficient of the discharge section ψ_z also influences the minimum rotating speed. According to previous research (Liu et al., 2010), the sectional area utilization coefficient of the shearer drum without spillbed should be fulfilled:

$$0.242\sqrt{D_c} \leq \psi_z \leq 0.321\sqrt{D_c} \tag{24}$$

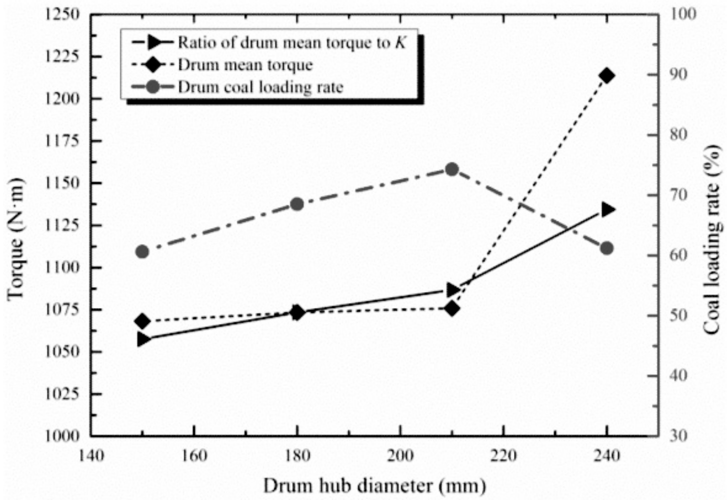

Fig. 14. Influence of drum hub diameter on drum torque and coal loading rate

(coal loading in drum up cutting mode).

According to the value of D_c, the sectional area utilization coefficient would appear as $\psi_z \geq 0.176 \sim 0.2338$. Substituting $\psi_z = 0.176$ and $\psi_z = 0.2338$ into Equation (23), the minimum rotating speed of the four shearer drums with hauling speed 1 m/min can be calculated, shown in Table 3.

Table 3. Minimum rotating speeds of drums.

Drum hub diameter	150 mm	180 mm	210 mm	240 mm
ψ_z= 0.176	39.38 r/min	42.08 r/min	45.8 r/min	51.01 r/min
ψ_z= 0.2338	29.64 r/min	31.68 r/min	34.48 r/min	38.4 r/min

According to Table 3, when $\psi_z = 0.2338$, the minimum rotating speeds of the four shearer drums are all less than the working rotating speed 45 r/min. When $\psi_z = 0.176$, the minimum rotating speed of the shearer drum with 240 mm hub is larger than 45 r/min. That is to say, the shearer drum will be clogged only when the sectional area utilization coefficient ψ_z is small. From Figure 14, it can be seen that the coal loading rate greatly decreases when the drum hub diameter is 240 mm, which means there is clogging in the shearer drum. So it is suggested that the sectional area utilization coefficient should be as small as possible when calculating the rotating speed and the structural parameters. Meanwhile, it also proves that Equation (24) can give a good guidance in the design of the shearer drum for thin coal seam. From the changes of the torques in Figure 14, it can be seen that the torques will greatly increase due to clogging in the drum. Thus, in order to avoid poor loading performance and high torque, firstly it should be ensured that the rotating speed of the shearer drum is larger than the minimum rotating speed. The above research shows that Equation (23) may be used as a method to determine the minimum rotating speed, which will not clog the drum.

Table 4. Test results of coal loading in drum down cutting mode by four different hub diameter drums.

Coal loading mode	Drum hub diameter (mm)	Effective loaded coal (kg)	Total mass (kg)	Coal load ing rate (%)	Mean torque (Nžm)	Mean hauling speed (m/min)	K
Down cutting mode	150	32.25	76.06	42.4	1187.5	1.02	1.02
	180	34.06	69.94	48.7	1220.8	1.01	1.01
	210	47.30	88.74	53.3	1252.1	0.98	0.98
	240	47.81	86.93	55	1397.1	1.02	1.02

Table 4 shows the test results of the four shearer drums with different diameters when rotating speed is 45 r/min in drum down cutting mode. Comparing Table 2 with Table 4, it can be seen that the loading rate in drum down cutting mode is obviously smaller than that in drum up cutting mode under the same conditions. As the drum hub diameter increases, the loading rate also increases.

Figure 15 shows the influence of the drum hub diameter on the coal loading rate and the torque under the condition of coal loading in drum down cutting mode, from which it can be seen that the growth rate of the loading rate decreases with the hub diameter. According to the above analysis on the influence of the hub diameter in drum up cutting mode, if the minimum rotating speed of the shearer drum is also calculated according to small sectional area utilization coefficient, then there will be clogging in drum down cutting mode when the hub diameter is 240 mm. But according to Figure 15, there is no clogging. This is because the coal in front of the drum can easily be taken to the back in drum down cutting mode, which reduces the amount of the coal in the cutting area, leaving enough space to store others. Thus, when calculating the minimum rotating speed in drum down cutting mode, the value of the sectional area utilization coefficient should be increased properly. It can be concluded that as the torque changes with the drum hub, the torque in drum down cutting mode is much higher than that in drum up cutting mode. This mainly depends on the differences of the contacts and interactions of vanes and picks with the excavated coal in the two cutting modes.

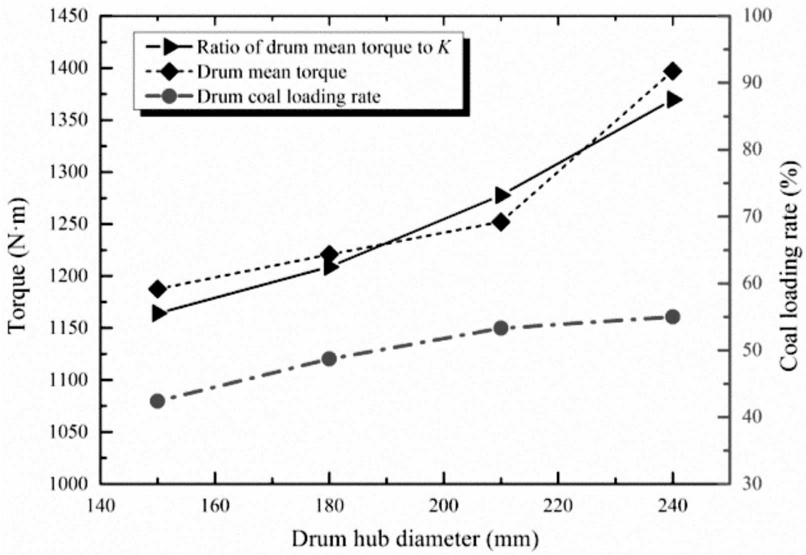

Fig. 15. Influence of drum rub diameter on drum torque and coal loading rate (coal loading in drum down cutting mode).

FURTHER RESEARCH AND ANALYSIS

Drum (a) and drum (c) in Figure 12 were further studied, and test results were shown in Table 5. The effect of web depth on coal loading rate in drum up cutting mode was studied from test 1 to test 7, while that in drum down cutting mode was studied from test 8 to test 14. The influence of hauling speed on coal loading rate in drum up cutting mode was discussed from test 15 to test 18, while that in drum down cutting mode was studied from test 19 to test 22. For calculating the drum minimum rotating speed, the sectional area utilization coefficient was valued 0.176 and 0.21 in drum up cutting mode and drum down cutting mode, respectively.

From Table 5, we could see that the minimum rotating speed increases gradually while coal loading rate decreases with drum web depth increasing more or less. From test 1 to test 3, the calculated minimum rotating speed is smaller than experimental rotating speed, so coal will not be clogged in theoretical. But with web depth increasing, coal loading rate increases firstly and decreases later, which is mainly because the angle of wrap of vane increases as web depth increases. When the angle of wrap of vane increases a little, the coal loading process will not be influenced. As the angle of wrap of vane increases above the certain value, the coal movement process and trace will be affected. So the coal was carried to the space behind the drum instead of being conveyed to the goaf side of drum, which can be concluded from test 4 to test 7. As seen from test 8 to test 14, even the experimental rotating speed is bigger than minimum rotating speed; the coal loading rate still has a trend to decrease, which is caused by the previously speculated reason. So when studying how the drum web depth influences the coal loading rate, not only the coal clogging but also the influence of angle of wrap of vane on coal movement should be considered, which will be further researched in future. From test 15 to test 22, the web depth is of certain value, the minimum rotating speed increases with the hauling speed. When experimental rotating speed is bigger than minimum rotating speed, the coal loading rate increases with the hauling speed; when experimental rotating speed is smaller than minimum rotating speed, the coal loading rate will decrease immediately. All the results verify Equation (23) accuracy, which is deduced in this paper.

Table 5. Influence of web depth and hauling speed on mean torque and coal loading rate.

NO.	Drum	Coal loading mode	Web depth (m)	Mean cutting torque (Nžm)	Coal loaing rate (%)	Mean hauling speed (m/min)	Calculated minimum rotating speed (r/min)	Experimental rotating speed (r/min)
1	(a)	up cutting mode	0.30	807.52	74.6	0.95	32.3	45
2	(a)	up cutting mode	0.35	928.72	75.3	1.02	40.5	45
3	(a)	up cutting mode	0.4	1017.83	68.4	0.99	44.9	45
4	(a)	up cutting mode	0.45	1213.85	61.2	1.07	54.6	45
5	(a)	up cutting mode	0.5	1262.13	53.3	0.92	52.2	45
6	(a)	up cutting mode	0.55	1672.87	44.4	1.03	64.2	45
7	(a)	up cutting mode	0.6	1840.24	30.7	0.96	65.3	45
8	(a)	down cutting mode	0.30	631.01	65.2	0.9	25.7	75
9	(a)	down cutting mode	0.35	715.25	62.4	0.92	30.7	75
10	(a)	down cutting mode	0.4	876.91	57.3	1.03	39.2	75
11	(a)	down cutting mode	0.45	934.72	52.2	0.98	41.9	75
12	(a)	down cutting mode	0.5	1116.57	39.6	1	47.6	75
13	(a)	down cutting mode	0.55	1286.54	28.9	0.99	51.8	75
14	(a)	down cutting mode	0.6	1759.15	13.5	1.09	62.1	75
15	(c)	up cutting mode	0.45	499.27	71.7	0.53	22.4	45
16	(c)	up cutting mode	0.45	762.9	73.5	0.79	33.3	45
17	(c)	up cutting mode	0.45	1184.51	67.1	1.07	45.4	45
18	(c)	up cutting mode	0.45	1527.38	56.6	1.42	61.4	45
19	(c)	down cutting mode	0.45	612.33	36.2	0.49	17.3	45
20	(c)	down cutting mode	0.45	1052.21	45.6	0.82	28.9	45
21	(c)	down cutting mode	0.45	1220.8	48.7	1.01	35.6	45
22	(c)	down cutting mode	0.45	1397.54	51.1	1.27	44.8	45

To further verify the effectiveness of the mathematical model for the restrictive effect of drum capacity on rotating speed, an orthogonal test in three factors and three levels (the diameter of the drum hub, hauling speed, and rotating speed) is also conducted using the (b), (c), and (d) shearer drums in Figure 12. Because the hauling speed of the testbed is under constant control, the hauling speed can be constant. To reduce the influence of the hauling speed errors, control the error between the actual hauling speed and nominal within 5%. Set the compressive strength of the artificial coal wall as 1.06 MPa, web depth as 0.45 m. Table 6 shows the orthogonal test result of the influence of the drum hub diameter, hauling speed, and rotating speed on the loading performance of the shearer drum in drum up cutting mode. The analysis of the scale of their influence is shown in Table 7.

Table 6. Orthogonal test results of drum hub diameter, hauling speed, and rotating speed (coal loading in drum up cutting mode).

NO.	Drum hub diameter (mm)	Rotating speed (r/min)	Hauling speed (m/min)	Coal loading rate (%)
1	150	45	0.5	58.5
2	150	70	1	62.8
3	150	105	1.5	52.1
4	180	45	1	68.5
5	180	70	1.5	64.7
6	180	105	0.5	38.3
7	210	45	1.5	48.9
8	210	70	0.5	54.4
9	210	105	1	57.3

Table 7. Significance analysis results of three factors affecting coal loading in drum up cutting mode (drum hubdiameter, hauling speed, and rotating speed).

Variation source	Drum hub diameter	Rotating speed	Hauling speed	Error	Total
Sum of deviation square	31.81	222.32	237.05	176.17	667.34
DOF	2.00	2.00	2.00	2.00	8.00
MS	15.90	111.16	118.52	88.08	
F value	0.18	1.26	1.35		

From Table 7, the loading rate is mainly influenced by the rotating speed and hauling speed of the shearer drum. The influence of drum hub diameter is not significant. The rotating speed of the shearer drum mainly influences the tangential speed and axial speed of the coal flow. The match between hauling speed and rotating speed mainly affects the amount of the excavated coal per unit time and the filling situation in the shearer drum. The drum hub diameter mainly influences the volume of the drum. The clogging depends on the rotating speed, hauling speed, and the drum hub diameter together. According to the above analysis of the influence of the drum hub diameter on the drum loading performance, drum clogging greatly affects the loading rate. It can be concluded from the experimental conditions and the calculation method of the minimum rotating speed that the shearer drum of test 7 will be clogged, which is due to its low loading rate. According to Table 6, the loading rate of the test 6 is much lower than that of the test 7 due to the centrifugal force of resulting from the vane. As the rotating speed increases, the amount of the coal in the drum decreases and the centrifugal force increases. The coal moves to the margin of the vane, affecting the axis output of the coal. According to the changing degree of the loading rate shown in Table 7, the centrifugal force is an important factor, which influences the loading rate of the shearer drum. When the hauling speed is low and the rotating speed is high (namely, the filling amount of the coal is small in the drum), the loading rate will greatly decrease. Meanwhile, the little influence of the drum hub diameter shows that the insufficient volume problem resulting from oversize diameter can be resolved through adjusting the matching relationship between the rotating speed and hauling speed. According to the experiment conditions and results in Table 6 and Table 7 as well as the above analysis, the matching relationship between the rotating speed and hauling speed plays a vital role in the clog. Hauling speed has the most significant influence on it.

CONCLUSION

(1) Taking the clearance ring into consideration, this paper establishes the mathematical model for the restrictive effect of drum capacity on rotating speed according to the operation features of the shearer drum and the features of the excavated coal. According to the simulation analysis of the mathematical model, the hauling speed of the shearer drum has the most significant influence on the minimum rotating speed. The influence of the diameter of the drum hub and the web depth on the minimum rotating speed increases as the hauling speed increases. The orthogonal test on shearer drums of different hub diameters also proves that hauling speed has the great influence on the clogging.

(2) The model experiment shows that the restrictive mathematical model of drum capacity on drum rotating speed is effective and more accurate for determining the minimum rotating speed, which can avoid the drum clogging. When the rotating speed is higher and hauling speed is lower, the drum will not be clogged, but the centrifugal force will severely reduce the drum loading rate. Because of the differences of drum up cutting mode and drum down cutting mode, the sectional area utilization coefficient of shearer drum should be selected, the smaller value and the higher value, respectively, under the same structural and working parameters.

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نموذج تطبيقي عن أدنى سرعة دوران لأسطوانة قص لتجنب الانحشار

كويدونج جاو، شين تشانغ، كاو جيانغ، يانغ يانغ، غوانغجون يين، بنج ليو

معهد الهندسة الميكانيكية والالكترونية، جامعة شاندونغ للعلوم والتكنولوجيا، تشينغداو 266590، الصين

الخلاصة

يعرض هذا البحث دراسة عن الحد الأدنى لسرعة دوران اسطوانة قص عروق الفحم الرقيقة التي طالما تميل للانحشار. أولاً، بنيت الدراسة نموذجاً عن قدرة أسطوانة القص مع الأخذ في الاعتبار حلقة الخلوص. بعد ذلك، وضعت نموذجاً رياضياً للتأثير التقييدي لقدرة الأسطوانة على سرعة الدوران وفقاً لخصائص التشغيل الخاصة بأسطوانة القص وخصائص الفحم المحفور. وأخيراً، تم التحقق من دقة وفعالية النموذج الرياضي من خلال اختبار النمذجة. وأظهرت النتائج أن النموذج الرياضي يستطيع أن يعمل على تحديد الحد الأدنى لسرعة الدوران التي لا تؤدي إلى انسداد أسطوانة القص. عندما تكون سرعة الدوران أكبر بكثير من الحد الأدنى لسرعة الدوران، فإن قدرة الأسطوانة ستتأثر بقوة الطرد المركزي. وبموجب نفس المعلمات الهيكلية والتشغيلية، يكون معامل استخدام المساحة المقطعية الخاص بمقطع تفريغ أسطوانة القص أكبر عندما تكون الأسطوانة في وضع القص لأعلى مقارنةً بوضع القص لأسفل.