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Drum Cutting Specific Energy Consumption Model Built by Cutting Curves Analysis

Gao Kui-Dong, Du Chang-Long*, Jiang Hong-Xiang
College of Mechanical and Electrical Engineering, China University of Mining and Technology (CUMT)
Xuzhou 221008, China, telephone:15162120553
*Corresponding author, e-mail: gaokuidong@cumt.edu.cn

Abstract

For so much error caused in drum's cutting specific energy consumption calculation when using sharp cutter's cutting specific energy formula, the drum's torque mathematical model and cutting specific energy consumption mathematical model which took Goktan's conical pick cutting mathematical model as basic was established refer to the drum cutting curves of the sequence drum, the punnett square drum, the aberrance 1 drum and the aberrance 2 drum. The tests of four type drums and four sequence drums which installed different cone angles were carried out in cutting test bed. The results indicate that: the similarity of calculate result and test result can support the theoretical research;cutting torque and cutting specific energy consumption rise with the cone angle increasing; the minimum torque and cutting specific energy consumption was produced by 2-starts vane punnett square drum, 3-tarts vane aberrance drums produced more larger torque and cutting specific energy consumption；Using punnett square drum in coal cutting can reduce cutting specific energy consumption, but 3-tarts vane aberrance drums have no advantage compared with 2-tarts vane sequence drum in reducing cutting specific energy consumption.

Keywords: *shearer drum, cutting specific energy consumption, pick arrangement, model test*

1. Introduction

Cutting specific energy consumption is used to describe the energy of cutting material per unit volume, and it is an important index for evaluating pick and drum cutting performance. Using cutting specific energy consumption as evaluation standard, vast Simulations and experiments of picks and drums cutting performance were studied by scholars[1]-[10]. Some specific energy consumption decrease methods were got and it provided some references for picks and drums design. Specific empirical formula of cutting specific energy consumption was given by the former Soviet Union scholars according to theoretical analysis and test. But, the object of these studies were single radial pick. For the difference of conical pick cutting process and radial pick cutting process, using those experimental formulas to calculate the conical pick cutting force will make much error. Moreover, single pick cutting was quite different from drum cutting. When drum was cutting, each pick cutting process would be affected by adjacent picks. For these reason, the former cutting specific energy consumption is not suitable for calculate drum cutting specific energy consumption. Therefore, the drum's torque mathematical model and cutting specific energy consumption mathematical model which took Goktan's conical pick cutting mathematical model as basic were established, and the accuracy of the mathematics models were verified by using model test.

2. Mathematical Model Building

Conical picks cutting theory based on the maximum tensile stress was put forward by British scholar Evans[11] in 1984, and then the mathematics model of Conical picks cutting theory was developed and amended by Roxb, Liu[12] and Goktan[13] . But, Goktan's theoretical mathematical model calculating results were the most similar to experimental results. So, in this paper, the building o mathematical model work of drum cutting specific energy consumption took Goktan's theoretical model as a foundation. Figure 1 is Kinematics diagram of the pick-tip, M point in Figure represents the *i-th* pick-tip's initial position; M_1 represents the *i-th* pick-tip's position after drum has moved for time t, and the drum's center coordinate xoy becomes xo_1y_1.

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As show in Eq(1), the motion equation of pick can be got from the relationship between parameters in Figure 1.

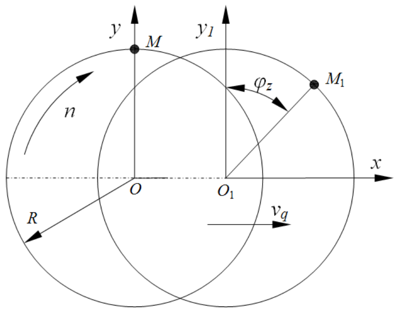


Figure 1. Kinematics diagram of the pick-tip

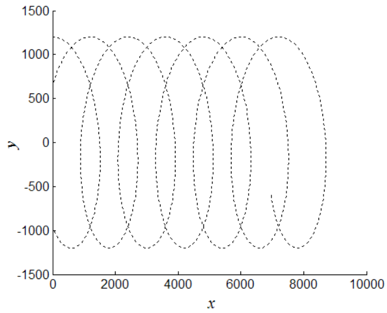


Figure 2. Cutting trace of a pick

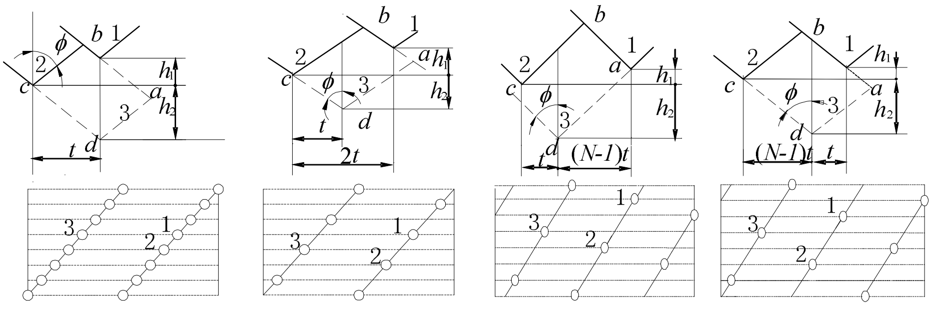
$$\begin{cases} x = v_q t_s + R\sin\varphi_z \\ y = R\cos\varphi_z \\ \varphi_z = \dfrac{\pi n}{30} t_s \end{cases} \quad (1)$$

Where, v_q is hauling speed of drum,m/min; n is rotating speed of drum, r/min; R is radius of drum, m; t_s is rotating time of drum, s; φ_z is rotated angle of pick,°.

According to Eq(1), cutting trace of a pick was carried out ,and it was shown in Figure 2. Figure 2 indicated that the cutting trace of a pick was spiral, and coal breaking area didn't shaped like "crescent" which mentioned by former scholars. So, theoretical average cutting thickness of single pick (h) can be approximate represented as h=1000v_q/nm, m is the pick number in each cutting line. The four picks arrangement types (the sequence type, the punnett square type, the aberrance 1 type and the aberrance 2 type)are widely used at present. These different picks arrangement and breakout patterns were shown in Figure 4. According to Figure 4, pick cutting type and actual cutting thickness are greatly influenced by the pick arrangement during cutting process. Pick effective cutting depth isn't measured by theoretical average cutting thickness, but by broken length l_{cd} and l_{ad}, so blade-pick cutting thickness (h_p) can be expressed by Eq(2):

$$h_p = \frac{l_{ad} + l_{cd}}{2}\cos\phi = \frac{e_0 s / \sin\phi + e_1 h_1 / \cos\phi}{2}\cos\phi = \frac{e_0 s\cot\phi + e_1 h_1}{2} \quad (2)$$

Where, e_0 is the sequence take 1.5, the punnett square take 2, the aberrance 1 and the aberrance 2 take 1.5N-1, N is helical blade number; e_1 is the sequence, the punnett square and the aberrance 2 take 0.5, the aberrance 1 take -0.5; t is cutting line spacing, m; h_1 is the sequence $h_1 = mhs / 2\pi R \tan\varphi$, the punnett square $h_1 = mhs / \pi R \tan\varphi$, the aberrance 1 and the aberrance 2 $h_1 = Nmhs / 2\pi R \tan\varphi$, m; ϕ is cutting angle, $\phi = \arctan[2\pi tRN \tan\varphi / m / h / (2\pi R \tan\varphi - e_2 tN)]$,°; e_2 is the sequence, the punnett square and the aberrance 1 take 1, the aberrance 2 take *N*-1; φ is Blade Helix angle, °.



(a) sequence type;(b) punnett square type;(c) aberrance 1 type; (d) the aberrance 2 type

Figure 4. Different picks arrangement types and breakout patterns

According to Goktan theoretical mathematical model, the mean cutting force of blade pick can be expressed by Eq(3) .

$$F = \frac{4\pi\sigma_t h_p^{\,2} \sin^2\left[0.5(\theta+\beta)+\eta\right]}{\cos\left[0.5(\theta+\beta)+\eta\right]} \qquad (3)$$

Where, θ is cone angles,°; β is impact angle,°; η is friction angle,°; σ_t is coal compression strength,°.

Ignore the effect of skew angle and inclination angle, the mean value cutting force of top disc-pick can be expressed by Eq(4).

$$F' = \frac{4\pi\sigma_t h^2 m^2 \sin^2\left[0.5(\theta+\beta)+\eta\right]}{j^2 \cos\left[0.5(\theta+\beta)+\eta\right]} \qquad (4)$$

Where, *j* is the number of top disc-picks.

According to Eq(3) and Eq(4), the torque of drum can be expressed by Eq(5).

$$T = 0.5(Fk + F'j)R = \frac{2\pi\sigma_t \sin^2\left[0.5(\theta+\beta)+\eta\right]R}{\cos\left[0.5(\theta+\beta)+\eta\right]}\,(h_p^{\,2}k + \frac{h^2m^2}{j}) \qquad (5)$$

Where, *k* is the number of blade picks.

If the displacement of shear is l, the cutting consumption W of drums can be expressed by Eq(6).

$$W = 2\pi nTl / v_q \qquad (6)$$

The crumbling volume of coal V can be expressed by Eq(7).

$$V = 2ldR \qquad (7)$$

where, *d* is cutting depth, m.

According to Eq(6) and Eq(7), cutting specific energy consumption w can be expressed by Eq(8).

$$w = \frac{W}{v} = \frac{2\pi^2 \sigma_t \sin^2\left[0.5(\theta+\beta)+\eta\right] n}{d v_q \cos\left[0.5(\theta+\beta)+\eta\right]} \; ({h_p}^2 k + \frac{h^2 m^2}{j}) \quad (8)$$

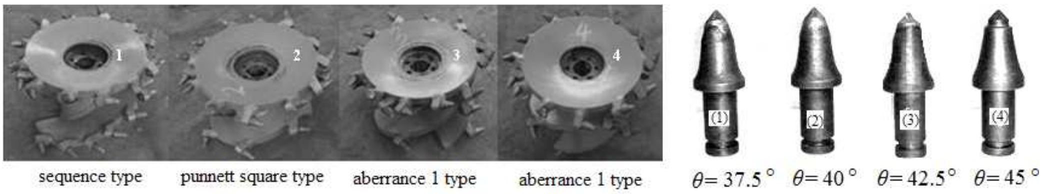


Figure 5. Test drums and picks

3. Model Test of Drum Cutting

To validate the correctness of the mathematical model, the tests of four type drums and four sequence drums which installed different cone angles were carried out in cutting test bed[14]. Test is divided into two groups, then the sequence drum, the punnett square drum, the aberrance 1 drum and the aberrance 2 drum with the same picks whose cone angle were 40°were tested in group 1; the sequence drums with different cone angle picks (37.5°,40°,42..5°and 45°) were tested in group 1. R otating speed is 125 r/min; hauling speed was 3.1 m/min; pick installation angle was 50 °, Th e tested coal wall tensile strength was 0.33 MPa and its density was 1483 kg/m3. The result was shown in Table 1. The torque and cutting specific energy consumption value of theory and test was shown in Table 2, and the cutting specific energy consumption value of test can be obtained by Eq(9) .

$$w_0 = \frac{2\pi T_0 n t' \rho}{60M} \quad (9)$$

Where, T_0 is test torque, N·m;t' is cutting time, s; ρ is coal density, kg/m^3;*M* is weight of broken coal, kg.

Table 1 Test results

Test object		Mean torque/N·m	Cutting time/s	weight of broken coal /kg
Cone angle	37.5	1183	21	277.6
	40	1219	20.7	274.7
	42.5	1251	19.8	263
	45	1273	22.3	292
Arrangement type	punnett square	1109	17.6	235.7
	aberrance 1	1339	15.4	215.7
	aberrance 2	1267	20.1	276.7

4. Analysis of Test Results

According to Table 2, the bar charts of cutting specific energy consumption value and the torque along with cone angle and picks arrangement were shown in Figure 6 to Figure 9. From Figure 6 and Figure 7, it can be seen that: Regardless of the test and the theory, cutting specific energy consumption value and the torque enlarged with the cone angle increasing. The main reason is due to cone angle increase, the ability of pick wedge in coal is reduced and pick tip got larger force; The variation tendency of the torque and cutting specific energy consumption value of the theory is consistent with the test. The ratio of theoretical torque to experimental torque increased from 0.662 to 0.741 as cone angle increasing, while the ratio of theoretical cutting specific energy consumption value to experimental increases from 0.685 to 0.758.The ratio increases with the same trend. Thus it can be seen that the influence of cone angle on cutting force could not be precisely expressed by Goktan semi-empirical formula, and further research was desperately needed.

Table 2 Cutting torque and specific energy consumption value of calculate and test

Test object		Theoretical value		Test value		Ratio of theoretical and test	
		Mean torque T /N·m	Cutting specific energy consumption w /10^6 J/m^3	Mean torqueT_0 /N·m	Cutting specific energy consumption w_0 /10^6 J/m^3	Ratio of torque	Ratio of cutting specific energy consumption
Cone angle	37.5	783.3	1.1886	1183	1.7362	0.662	0.685
	40	833.18	1.2644	1219	1.7824	0.683	0.709
	42.5	886.25	1.345	1251	1.8274	0.708	0.736
	45	942.86	1.4308	1273	1.8868	0.741	0.758
Arrangement type	punnett square	763.72	1.159	1109	1.6064	0.689	0.721
	aberrance 1	782.25	1.1872	1339	1.8546	0.584	0.640
	aberrance 2	752.8	1.1424	1267	1.786	0.594	0.640

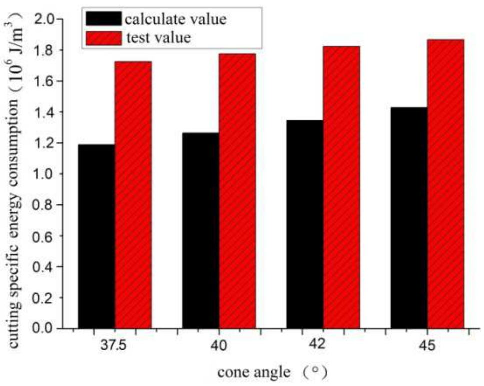


Figure 6. Relationship between cutting specific energy consumption and cone angle

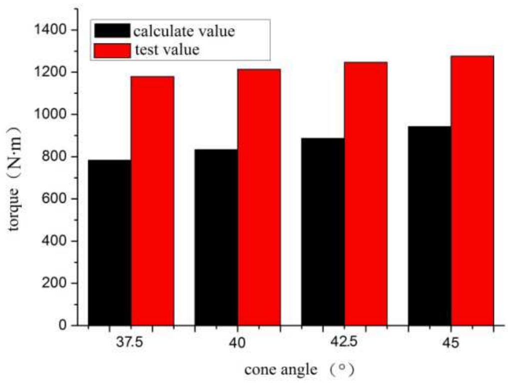


Figure 7. Relationship between torque and cone angle

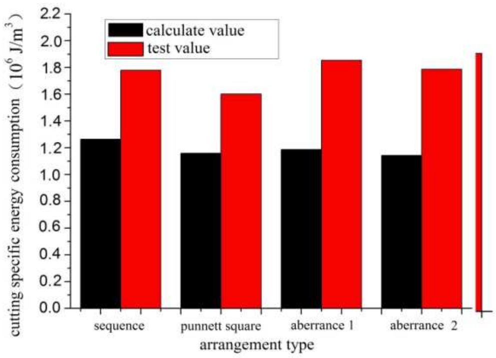


Figure 8. Relationship between cutting specific energy consumption and picks arrangement

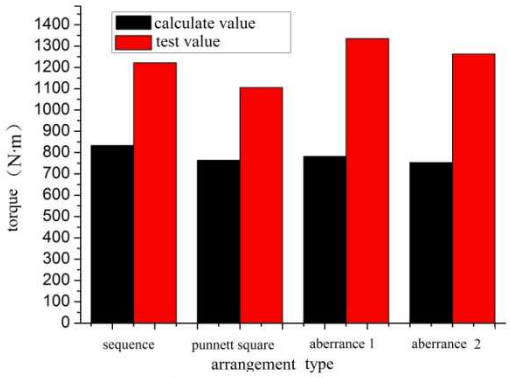


Fig 9. Relationship between torque and picks arrangement

From Figure 8 and Figure 9, it can be seen that: according to theoretical calculation, the cutting specific energy consumption value and the torque of sequence drum should be the maximum, the aberrance 1 drum comes second, and the aberrance 2 drum is the minimum. But the experimental results show that cutting specific energy consumption value and the torque of aberrance 1 drum is the maximum, the sequence drum come second, and the punnett square drums is the minimum. It's mainly due to blade number of sequence drum and punnett square drum, those blades number is two, and the aberrance 1 and the aberrance 2 is three. The extra torque caused by blade loading performance, then it seems that with same blade number, the cutting specific energy consumption value can be reduced by using the punnett square, and three-blade aberrance drum have no advantage in reducing the cutting specific energy consumption value than the two-blade sequence drum; According to the ratio of theoretical value to test's, the theoretical calculate result of the sequence drum is most close to the test's, while the deviation of the aberrance drum's is biggest, and its mainly caused by the aberrance drum cutting complexity; In addition, according to Table 2, the cutting specific energy consumption value ratio of theoretical value to test's of the aberrance 1 drum is same with the aberrance 2 drum, but the torque ratio is different, and its mainly caused by weighing error or artificial coal wall configuration is not completely uniform.

The test results show that: variation tendency of the test results were same with the theoretical model simulated results; the consistency of theoretical and test's (ratio is 0.584~0.758) were far higher than the cutting specific energy consumption calculate results by the former Soviet union's formula (compared with the test result, its error was one or two orders of magnitudes). Finally, all of work can proved the correctness of this research. This model building method of curve analysis and experimental verification can applied to many fields, especially in path planning and circuit design [15],[16].

5. Conclusion

(1) Based on the Goktan semi-empirical formula of conical picks cutting force, the formula of cutting torque and cutting specific energy consumption of the sequence drum, the punnett square drum, the aberrance 1 drum and the aberrance 2 drum are derived. According to the test, variation tendency of the test results were the same with the theoretical model simulate result, it proved that the built model was exact.

(2) Cutting torque and cutting specific energy consumption rise with the cone angle increasing; the minimum torque and cutting specific energy consumption was produced by 2-starts vane punnett square drum, 3-tarts vane aberrance drums produced more larger torque and cutting specific energy consumption;using punnett square drum in coal cutting can reduce cutting specific energy consumption, but 3-tarts vane aberrance drums have no advantage compared with 2-tarts vane sequence drum in reducing cutting specific energy consumption.

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