Orthogonal model test on the drum coal loading performance of a thin seam shearer

***Kuidong Gao*[1,2]*, Qingliang Zeng*[1]*, Changlong Du*[2] *and* Su Yang*[1]**

In China, the mechanised mining of thin coal seam mainly relies on a drum shearer. However, the diameter of the drum is relatively small, and the loading rate is relatively low due to the limitation of the height of the coal seam. To solve this problem, this paper, based on the modified cutting test bed and existing modelling drum, conducts three factor and three level orthogonal tests, testing the influence exerted by the drum hub diameter, cutting depth, vane helix angle, drum rotation speed and hauling speed on the coal loading rate. These tests determine the significant effects of the five factors mentioned above on the rate of coal loading with drum ejection and pushing, guiding the structural design and operating parameter selection of shearer drums used in thin coal seams. According to the research, we concluded that: the drum hub diameter has less influence on the coal loading rate than drum rotation speed and hauling speed do; the cutting depth of the drum has greater influence on coal loading rate than the drum rotation speed and hauling speed do; in coal loading with ejection, the angle of the helical vane exerts less impact on the coal loading rate than the drum rotation speed and hauling speed with only a small difference.

Keywords: *drum coal loading performance, thin seam shearer, model test, drum hub, drum cutting depth, rotation speed, hauling speed.*

1. Introduction

As medium and thick coal seams decrease in China, the mining of thin seams has attracted the attention of the domestic mining industry, increasing investment from major Chinese coal mine enterprises. Chinese mining equipment researchers have focused on the performance of thin seam shearers. A plough shearer is used to mine a coal seam of fewer than 1.3 m in Europe and America, while in China a drum shearer is used. Due to the mining thickness limit, a Chinese shearer for thin seams has a smaller drum with some differences in working conditions, and the performance of such a small drum and the drum of shearers for medium and thick seams has received increasing attention from researchers.

The performance of thin seam shearers is mainly affected by cutting and loading performance of the drum. After having performed many studies on cutting performance, Chinese researchers have studied the law of the influence of cutting pick structure, drum structure parameters and motion parameters on drum cutting load, cutting lump coal rate and cutting dust amount (Liu S.Y. et al., 2011a; Gao K.D. et al., 2014; Liu X.H. et al., 2015). Foreign researchers have also performed many studies on drum cutting performance (Achanti V.B. and Khair A.W., 2001; Hekimoglu O.Z. and Ozdemir L., 2004; Somanchi S. et al., 2006; Krauze K. and Kotwica K, 2007; Krauze K. et al., 2009). Based on the similarity in cutters and operating parameters between thin seam shearers and medium and thick seam shearers, research on cutting performance of thin seam shearers can learn from the method and conclusion of more mature studies on medium and thick shearer performance. As for drum coal loading performance of thin coal seam shearers, only a few previous studies can be used for reference, and most of them were performed by Chinese researchers because foreign researchers mainly focused their studies on that of medium and thick coal seam shearers. Peng S.S. and Chiang H.S. (1984) determined several main factors that affect the coal loading performance of medium thickness seam shearer drums in their work of "Longwall Mining". Brooker C.M. (1979) summarised the former studies regarding medium thickness seam shearer drums, from which he obtained the influence of the drum's structural parameter and operating parameter on coal loading performance. He also provided the range of parameters, mutual relation of parameters, and the computing method of relevant structural parameters. Morris C.J. (1980) adopted computer technology to predict the coal loading performance of shearer drums under different working conditions, which obtained good results. Hurt K.G. and Mcstravick F.G. (1988) claimed in their studies that the main factors affecting coal loading performance of medium thickness shearer drums are helix vane number, vane helix angle vane depth, coal port size rotation speed, etc. Based on theoretical analysis and tests, Ludlow J. and Jankowski R.A. (1984) claimed that a medium thickness seam shearer drum with over-sized wrap angle can easily cause circling-coal and increase dust, while the undersized wrap angle is bad for broken coal and the rock's delivery to the scraper

[1] *Kuidong Gao, Qingliang Zeng, Su Yang,* College of Mechanical & Electrical Engineering, Shandong University of Science & Technology, Qingdao 266590, Shandong, China, gaokuidong22@163.com, qlzeng@163.com, ys10110504@163.com
[2] *Kuidong Gao, Changlong Du,*School of Mechanical & Electrical Engineering, China University of Mining & Technology, Xuzhou 221116, Jiangsu, China, jdjxx3@cumt.edu.cn

conveyor. Ayhan M. and Eyyuboglu E.M. (2006) compared the coal loading performance and cutting performance of the globoid drum and the cylindrical drum, from which it is demonstrated that the coal loading performance of a globoid drum is better than a cylindrical drum. The orthogonal model test method was used by Liu S.Y. et al. (2011b) to study the effect condition of the vane helix angle, rotation speed and hauling speed on coal loading rate in drum pushing mode. Bołoz Ł. (2013) designed a type of longwall shearer applicable for thin and hard coal seams mining. This shearer operation technology and possible day output achievement was introduced in detail in his paper. Wydro T. (2015) studied the influences of filling efficiency and coal plate on transport efficiency of bulk coal with the help of a self-developed drum test bench for coal transport. The coal loading process of a shearer was simulated by Gospodarczyk P. (2016) using PFC3D, and the drum's transport effect and coal particles' movements under circumstances of down cutting and up cutting with/without loader were studied. Gao K.D. et al. (2014, 2015, 2017) used model testing to ensure the best vane helix angle in their test, and also studied the influence of mining face angle, drum position parameters and ranging arm thickness on coal loading performance, from which some useful conclusions were reached.

Despite the same structure of the drum for thin, medium and thick seam shearers, concerning coal loading, the drum of thin seam shearers performs much worse than that of medium and thick seam shearers with the former's coal loading rate being less than 70%. Because coal capacity inside the drum of thin seam shearers is limited by smaller drum diameter and bigger diameters of the drum hub and vane, some companies choose a drum with a bigger cutting depth than that in medium and thick shearers to increase coal output per unit time (Figure 1 shows the drum of thin seam shearers and that of medium/thick seam shearers). Furthermore, as the drum coal loading performance is affected by the drum hub diameter, cutting depth, vane helix angle, drum rotation speed and hauling speed that also correlate with each other, a single factor experiment cannot reflect or obtain specific effects of the parameters, while a comprehensive experiment involves great work and high cost. Thus, this paper conducts an orthogonal experiment with existing equipment to study the specific influence of structure and operation parameters of the drum on coal loading rate.

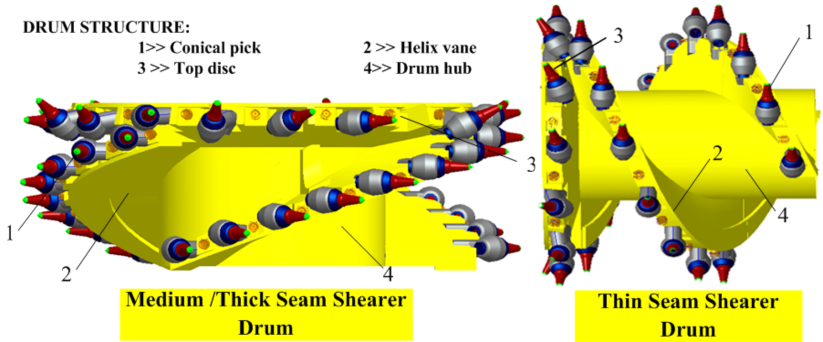


Fig. 1. Drums of different shearers.

2. Test Equipment and Method

2.1 Test Equipment

The test bed is a modified test bed from the former coal rock cutting test bed (Liu S.Y. et al., 2011a, 2011b), as shown in Figure 2. The modified test bed retains its working principle and basic structure including main and auxiliary transmission system, hydraulic control system, signal acquisition system and cutting head (of the drum), but its main transmission system and signal acquisition system are transformed. The main transmission system had the following parameter changes. The power of the cutting machine is increased by changing the ordinary machine with a power level of 15 kW to a constant torque one with a power level of 30 kW, the cutting ability of the test bed was enhanced, the power loss was reduced due to the lower frequency, the gear ratio of the reducer was increased from 8:1 to 10:1, the drum rotation speed was set as 0~135 r/min, the stand for the coal wall translation was added, and the range for coal wall platform expanded, enabling the drum vane to cut rock from both the left and right sides. The signal acquisition system transformations include adding a push and pull strength sensor to the back of pushing hydraulic cylinder in the main transmission system to test the stress of fuel cylinder, adding a hydraulic pressure sensor to the hydraulic motor in the auxiliary transmission system to measure the fuel pressure changes in translation driving system, changing the high range value of the torque sensor from 2,000 N·m to 3,000 N·m, adding a Hall current sensor to the access line for machine power to monitor the current change when the machine is working, increasing the sampling frequency of the signal acquisition system and adding two sampling channels for voltage signal. To test the physical and mechanical parameter of the artificial coal wall, the test measures the compressive strength of the wall used the MTS815.02 electro-hydraulic servo testing machine. Figure 3 shows the compressive strength curve of the wall, from which we can see that the compressive strength of the wall is 1.06 MPa and the elastic modulus is 102.4 MPa.

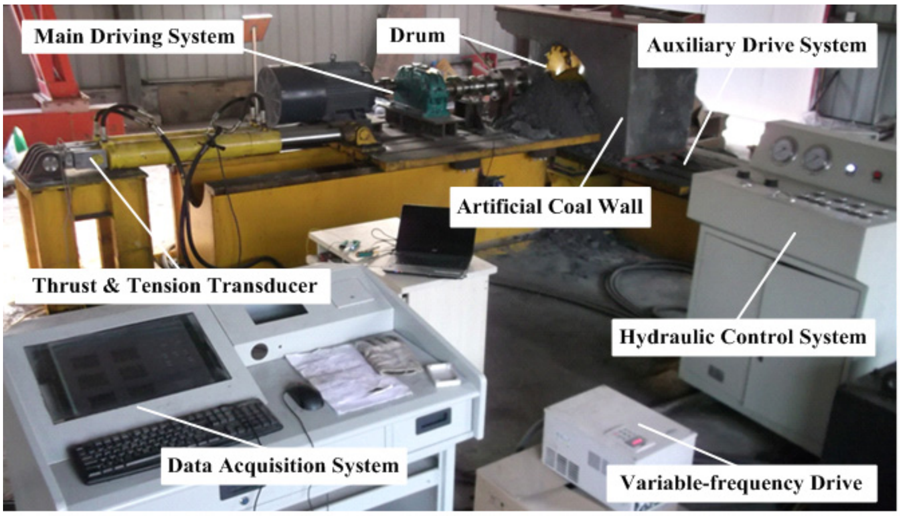


Fig. 2. Coal loading test bed.

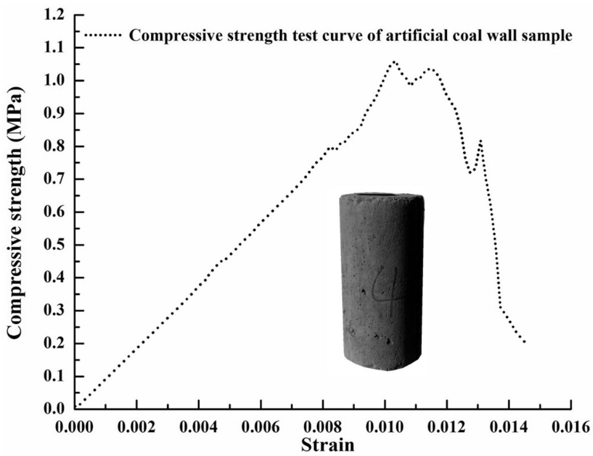


Fig. 3. Artificial specimens.

2.2 Test Method

This test is mainly used to study the role of the drum structure and motion parameters' influence on the coal loading performance, for which statistics of the loading rate are critical. Due to the large difference in the test bed and the real working conditions of the drum shearer for thin seams, the distribution of loaded coal is not identical to that in real conditions. Based on the systematic analysis, the author classifies the calculating areas for an effective number of loaded coal to reduce errors. For example, the effective loading area starts from the drum cutting edge of the shaft block in terms of the traction direction and from the edge of the coal wall regarding the axial direction of the drum, as shown in Figure 4. This method ignores the distance between coal outlet and the middle trough of the scraper, which exists in real conditions, but reduces calculating errors caused by different coal accumulation in the coal outlet. Additionally, this method excludes the amount of coal falling from the back of the drum or the float coal area of the drum's back to depth web of the drum. As a thin seam shearer has a smaller drum, but relatively thicker rocker arm, the coal and float coal from the drum's back are prevented from entering the scraper conveyor by the rocker arm when the front drum cuts and transmits coal. Therefore, this method enables the test result to be applicable to the real working conditions of the front drum. According to the above method, it is known that the modified test bed enables feed from both the left and right sides to simulate the coal loading with ejection and pushing. Figure 5 presents the method of coal loading with ejection and pushing in real production processes and in the test, showing that the loading method of the drum is decided by the rotating direction of the helical vane and hauling speed and direction.

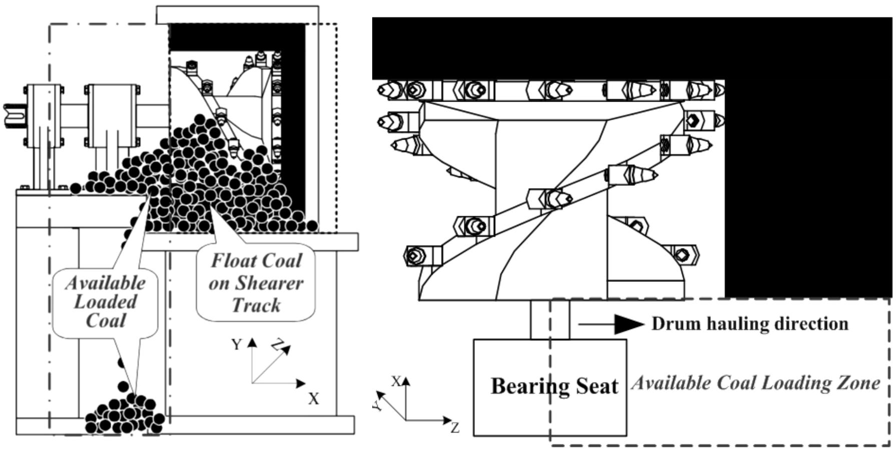
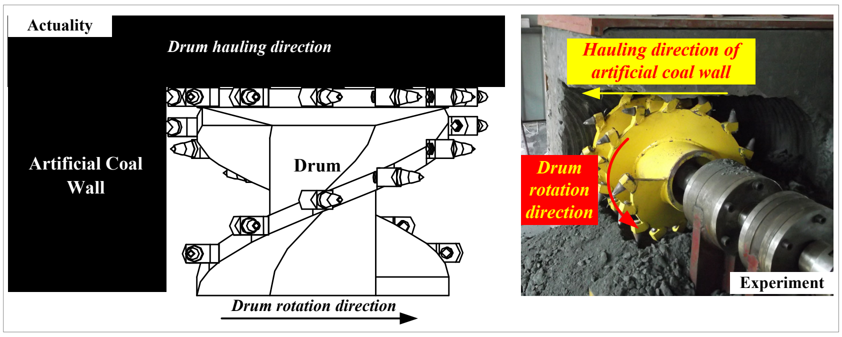
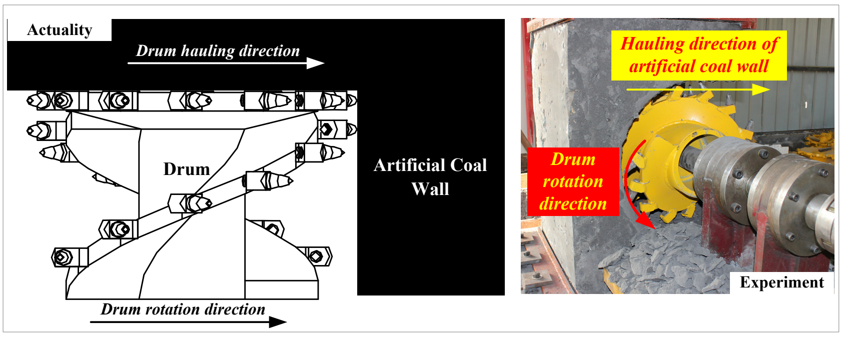


Fig. 4. Scheme of available coal loading zone.



(a) Coal loading with drum ejection



(b) Coal loading with drum pushing

Fig. 5. Two types of coal loading modes.

3. Test results and its discussion

By conducting the orthogonal test of three factors and three levels, this paper studies the influence of the drum hub diameter, cutting depth, vane helix angle, drum rotation speed and hauling speed on the loading rate.

3.1 The orthogonal test for influence of the drum hub diameter, hauling speed and rotation speed on coal loading performance

The drums used in this test are shown in Figure 6. All three of the drums have the same drum diameter, vane diameter, vane helix angle, drum width and optimal line spacing. The drum diameter is 530 mm, the vane diameter is 420 mm, the vane helix angle is 21°, the drum width is 450 mm, and the optimal line spacing is 40 mm. The three drum hub diameters are 150 mm, 180 mm and 210 mm. Table 1 shows the orthogonal test results of the drum hub diameter, hauling speed and rotation speed in drum ejection mode. Table 2 shows the significance analysis results of the three factors affecting the coal loading rate with drum ejection.

Fig. 6. Three different hub diameter test drums.

From Table 2, the ejection coal loading rate is mainly influenced by the rotation speed and hauling speed of the shearer drum. The influence of the drum hub diameter is not significant. The rotation speed of the shearer drum mainly influences the tangential speed and axial speed of the coal flow. The match between hauling speed and rotation speed mainly affects the amount of the falling coal per unit time and the filling situation in the shearer drum. The drum hub diameter mainly influences the volume of the drum. The blockage depends on the rotation speed, hauling speed together and the drum hub diameter. In this test, it can be concluded from the experimental conditions that the seventh test was blocked, which was the reason for its low loading rate. According to Table 1, the loading rate of the sixth test is much lower than that of the seventh test due to the centrifugal force resulting from the vane. As the rotation speed increases, the amount of the coal in the drum decreases, and the centrifugal force increases. The centrifugal force can cause the coal to move to the margin of the vane, affecting the axis output of the coal. Thus, in the sixth test, the hauling speed is low, and the rotation speed is high, causing the filling amount of the coal in the drum to be small, resulting in the loading rate greatly decreasing. According to the changing degree of the loading rate shown in Table 6, we can conclude that the centrifugal force is an important factor that influences the coal loading rate of the shearer drum, and we should make the best effort to avoid or reduce the influence of centrifugal force in the coal loading processes with drum ejection. Meanwhile, the little influence of the drum hub diameter can also help us to conclude that the insufficient volume problem resulting from oversize diameter can be resolved through adjusting the matching relationship between the rotation speed and hauling speed.

Tab. 1. Orthogonal test results of drum hub diameter, hauling speed and rotation speed (coal loading with drum ejection).

No.	**Drum hub diameter** [mm]	**Rotation 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

Tab. 2. Significance analysis result of the three factors affecting the coal loading rate with drum ejection (drum hub diameter, hauling speed and rotation speed).

Variation source	Drum hub diameter	Rotation 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		

Table 3 shows the orthogonal test results of the drum hub diameter, hauling speed and rotation speed in the drum pushing mode. Table 4 shows the significance analysis results of the three factors affecting coal loading rate with drum pushing. From Table 4, it can be seen that in the conditions of this test, the hauling speed exerts the biggest influence on coal loading rate with pushing, drum rotation speed has the second largest influence, and the drum hub diameter has the least influence. When the drum loads coal by pushing, the coal accumulation under the drum vane is the main factor of loading rate, while coal accumulation is decided by the hauling speed and drum rotation speed. Figure 7 shows the curve demonstrating the correlation of hauling speed and the specific value of the drum rotation speed to drum loading rate. A sound positive linear relation is found, verifying the former hypothesis of the coal accumulation under the drum vane being the main factor of drum coal loading rate in coal loading with drum pushing. Table 4 shows that the hauling speed has a greater impact on loading rate than the drum rotation speed. Moreover, this occurs mainly because with certain drum rotation speeds, an increase in hauling speed not only adds to the amount of falling coal per unit time but also causes greater lateral stress in haulage direction given by the drum hub and vane. The stress both decreases the amount of coal falling from drum hub and helps to shorten the transmitting speed of the vane thrust inside the coal to improve the probability of the coal's axial movement, increasing the drum's loading rate. Thus, in choosing parameters of the drum for pushing loading, hauling speed should be increased as much as possible within a proper range.

Tab. 3. Orthogonal test results of drum hub diameter, hauling speed and rotation speed (coal loading with drum pushing).

No.	**Drum hub diameter** [mm]	**Rotation speed** [r/min]	**Hauling speed** [m/min]	**Coal loading rate** [%]
1	150	45	0.5	33.3
2	150	70	1	44.6
3	150	105	1.5	42.2
4	180	45	1	48.7
5	180	70	1.5	56.3
6	180	105	0.5	27.1
7	210	45	1.5	62.8
8	210	70	0.5	30.4
9	210	105	1	38.4

Tab. 4. Significance analysis result of the three factors affecting coal loading with drum pushing (drum hub diameter, hauling speed and rotation speed).

Variation source	**Drum hub diameter**	**Rotation speed**	**Hauling speed**	**Error**	**Total**
Sum of deviation square	30.72	235.07	835.47	29.04	1130.30
DOF	2.00	2.00	2.00	2.00	8.00
MS	15.36	117.53	417.73	14.52	
***F* value**	1.06	8.09	28.77		

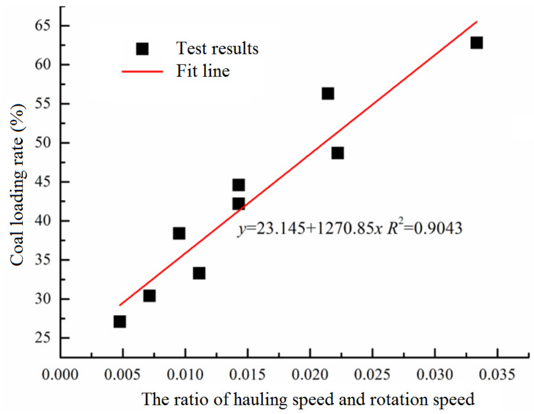


Fig. 7. The relationship between the coal loading rate and the ratio of hauling speed to rotation speed.

The above two orthogonal tests show that the drum hub diameter has little influence on loading performance, which is based on the conditions of this test. Despite different diameters of the drums used in the test, each drum has enough depth for the vane. Combined with the analysis of the impact of the drum hub diameter on drum coal loading performance, it can be perceived that coal loading rate with ejection decreases due to coal blockage as the vane depth decreases. Thus, the choice of the structure design of the drum and working parameters should prioritise coal capacity of the drum.

3.2 The orthogonal test for influence of the drum cutting depth, hauling speed and rotation speed on coal loading performance

The drum used in this test is shown in Figure 8. The drum diameter is 530 mm, the vane diameter is 420 mm, the vane helix angle is 21°, the width is 650 mm, the hub diameter is 240 mm, and the optimal line spacing is 40 mm. Table 5 is the orthogonal test result of the drum cutting depth, hauling speed and rotation speed in the drum ejection mode. Table 6 is the significance analysis result of the three factors affecting the coal loading rate with drum ejection.

Fig. 8. 650 mm width test drum.

Tab. 5. The orthogonal test result of the drum cutting depth, hauling speed and rotation speed (coal loading with drum ejection).

No.	**Cutting depth** [m]	**Rotation speed** [r/min]	**Hauling speed** [m/min]	**Coal loading rate**[%]
1	0.3	45	0.5	71.4
2	0.3	70	1	76.2
3	0.3	105	1.5	64.8
4	0.4	45	1	64.7
5	0.4	70	1.5	73.8
6	0.4	105	0.5	36.6
7	0.5	45	1.5	46.1
8	0.5	70	0.5	42.4
9	0.5	105	1	49.2

Tab. 6. Significance analysis result of the three factors affecting coal loading with drum ejection (drum cutting depth, hauling speed and rotation speed).

Variation source	Cutting depth	Rotation speed	Hauling speed	Error	Total
Sum of deviation square	1225.53	814.16	404.33	188.17	2632.18
DOF	2.00	2.00	2.00	2.00	8.00
MS	612.76	407.08	202.16	94.08	
***F* value**	6.51	4.33	2.15		

Table 6 shows that the cutting depth of the drum exerts the largest influence on coal loading rate with drum ejection, the drum rotation speed has the second largest influence, and the hauling speed has the least influence. Under this experimental condition, coal can be more easily ejected to goaf beyond the drum hub with an increase in the cutting depth, which is the main reason for it having the largest influence. With low rotation speed, coal has enough time to slide downwards on the drum due to gravity and thus increase the loading rate. With a high rotation speed, it is more difficult for coal to slide due to gravity, which is mainly affected by the tangential and axial speed of the vane. The tangential speed increases faster than the axial speed. Thus, the influence of the drum rotation speed ranks second only to that of the cutting depth.

Table 7 shows the orthogonal test results of the drum cutting depth, hauling speed and rotation speed in drum pushing mode. Table 8 shows the analysis of the influence extent of the three factors on coal loading performance with drum pushing. In this test, due to the high hauling speed and low drum rotation speed, the drum gets stuck and stops rotating, with the value shown in the torque sensor exceeding the maximum torque of the machine. To ensure the test and correlation among factors, the hauling speed is changed from 0.5 m/min, 1 m/min and 1.5 m/min to 0.5 m/min, 0.75 m/min and 1 m/min.

Tab. 7. The orthogonal test result of the drum cutting depth, hauling speed and rotation speed (coal loading with drum pushing).

No.	**Cutting depth** [mm]	**Rotation speed** [r/min]	**Hauling speed** [m/min]	**Coal loading rate**[%]
1	0.3	45	0.5	62.9
2	0.3	70	0.75	62.3
3	0.3	105	1	58.4
4	0.4	45	0.75	55.3
5	0.4	70	1	57.7
6	0.4	105	0.5	34.5
7	0.5	45	1	45.6
8	0.5	70	0.5	31.1
9	0.5	105	0.75	26.3

Tab. 8. Significance analysis result of the three factors affecting coal loading with drum pushing (drum cutting depth, hauling speed and rotation speed).

Variation source	Cutting depth	Rotation speed	Hauling speed	Error	Total
Sum of deviation square	1086.65	352.01	184.03	3.38	1626.06
DOF	2.00	2.00	2.00	2.00	8.00
MS	543.32	176.00	92.01	1.69	
***F* value**	321.49	104.14	54.45		

Table 8 demonstrates that with drum pushing, the cutting depth of the drum still has a major influence on loading rate. Its *F* value and the *F* value of the drum rotation speed and hauling speed shows cutting depth has a greater influence on coal loading rate with pushing than on coal loading rate with ejection. The drum rotation speed has a greater influence than hauling speed on pushing loading rate, and the main reason for this may be that the small range of hauling speed makes it difficult to enable the amount of falling coal necessary to meet the filling capacity of the drum.

From the statistics seen in Table 5 and Table 7, it can be determined that with a larger cutting depth, coal loading with ejection performs better than coal loading with pushing. As the cutting depth of the drum of a thin seam shearer is usually relatively large, the diameter is designed to be approximately 0.7 to 0.85 of the mining height. As the front drum cuts the most coal, a thin seam shearer should adopt coal loading with ejection.

3.3 The orthogonal test for influence of the drum vane helix angle, hauling speed and rotation speed on coal loading performance

The drums used in this test are shown in Figure 9. All three of the drums have the same drum diameter, vane diameter, hub diameter, drum width and optimal line spacing. The drum diameter is 530 mm, the vane diameter is 420 mm, the hub diameter is 200 mm, the drum width is 330 mm, and the optimal line spacing is 30 mm. Their drum vane helix angles are 15°, 18° and 21°. Table 9 shows the orthogonal test results of the drum vane helix angle, hauling speed and rotation speed in drum ejection mode. Table 10 shows the significance analysis results of the three factors affecting coal loading rate with drum ejection.

Fig. 9. Three different vane helix angle test drum.

Tab. 9. The orthogonal test result of vane helix angle, hauling speed and rotation speed (coal loading with drum ejection).

No.	Helix angle [°]	Rotation speed [r/min]	Hauling speed [m/min]	Coal loading rate [%]
1	15	45	0.5	74.1
2	15	70	1	81.6
3	15	105	1.5	71.7
4	18	45	1	77.4
5	18	70	1.5	78.9
6	18	105	0.5	64.3
7	21	45	1.5	76.3
8	21	70	0.5	69.2
9	21	105	1	63.1

Tab. 10. Significance analysis result of the three factors affecting coal loading with drum ejection (vane helix angle, hauling speed and rotation speed).

Variation source	Helix angle	Rotation speed	Hauling speed	Error	Total
Sum of deviation square	60.41	195.96	67.31	6.36	330.04
DOF	2.00	2.00	2.00	2.00	8.00
MS	30.20	97.98	33.65	3.18	
***F* value**	9.49	30.80	10.58		

Table 10 shows under coal loading with ejection, drum rotation speed exerts the biggest influence on loading rate of the drum, hauling speed has the second largest influence, and the vane helix angle has the least influence. The main reason for this is the small cutting depth of the drum in this test, which avoids coal blockage. In this condition, coal's moving path controlled by the vane is the key to the loading rate of the drum. According to the classification of effective loading areas in this research, with high rotation speed, coal will float after being thrown to the back of the shaft block to a lower loading rate, which explains the lower loading rate, with the rotation speed of 105 r/min being more efficient than any other speed. Based on the rising angle of the helical vane and F value of the hauling speed, it can be perceived that in this test, the hauling speed and the vane helix angle exert the same influence on the loading rate of the drum.

Table 11 shows the orthogonal test results of the drum vane helix angle, hauling speed and the rotation speed in drum pushing mode. Table 12 shows the analysis of the influence extent of the three factors on coal loading performance with drum pushing.

Tab. 11. The orthogonal test result of vane helix angle, hauling speed and rotation speed (coal loading with drum pushing).

No.	Helix angle [°]	Rotation speed[r/min]	Hauling speed[m/min]	Coal loading rate[%]	Ratio of hauling speed and rotation speed
1	15	45	0.5	59.5	0.0111
2	15	70	1	69.7	0.0143
3	15	105	1.5	68.19	0.0143
4	18	45	1	69.16	0.0222
5	18	70	1.5	63.22	0.0214
6	18	105	0.5	48.33	0.0048
7	21	45	1.5	61.29	0.0333
8	21	70	0.5	46.62	0.0071
9	21	105	1	56.69	0.0095

Tab. 12. Significance analysis result of the three factors affecting coal loading with drum pushing (vane helix angle, hauling speed and rotation speed).

Variation source	Helix angle	Rotation speed	Hauling speed	Error	Total
Sum of deviation square	179.22	47.63	351.15	4.71	582.71
DOF	2.00	2.00	2.00	2.00	8.00
MS	89.61	23.81	175.58	2.36	
***F* value**	38.02	10.10	74.50		

Table 12 shows that under coal loading with drum pushing, hauling speed exerts the largest influence on loading rate, vane helix angle has the second largest influence, and drum rotation speed has the least influence. The reason for the largest influence of hauling speed lies in the coal accumulation under the vane, which is similar to the reason for the largest influence of hauling speed in the former orthogonal test involving the drum hub diameter, hauling speed and drum rotation speed. The main difference compared to that test is that the vane helix angle exerts greater influence than the drum rotation speed. This is mainly because the difference in the vane helix angle leads to different pushing directions of the vane to the coal flow, resulting in different transmitting directions of stress in the coal flow that decides the coal flow's moving direction. With a smaller rise angle of the helical vane, the thrust of vane moves more towards the axle, which means a greater possibility of coal flow moving to the axle and a higher loading rate of the drum. Table 11 shows that with the rise angle being 15°, the drum can achieve a sound loading rate even with a small cutting amount for a single turn and insufficient accumulated coal under the vane. This shows that a small rise angle of the helical vane for the drum is essential for improving the loading rate.

4. Conclusions

This paper, through the orthogonal test of three factors and three levels, studies the various influences of the drum hub diameter, cutting depth, vane helix angle, drum rotation speed and hauling speed on the coal loading rate with drum ejection and pushing. The results show that under the conditions of this test, the drum hub diameter has less influence on the two coal loading rates than drum rotation speed and hauling speed do; the cutting depth of the drum has greater influence on the two rates than the drum rotation speed and hauling speed do; in coal loading with ejection, the rise angle of the helical vane exerts less impact on the coal loading rate than the drum rotation speed and hauling speed with only a small difference; in coal loading with drum pushing, the vane helix angle exerts less impact on the loading rate than the hauling speed, but more than the drum rotation speed.

Furthermore, the analysis of the experimental results shows that with a larger cutting depth of the drum, coal loading with drum ejection should adopt a vane with a small helix angle to increase the ratio of the coal's axial velocity to tangential speed to improve the drum's coal loading rate. In coal loading with drum pushing, the hauling speed can be improved to increase the accumulated coal under the vane with the premise of enough vane depth to improve drum coal loading performance. A drum with a large cutting depth in coal loading with drum pushing should use a vane with a small rise angle to ensure the stress of vane on the coal is transmitted towards the coal outlet to increase loading rate. In the mining of thin seams, the shearer should always use the method of coal loading with the front drum ejection and the back drum pushing. The centrifugal force generated when coal makes a tangential movement with the vane is one of the main factors of coal loading rate with drum ejection. When the drum rotation speed is relatively high, hauling speed, with the premise of no coal blockage, should be increased to fill more coal in the drum to lessen the radial motion of the coal caused by centrifugal force. Additionally, the adoption of a vane with a small rise angle and non-vertical vane towards the coal outlet can also effectively decrease the centrifugal force on the coal to improve the loading performance of the drum.

Acknowledgments: *This work was supported by the Science and technology development program of Shandong province (grant No.2014GGX103043), China Postdoctoral Science Foundation Funded Project (project no. 2016M592214), the Postdoctoral Innovation Foundation Funded Project of Shandong Province (project no. 201603057) and Postdoctoral applied research project of Qingdao City(project no. 2016120).*

References

Achanti V.B., Khair A.W.: Cutting efficiency through optimised bit configuration – an experimental study using a simulated continuous miner, In: *Mineral Resources Engineering, Vol. 10, No. 4, 2001, pp.427–434*.

Ayhan M., Eyyuboglu E.M.: Comparison of globoid and cylindrical shearer drums' loading performance, In: *Journal South African Institute of Mining and Metallurgy, Vol. 106, No. 1, 2006, pp.51-56.*

Bołoz Ł.: Unique project of single-cutting head longwall shearer used for thin coal seams exploitation, In: *Archives of Mining Sciences, Vol. 58, No. 4, 2013, pp.1057-1070.*

Brooker C.M.: Theoretical and practical aspects of cutting and loading by shearer drums, In: *Colliery Guardian, Vol.1, 1979, pp.9–16*.

Gao K.D., Du C.L., Liu S.Y., Fu L.: Analysis on significance of the factors influencing shearer drum cutting performance, In: *International Journal of Oil, Gas and Coal Technology, Vol. 7, No. 4, 2014, pp.386-398*.

Gao K.D., Du C.L., Dong J.H., Zeng Q.L.: Influence of the drum position parameters and the ranging arm thickness on the coal loading performance, In: *Minerals, Vol. 5, No. 4, 2015, pp. 723-736.*

Gao K.D., Wang L.P., Du C.L., Li J.N., Dong J.H.: Research on the effect of dip angle in mining direction on drum loading performance: a discrete element method, In: *International Journal of Advanced Manufacturing Technology, Vol. 89, No. 5, 2017, pp. 2323-2334.*

Gospodarczyk P.: Modeling and simulation of coal loading by cutting drum in flat seams, In: *Archives of Mining Sciences, Vol. 61, No. 2, 2016, pp. 365-379.*

Hekimoglu O.Z., Ozdemir L.: Effect of angle of wrap on cutting performance of drum shearers and continuous miners, In: *Mining Technology, Vol. 113, No. 2, 2004, pp.118–122*.

Hurt K.G., Mcstravick F.G.: High performance shearer drum design, In: *Colliery Guard, No.236, 1988, pp.425–429.*

Krauze K., Kotwica K.: Selection and underground tests of the rotary tangential cutting picks used in cutting heads of the longwall and roadway miners, In: *Archives of Mining Sciences, Vol. 52, No. 2, 2007, pp.195–217*.

Krauz, K., Kotwica K., Rączka W.: Laboratory and underground tests of cutting heads with disc cutters, In: *Archives of Mining Sciences, Vol. 54, No. 2, 2009, pp.239–260*.

Liu S.Y., Du C.L., Cui X.X., Gao K.D.: Characteristics of different rocks cut by helical cutting mechanism, In: *Journal of Central South University of Technology, Vol.18, No. 5, 2011a, pp.1518–1524*.

Liu S.Y., Du C.L., Zhang J.J., Jiang H.: Parameters analysis of shearer drum loading performance, In: *Mining Science and Technology (China), Vol. 21, No.5, 2011b, pp.621-624.*

Liu X.H., Liu S.Y., Tang P.: Coal fragment size model in cutting process, In: *Powder Technology, Vol. 272, 2015, pp.282-289.*

Ludlow J., Jankowski R.A.: Use lower shearer drum speed to achieve deeper coal cutting, In: *Mining Engineer, Vol. 36, No.3, 1984, pp.251–255.*

Morris C.J.: The design of shearer drums with the aid of a computer, In: *The Mining Engineer, Vol. 140, No.230, 1980, pp.289-295.*

Peng S.S., Chiang H.S.: Longwall Mining, *New York, John Wiley and Sons Press, 1984.*

Somanchi S., Kecojevic V.J., Bise C.J.: Analysis of force variance for a continuous miner drum using the design of experiments method, In: *International Journal of Mining, Reclamation and Environment, Vol. 20, No. 2, 2006, pp.111–126.*

Wydro T.: Influence of the plow filling and thread angle onto the plow head efficiency, In: *Archives of Mining Sciences, Vol. 60, No. 1, 2015, pp. 143-156.*