Full length article

Three-dimensional experimental study of loose top-coal drawing law for longwall top-coal caving mining technology

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Abstract

Based on the loose medium flow field theory, the loose top-coal drawing law of longwall top-coal caving (LTCC) mining technology is studied by using self-developed three-dimensional (3D) test device. The loose top-coal drawing test with shields and the controlled test without shields are performed in the condition without any boundary effect. Test results show that shields will cause reduction in drawing volume of coal in the LTCC mining. The deflection phenomenon of drawing body is also observed in the controlled test, which is verified that the deflection of drawing body is caused by shield. It is found that the deflection angle decreases with increasing caving height, with the maximum value of $\alpha_{\text{coal}}$ and the minimum value of 0. In addition, the formula to calculate the drawing volume is proposed subsequently. The deflection of drawing body is numerically simulated using particle flow code PFC$^{\circledast}$ and the proposed formula to calculate drawing volume in LTCC is also verified.

1. Introduction

Longwall top-coal caving (LTCC) mining technology is a productive and economical method to extract thick coal seams, and thus is widely used in many coal mines in China (Wang, 2009; Wang et al., 2014). Although some hypotheses on top-coal drawing process were proposed (e.g. Wang and Fu, 2002; Wang et al., 2004, 2010, 2014; Unver and Yasitli, 2006; Vakili and Heblewhite, 2010; Karekal et al., 2011), the top-coal drawing law still remains unclear in the process of top-coal drawing, which is one of the limitations of improving the recovery ratio of the top-coal. The loose medium flow field theory is one of the most important hypotheses in terms of the slope shield tail beam and the shield periodic step advance. However, the shield and the advance make the drawing process of top-coal and metal ore very different (Wang and Fu, 2002). Many researchers analyzed the effects of the shield of top-coal caving technology. Wu and Zhang (2001) proposed a new concept of the relation between shield and surrounding rock in the LTCC faces. Nan et al. (2002) analyzed the effect of the parameters of top-coal caving shield on the recovery ratio. Yan et al. (2002) proposed a method to determine the shield capacity using the LTCC mining technology. However, most studies did not consider the combining effect of the shield and spatial shape of drawing body. Moreover, some tests on the LTCC technology were merely concentrated on two-dimensional (2D) cases (Jiang, 1990; Bai et al., 2001; Wang and Fu, 2002; Zhai, 2002; Wang et al., 2004). Unfortunately, the 2D simulation cannot truly reflect the movement law of loose top-coal and fragmented rock along the coal seam dip direction. Thus we cannot understand the three-dimensional (3D) drawing law of loose top-coal in longwall caving mining method only from 2D simulation.

In this study, based on the loose medium flow field theory, we conduct the loose top-coal drawing test with shields and controlled test without shields by using self-developed 3D test device for the LTCC mining. As for the controlled test, the effects of other factors during the test are ignored but the effect of shields on the loose top-coal drawing law in top-coal caving is analyzed. Meanwhile, the PFC$^{\circledast}$ models are established to verify the results obtained from 3D physical model test.

2. Loose medium flow field theory

During the process of coal face advancing of the LTCC panel, the top-coal and immediate roof above the shields are basically broken and can then be regarded as loose media. Thus the caving top-coal moving and drawing process complies with the law of loose medium flow. As shown in Fig. 1, the drawing opening of the shield is the free boundary for the loose media composed of loose coal and...
loose immediate roof. The interaction forces between particles of the loose media can be released in the opening. The loose media above and behind the shield will move towards the drawing opening along the path of minimum resistance, and a motion field which is similar to traction flow will be formed in the loose media. Such moving and drawing process of top-coal is called as the loose medium flow field model (Wang and Fu, 2002; Wang et al., 2004, 2010, 2013, 2014).

3. 3D similar simulation tests on loose media

3.1. Test device

The physical model tests are conducted using self-developed 3D test device in top-coal caving laboratory at China University of Mining and Technology (Beijing) (CUMTB). Fig. 2 shows the test device with dimensions of 1000 mm × 500 mm × 600 mm.

3.2. Materials

The geometrical ratio of the shield prototype to physical model is 20:1, and the height of caving shield (Fig. 2b) is 100 mm. The materials used in this study are shown in Fig. 3. Loose coal is simulated by black granite particles, with diameter of 5–10 mm, friction angle of 36.1°, and density of 1712 kg/m³. The loose immediate roof is simulated by white marble particles with diameter of 10–20 mm, friction angle of 37.7°, and density of 1782 kg/m³. The thicknesses of loose coal and immediate roof in the test are 300 mm and 200 mm, respectively.

3.3. Layout of marked particles and test schemes

The particles are marked to analyze the flowing characteristics of loose media and locate the spatial shape of drawing body. In order to keep the same flowing characteristics as the materials used, the marked particles are selected from the materials used with diameter of 5–10 mm. The different ID number on each marked particle is given to represent its coordinate (Wang et al., 2003; Tao et al., 2009). The marked particles are located every 30 mm in height direction along 4 planes (X, Y, X + 45° and X – 45°) during the process of filling materials in the test box, as shown in Fig. 4.

As for the controlled test, two schemes are designed as models 1 and 2. Model 1 is the loose top-coal drawing test with shields, and the test box with shields is shown in Fig. 5a. Model 2 is the controlled test without shields, as shown in Fig. 5b. Each model test is done for three times to reduce the influence of test error.

4. Test results and analysis

The 3D similar simulation tests can represent the top-coal drawing process. After comparing and analyzing the results of two physical models, the key point is to study the impacts of shields on the drawing volume (i.e. the volume of drawing body) and the developing process of the drawing body.
4.1. Relation between drawing volume and height of drawing body

The drawing volume of the loose top-coal is recorded when the marked particles located in different layers reach the drawing opening. The drawing volume \( Q \) under the height of drawing body \( H_f \) can be calculated through dividing the mass of the drawn loose coal by its density. The relation between \( H_f \) and \( Q \) is illustrated in Fig. 6 based on the average values obtained from three tests. Eqs. (1) and (2) were obtained by regression analysis of the test data.

For the loose top-coal drawing test, we have

\[
Q = 0.4233H_f^{2.571}
\]

(1)

For the controlled test without shields, we have

\[
Q' = 1.214H_f^{3.14}
\]

(2)

where \( Q \) and \( Q' \) are the drawing volumes of model tests 1 and 2, respectively. In Eq. (1), we have \( R^2 = 0.9994 \); and in Eq. (2), \( R^2 = 0.9993 \).

It can be found from Fig. 6, Eqs. (1) and (2) that the relation between \( Q \) and \( H_f \) follows the law of power function both in the loose top-coal drawing test and the controlled test. The drawing volume under different heights in the loose top-coal drawing test is less than that in the controlled test, and the difference can be attributed to the presence of shields.

When the height of drawing body \( H_f \) is lower than that of shield \( h \) (\( h = 10 \text{ cm} \) in the test), the difference between the loose top-coal drawing test and the controlled test is the minimal; while the drawing volume in the loose top-coal drawing test is considerably less than that in controlled test when \( H_f > 10 \text{ cm} \).

Most researchers utilized the ellipsoid theory of the metal mines to analyze the top-coal drawing law during top-coal caving without taking shields into consideration. This paper has verified the difference of the drawing volume between the loose top-coal drawing test (representing coal mine) and the controlled test (representing metal mine). Furthermore, the difference of drawing body can lead to various developing processes of drawing body evidently. Consequently, it is extremely significant to study how shields affect the spatial shape of drawing body.

In this study, we define \( \Delta Q \) as the decrement of the drawing volume which is caused by the shields in the LTCC mining.
shown in Fig. 7, $\Delta Q$ increases with the increment of $H_t$, and this relation can be expressed as

$$\Delta Q = f(H_t) \tag{3}$$

Therefore, in the LTCC mining, the drawing volume can be calculated by

$$Q = Q' - \Delta Q \tag{4}$$

The controlled test can be regarded as single opening drawing of metal mines. Therefore, according to the ellipsoid theory of metal mines (Malakhov, 1958; Xie, 2008), the drawing volume of the controlled test can be calculated by

$$Q' = \frac{\pi}{6} KH_t^{3-n} \tag{5}$$

where $K$ and $n$ are the test constants. Substituting Eq. (4) in Eq. (5) yields

$$Q = \frac{\pi}{6} KH_t^{3-n} - f(H_t) \tag{6}$$

In field practice, the first term in Eq. (6) is determined by the flowing property of loose coal; the second is determined by the parameters of shields. The form of Eq. (3) is analyzed as follows. When $H_t < h$, the drawing body has small volume and no fixed shape. Thus the focus is shifted to the relation between $\Delta Q$ and $H_t$ when $H_t > h$. According to Eq. (4), $\Delta Q$ under different $H_t$ can be calculated by the test data, and the results are shown in Fig. 7.

As can be seen in Fig. 7, when $H_t > h$, $\Delta Q$ and $H_t$ show a good linear relationship. The least square method can be used to make the regression calculation in Fig. 7, and the relation between $\Delta Q$ and $H_t$ can be written as

$$\Delta Q = 20.6H_t - 102.2 \tag{7}$$

In Eq. (7), we have $R^2 = 0.9748$.

In practice, the precise result is difficult to be acquired and then the linear relation, Eq. (7), can be utilized to determine the expression of Eq. (3). The general form is written as follows when $H_t > h$:

$$f(H_t) = AH_t + B \tag{8}$$

where $A$ and $B$ are the test constants when the shield is taken into consideration. Constants $A$ and $B$ can be determined by the height of shield, the angle of the shield tail beam, the friction coefficients of the top-coal and the tail beam, etc.

When $H_t > h$, the drawing volume in the LTCC mining can be calculated by

$$Q = \frac{\pi}{6} KH_t^{3-n} - AH_t - B \tag{9}$$

The essence of Eq. (9) is a modification of the classical ellipsoid theory in metal mines by considering the impact of shields. The modification can much more precisely describe the loose top-coal’s drawing law in the LTCC mining; furthermore, it provides a more accurate method to calculate the drawing volume.

4.2. Developing process of drawing body

By analyzing the ID numbers of marked particles which were drawn out during the test, the initial spatial coordinates of marked particles can be obtained, with which the developing process of drawing body’s spatial shape can be plotted accordingly. For better analysis and observation, morphological analysis of drawing body is conducted in four planes: XOZ, YOZ, $(X + 45^\circ)OZ$ and $(X - 45^\circ)OZ$.

The developing process of drawing body is illustrated in Fig. 8. The ellipses in Fig. 8 are plotted by fitting the coordinates of marked particles in the boundary of drawing body in different caving heights.

We can know from Fig. 8 that, in the drawing process of the LTCC mining, the boundaries of drawing bodies in different planes can be well fitted in ellipse shape.

Due to the asymmetry of shields in the direction of advancing face, the drawing body shows an obvious deflection towards the front of shields (direction of $X_+$) in XOZ plane, as illustrated in Fig. 8a. In YOZ plane, the drawing body is symmetric in terms of the $Z$-axis, as illustrated in Fig. 8b. This is due to the fact that the friction coefficient between shields and top-coal is smaller than that of the top-coal, suggesting that the speed of flow in the area near the shield tail beam is higher than that in the area far away from tail beam. Consequently, the difference of friction coefficient leads to the deflection of drawing body. The deflection phenomenon can be also explained that the impact of the shields on the stress field (especially confining stress) is inversely proportional to the distance from the shields.

In order to observe the spatial shape of drawing body, a study on the drawing body is conducted in $(X + 45^\circ)OZ$ and $(X - 45^\circ)OZ$ planes. As illustrated in Fig. 8c and d, we can see that the drawing body still shows deflection towards the front of shields. However, the deflection angle of drawing body decreases because of the decrement of shield’s asymmetry compared with XOZ plane.

As illustrated in Fig. 8a, c and d, as the height of drawing body increases, the deflection angle of drawing body towards the front of shields reduces. In order to demonstrate the deflection of drawing body caused by the shields in direction of advancing face, the developing process of drawing body in XOZ plane in the controlled test is illustrated and compared with the loose top-coal drawing test. The results are shown in Fig. 9.

In Fig. 9, we can know that the deflection of drawing body towards the front of shields (the direction of $X_+$) in XOZ plane in the loose top-coal drawing test is indeed caused by the presence of shield, which is verified by the controlled test. In the loose top-coal drawing test, the deflection degree of drawing body towards $X_+$-direction in XOZ plane is influenced by the height of shields, the angle of tail beam, the friction coefficient between shield tail beam and top-coal, etc.

The analysis above shows that the deflection of drawing body exists towards the front of the shield during the developing process of drawing body, which is observed through 3D similar simulation test for the first time. Through the controlled test, the fact that the deflection is caused by the shield is verified.

4.3. Deflection of drawing body

When analyzing the deflection phenomenon of drawing body, the eccentricity of ellipse $\varepsilon$ and deflection angle $\theta$ (angle between
the direction of the long axis of ellipse and the direction of gravity) of the fitted ellipse of drawing body boundaries in different planes are two key factors. The eccentricity $\varepsilon$ determines the overall shape of ellipse, i.e. a large $\varepsilon$ means the ellipse is a thin one while a small $\varepsilon$ means it is a fat one. The deflection angle $\theta$ determines the deflection extent of drawing body, which decreases with the decrement of $\theta$. When $\theta = 0^\circ$, the drawing body will not deflect.

In the loose top-coal drawing test, the relations between $\varepsilon$ and $H_f$ in XOZ and XOY planes are shown in Fig. 10.
It can be seen from Fig. 10 that, during the caving process, the value of $\varepsilon$ under different caving heights is within the range of $0.82$–$0.94$, roughly fluctuating with the caving height. The value of $\varepsilon$ is $0.89$ when the gangue reaches the caving opening.

The eccentricity of ellipse in XOZ plane is always larger than that in YOZ plane, illustrating that the asymmetry of shields in the direction of advancing face will change the spatial shape of drawing body. According to the definition of eccentricity, the width of ellipse in YOZ plane is larger than that in XOZ plane, as illustrated in Fig. 8a and b.

The differential value of $\varepsilon$ in XOZ and YOZ planes decreases with the increase of caving height $H_f$ and tends to be 0 when the gangue comes out. It is shown that the influence extent of shields on the overall shape of drawing body decreases with the increase of caving height. Thus there is a critical height $H_c$; when $H_f > H_c$, the influence of shields on drawing body is very slight or even negligible.

Deflection angle $\theta$ is the most important variable to show the deflection extent of drawing body. The relation between $\theta$ and $H_f$ during the test is shown in Fig. 11.

In Fig. 11, we can know that the deflection angle of ellipse in XOZ plane is larger than that in YOZ plane, and the maximum value is $21.53^\circ$ while the minimum value is $3.03^\circ$ in XOZ plane. Deflection angle of ellipse in YOZ plane is generally small, which is within the range of $0^\circ$–$4^\circ$. This is due to the fact that the deflection angle is caused by asymmetry of shield in the direction of advancing face. Thus the deflection angle is large in XOZ plane and decreases from XOZ plane to $(X \pm 45^\circ)$ YOZ plane, and finally reaches the minimum value in YOZ plane. In YOZ plane, because of the symmetry of shields in dip direction, the deflection angle tends to be 0.

When $H_f \to 0$, because of the limitation of tail beam of shield, the drawing body develops along the tail beam, so the deflection angle of ellipse in XOZ plane tends to be $\alpha_{\text{tail}}$, which is the angle between the direction of shield tail beam and the direction of gravity. In this test, $\alpha_{\text{tail}} = 30^\circ$.

When $H_f \to \infty$, the deflection angle of ellipse in XOZ plane tends to be 0, i.e. the influence of shields on drawing body is negligible.

The whole process that the deflection angle decreases with the increase in $H_f$ can be illustrated in Fig. 12.

4.4. Verification of the deflection by numerical simulation

In order to verify the existence of deflection of drawing body and Eq. (9), 3D numerical model is established by using PFC$^{3D}$ to carry out the loose top-coal drawing test with shields and the controlled test without shields. The boundary condition and initial state of PFC$^{3D}$ model are shown in Fig. 13.
In the loose top-coal drawing test model, the shield is simulated by “wall” in PFC. The value of \( \alpha_{\text{tail}} \) is set to be 40°, and the caving opening size is 1 m × 1.2 m (dip length × width). In the controlled test model, the caving opening size is 0.64 m × 1.2 m (length × width), which is the same size as the orthographic projection of caving opening in the loose top-coal drawing test model. Two models have the same mechanical parameters of particles, as shown in Table 1. The physico-mechanical parameters of shield are shown in Table 2.

The analysis focuses on the developing process of drawing body during the caving process. Drawing bodies are plotted in Fig. 14 under different caving heights.

From Fig. 14, we can know that, in the loose top-coal drawing test, when the caving height is low, the deflection phenomenon of drawing body is evident, which can be seen from the difference between the drawing body boundary and the ellipse without deflection (the dashed ellipse in Fig. 14) in XOZ plane. The difference is mainly in the upper left and lower right parts of the drawing body. The lower right part is caused by the limitation of shield tail beam, while the upper left part is due to the fact that the speed of flow in the area near the shield tail beam is higher than that in the area far away from tail beam. Consequently, the drawing body develops prior to the upper right part.

The difference in the upper left part of drawing body decreases with the increase in caving height gradually. When \( H_f = 29.81 \text{ cm} \) (the thickness of coal seam is 30 cm), the boundary of drawing body in the upper left part almost coincides with the ellipse shape without deflection, i.e. the deflection towards the front of the shield is very slight, which agrees with the results of similar simulation tests.

In the controlled test without shield, the drawing body is roughly an ellipsoid, with boundary matching the ellipse without deflection in different caving heights, i.e. the deflection phenomenon of drawing body does not appear in the controlled test. This result also agrees with similar simulation tests.

Comparing numerical simulation with similar simulation tests, the deflection of drawing body in the LTCC mining is verified. Comparing Fig. 14a with Fig. 14b, we can conclude that the deflection is caused by the existence of shield. To understand the relation between deflection angle of drawing body and caving height in similar simulation tests, the deflection angle is numerically simulated and compared with that in similar simulation tests. The results are shown in Fig. 15.

In Fig. 15, numerical simulation shows that deflection angle decreases with the increase in caving height. Because it is assumed \( \alpha_{\text{tail}} = 40^\circ \) in numerical simulation, when the caving height is very low, the deflection angle tends to be 40°. This verifies that when \( H_f \to 0 \), the deflection angle of ellipse in XOZ plane tends to be \( \alpha_{\text{tail}} \).

Under different caving heights, the deflection angle of drawing body in numerical simulation is basically consistent with that in similar simulation tests. When the caving height reaches the thickness of coal seam, the deflection angle tends to be \( 5.88^\circ \). This verifies that when \( H_f \to \infty \), the deflection angle of ellipse in XOZ plane tends to be 0.

### 4.5. Verification of Eq. (9)

In order to verify Eq. (9), the drawing volume under different caving heights in numerical simulation is calculated and compared with that in similar simulation tests. The results are shown in Fig. 16.
In Fig. 16, the relation between $Q$ and $H_f$ follows the law of power function both in the loose top-coal drawing test and the controlled test by numerical simulations. The results from numerical simulations and similar simulation tests have a good consistency in different caving heights. When the caving height is comparatively high ($H_f > 25$ cm), the drawing volume in the numerical simulations is larger than that in similar simulation tests, due to the fact that $\alpha_{\text{tail}} = 40^\circ$ in numerical simulation is larger than that in the similar simulation tests ($30^\circ$), thus the lower right part of drawing body in numerical simulations is larger.

Above analysis verifies the reasonability of the first term in Eq. (9). The second and third terms should be verified, i.e. whether $\Delta Q$ and $H_f$ have a linear relation when $H_f > h$. The data in numerical simulations are analyzed and shown in Fig. 17.

In Fig. 17, it is observed that the drawing volume in the loose top-coal drawing test is significantly smaller than that in the controlled test in numerical simulations (Fig. 17(a)), and the $\Delta Q$ and $H_f$ also show a good linear relation (Fig. 17(b)). The same conclusions can be drawn in the similar simulation test. It can now be noted that the second and third terms in Eq. (9) are verified by numerical simulations.

In other words, Eq. (9) can be used to calculate the drawing volume in the LTCC mining, which can truly describe the top-coal drawing law in three dimensions under caving mining method and provide a new method for calculating the drawing volume in the LTCC mining.

5. Conclusions

(1) The self-developed 3D test device can be used to carry out similar simulation test of LTCC effectively, which could provide a new method for studying the mechanism of top-coal caving in three dimensions.

(2) In the LTCC mining, the shields will cause the decrease in the drawing volume. By modifying the formula for calculating the drawing volume in the classical ellipsoid theory of metal mines, the formula to calculate the drawing volume in the LTCC mining is proposed.

(3) The deflection phenomenon of drawing body exists during the developing process of drawing body. The deflection of drawing body is caused by shield. The deflection angle decreases with the increase in caving height.

(4) The deflection of drawing body and the reasonability of Eq. (9) for calculating the drawing volume in the LTCC mining are verified by using numerical simulation (PFC3D). The results from numerical simulation and similar simulation test match well under different caving heights.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no
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References


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