An analysis of the gas-solid plug flow formation: New insights into the coal failure process during coal and gas outbursts

Wei Zhao, Yuanping Cheng, Pinkun Guo, Kan Jin, Qingyi Tu, Haifeng Wang

1. Introduction

1.1. Research on the outburst gas-solid flow state

Coal and gas outbursts are dynamic failures that can involve the sudden ejection of thousands of tons of coal and rock as well as large amounts of gas into a limited underground working space in a short period. The most obvious characteristic differing from common extrusions or slips of coal (rock) is that gas plays a vital role in the crushed coal transport. General coal extrusions or slips are controlled by crustal stress or coal's own weight and gas is hardly witnessed. Therefore, outbursts are violent and produce a much longer ejection distance of thousands of tons of coal and rock as well as large amounts of gas into a limited underground working space in a short period.

II. Significance of research

Significant amounts of coal powder exist in the upper area or on the edge of the coal dump. Hu [14] obtained a particle distribution from several outbursts, which consisted of up to 53.8% of coal powders of less than 100 μm.

In the last 150 years, based on the collective data of outbursts and experimental results, researchers have proposed several models to describe outbursts. These theories are primarily established from the viewpoint of a driven force of outbursts, including gas-driven, stress-driven, chemistry-driven and combined-effects-driven hypothetical theories. Factors including the in situ stress, mining stress, gas pressure, gas content, desorption rate, sorption capacity, particle size, coal strength, coal permeability, special geological structures etc. are believed to exert an influence on the occurrence of outbursts. All of the above theories tried to obtain a convincing explanation for one particular feature of the outbursts but failed to interpret the entire outburst. Thus, none of them are strongly reliable [2,4,5,12,23,28,34,41].

With respect to the gas-solid flow state of the outbursts, limited experimental results exist where an outburst is generally assumed to be an explosion. It is thought that the reason why outbursts lead to such significant destruction is that there is an air shock wave ahead of the outburst front, which is formed by the compression of a rapid coal-gas mixture flow [6,11,34,35,44,45]. Sun et al. [31] suggested that the fastest speed of a gas-solid flow is the sound velocity under the critical state. Furthermore, he noted that the loud sound occurring in the...
Zhongliangshan outburst was because the flow speed reaches the sound velocity and cannot be any faster. This critical state resembles a choking procedure that can stop an outburst along with a significant amount of noise. Overall, the previous analyses have all been made under the initial impression that the destruction of outbursts is of considerable power and large-scale influence. Therefore, a large flow speed appears to be more likely and acceptable. A simple ejection model was used to describe the transport of the coal-gas flow to be more likely and acceptable. A simple ejection model was used to describe the transport of the coal-gas flow, with a limit that objects can undergo a pushing force only once as it moves, and thus a large kinetic energy must be required to meet the transport demand of such a large mass. However, from the pneumatic conveying theory, we know that a flow of a great mass can be completed at a slow speed using a persistent high pressure. Moreover, the ejection force is not only applied once but is intermittent and pushes the coal from the beginning to the end of the transport. Previous studies on outburst flows only focus on the transport, without considering how outbursts form and develop and ignore the spallation of the outburst coal. Thus, it is worthwhile to find out how the coal-gas flow transports and what flow state it belongs to with the generation mechanism of the outbursts.

1.2. Classifications of pneumatic conveying

Pneumatic conveying, which is a process used to transport solid particles through confined pipes using a strong force of gas, is generally divided into two states: dilute-phase conveying and dense-phase conveying. The primary indices characterizing these two states are solid-gas ratio (solid mass in conveying per volume), gas velocity, and pressure loss. Although valuable, these parameters only provide a side description to a particular conveying system and cannot determine the accurate flow state. Thus, a classification with quantitative indices becomes difficult, and an accurate dividing line between the dense-phase and the dilute-phase is not available [24,26,37,42].

However, a qualitative description is generally accepted. K. Konrad [19] defined that when one or more cross sections are filled with powders, it is a dense-phase flow; otherwise, it is a dilute-phase flow. For one certain system, with a decrease in the gas flow speed, the flow will experience a variation in the suspension flow, stratified flow, dune flow, plug flow and blocking (Fig. 1) [9,29]. When a high-speed gas is supplied, the coal powders will float uniformly in the pipes, and the solid-gas ratio is relatively small. Then, when the gas speed is lowered until it cannot provide adequate power to blow the powders, a deposition will occur in the floor of the pipes, which leads to a stratified flow and an orderly dune flow. When the speed decreases again, the coal powders will fill one or more cross sections in the pipes, forming several solid plugs, which can be pushed forward by the gas pressure, and as it moves smoothly, a plug flow is formed. If the gas speed decreases even further to less than the blocking speed, the powder flow will cease and block the pipes. With a decrease in speed, the delivery capacity will increase significantly as the dilute-phase flow becomes the dense-phase flow.

1.3. Forming conditions of the plug flow

From engineering experience, to fulfill a high solid-gas ratio of powder transport, it is a need to maintain a low gas speed, which can be found easily in the plug flow. For an ideal plug flow transport, the most apparent characteristic is a solid plug appearing in the pipes, which is separated by a certain length of the gas plug. These air intervals typically need an artificial high-pressure air knife machine to assist in formation when proceeding with an industrial conveying process (Fig. 2). The artificial air knife can increase the efficiency and the capacity of the transport. When the solid powders are ejected into the pipes, the air knife cuts the flow part by part and pushes the solid away due to high pressure [38]. Therefore, an intermittent air knife, high gas pressure, low flow speed and continual high-density solid supply are the essential conditions of a steady plug flow. If the outburst coal-gas mixture is supposed to be transported in this manner, the above four conditions are necessary.

2. Theory

2.1. Model establishment and basic assumptions

The gas-solid flow of the outbursts is an ideal pneumatic conveying transported along the pipes, as indicated in Fig. 3. In this transport, the following simplified conditions must be adopted:

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Fig. 1. Flow state variation vs gas flow speed.

Fig. 2. Typical plug flow transport machine.

Fig. 3. Simplified model of an outburst. Note: Drawn lines are referred to the data introduced by Hu and Wen [15], Sun [31].
I. The crushing and carrying processes are assumed to be two separate stages appearing orderly. The crushing process is entirely dominated by the crustal stress whereas the carrying power is from the gas expansion energy. Before ejection, the coal has been crushed by the crustal stress and does not experience it during the transport.

II. Other energies, such as the remaining kinetic energy, heat loss, and sound energy, are neglected.

III. The roadway is horizontal without any dip angle.

IV. The density of the plug during transport remains the same.

2.2. Gas/coal flow speed calculations of outbursts

2.2.1. Gas flow speed

An outburst is a highly complex and largely changeable process that can hardly be analyzed without any simplification. Most experts tend to use the energy conservation method to describe this process [10, 13, 18, 21, 33, 36, 43]. The elastic energy of coal is ignored here because it only accounts for a few thousandths of the total outburst energy [43] and the coal is mainly carried by the gas in the development stage of an outburst. Therefore, the energy conversion can be expressed as follows:

\[ W = W_1 = W_2 \]

where \( W \) is the total energy that is consumed in the carrying process, MJ; \( W_1 \) is the gas expansion energy, MJ; \( W_2 \) is the carrying energy provided by the gas, MJ.

In a horizontal pipe with a cross section area of \( A \), the power required to transport the solids can be given as follows [8, 19]:

\[ W = \Delta P A \frac{m_c}{G} \]

where \( \Delta P \) is the total pressure drop of the conveyed pulverized coal, MPa; \( \tau_r \) is the mean gas flow velocity, m/s; \( A \) is the cross section area of the roadway, \( m^2 \); \( m_c \) and \( G \) are the mass and the mass flow rate of the coal powders, respectively, kg and kg/s.

The carrying energy of coal can be expressed as follows [13]:

\[ W_2 = L m_c \left[ g \left( \mu \cos \alpha \right) \sin \alpha \right] \]

where \( L \) is the transport length of the coal, m; \( g \) is the gravity acceleration, m/s\(^2\); \( \mu \) represents the friction coefficient; \( \alpha \) is the dip angle of the roadway, °.

When \( \alpha = 0 \), i.e., horizontal roadways, the expression can be written as follows:

\[ W_2 = \mu L m_c g \]

If all of the flow parameters are known for the beginning and the end of the transport, the mean velocity of the flow can be obtained using Eqs. (1), (2) and (4), as shown in Eq. (5) as follows:

\[ u_g = \frac{\mu L g G}{\Delta P A} \]

2.2.2. Coal flow speed

The mass conservation relationship can be satisfied with the conveying of the coal-gas flow (Eq. (6)) as follows:

\[ \Delta m_c v_c + \Delta m_g v_g = \Delta m_c u_c + \Delta m_g u_g \]

where \( \Delta m_c \) and \( \Delta m_g \) represent the mass of one small element in the transport of coal and gas, respectively, kg; \( v_c \) and \( v_g \) represent the corresponding speed of \( \Delta m_c \), \( \Delta m_g \) before ejection, respectively, m/s; \( u_c \) and \( u_g \) represent the corresponding speed of \( \Delta m_c \), \( \Delta m_g \) after ejection, respectively, m/s.

Because of the small mass of gas compared to that of coal, the role of gas can be ignored, and thus Eq. (6) can be written as follows:

\[ \rho_c v_c = \rho' u_c \]

where \( \rho_c \) is the apparent density of the coal before the outburst, kg/m\(^3\); \( \rho' \) is the density of the coal flow, kg/m\(^3\). If the cross section of the roadway is filled with coal when an outburst stops, this density can be approximately assumed to be the natural bulk density of the coal.

Then, using the fragmentation speed of coal, the coal flow speed in an outburst can be written as follows:

\[ u_c = \frac{P_c v_c}{\rho'} \]

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**Fig. 4.** Variation in the outburst parameters for the Zhongliangshan outburst (T-drilling temperature; P-gas pressure; C-concentration; Q-drilling gas quantity).

**Fig. 5.** Air knife generation in outburst coal.
Apart from the above equation, the coal flow speed can also be obtained using an empirical factor $\lambda$, which is in the range of 0.4–1 for plug flow (Eq. (9)) [38].

$$u_c = \lambda u_g$$

(9)

2.3. Solid-gas ratio of the coal-gas flow of outbursts

To investigate the gas released in an outburst, we typically use the gas emission quantity from the moment that the gas concentration begins to rise to the moment that the concentration returns to its original level. This duration may last tens of hours or even several days while the effective carrying process only lasts tens of seconds [20]. Thus, the gas released in the outbursts is primarily gas that does not contribute to the outbursts. In the transport process, the actual solid-gas ratio is significantly greater than the collected data.

Gas expansion can be treated as an adiabatic process that happens instantaneously [10,33,39], which conforms to the equation as follows:

$$P_1 V_1^n = P_0 V_0^n$$

(10)

where $P_1$ and $V_1$ are the gas pressure and the corresponding volume of the original coal before an outburst, respectively, MPa and m$^3$; $P_0$ is the gas pressure of the roadway, which is 0.1 MPa; $V_0$ is the corresponding volume at 0.1 MPa, m$^3$; $n$ is the adiabatic coefficient, which is typically taken as 1.3 for this case.

The gas expansion energy can be written as follows:

$$W_1 = \frac{P_0 V_0}{n-1} \left( \left( \frac{P_1}{P_0} \right)^{\frac{n-1}{n}} - 1 \right)$$

(11)

By introducing Eqs. (1) and (4) into Eq. (11), we can obtain the actual solid-gas ratio of the coal mass to the effective gas volume, as indicated in Eq. (12) as follows:

$$m_c/V_0 = \frac{P_0}{(n-1)\mu G L} \left( \left( \frac{P_1}{P_0} \right)^{\frac{n-1}{n}} - 1 \right)$$

(12)

3. Calculation results

The calculation is based on the data of the Zhongliangshan field outburst, which is the only detailed valuable experiment that exists in Chinese literature and has been widely studied by later researchers [15,31,42]. The coal mass ejected was 817 t, and the gas released was 38,540 m$^3$, including the gas did not contribute to the outburst. The coal was originated from the Longtan Formation in the southwest of China and belonged to the category of cooking coal, with the gas content of about 18.3 m$^3$/t. There were several faults and folds around the outburst site [30,25]. The entire process lasted for 39 s, and the highest gas emission rate recorded was 1200 m$^3$/min (the record limit of the monitor), which was easily exceeded by the high concentration gas flow a few seconds after the outburst began. The variation in the pressure, temperature, gas emission speed and sound were recorded, as indicated in Fig. 4.

Approximately 1.5–2 s after the outburst began, a decrease in the gas pressure was noted, which indicates that the coal crushing began before the gas expansion. The high-pressure gas pushed the fragment coal away and formed a flow with a pressure head of 0.3–0.6 MPa. Furthermore, there were several sounds being recorded in this outburst. The first crashing sound occurred 1.5 s after the process began. Then, sounds

Table 1

<table>
<thead>
<tr>
<th>Calculation parameters [3,15,30,31,36]</th>
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<tbody>
<tr>
<td>Outburst coal mass/t</td>
</tr>
<tr>
<td>Outburst period/t</td>
</tr>
<tr>
<td>Ambient pressure/MPa</td>
</tr>
<tr>
<td>Initial pressure/MPa</td>
</tr>
<tr>
<td>Pressure drop/MPa</td>
</tr>
<tr>
<td>Coal apparent density/kg · m$^{-3}$</td>
</tr>
<tr>
<td>Adiabatic coefficient $n$</td>
</tr>
<tr>
<td>Fragmentation rate/m · s$^{-1}$</td>
</tr>
</tbody>
</table>

Note: The initial outburst pressure is the average value of hole #1 and #2.

Table 2

<table>
<thead>
<tr>
<th>Calculation results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport energy/J</td>
</tr>
<tr>
<td>Gas need/m$^2$</td>
</tr>
<tr>
<td>Solid-gas ratio/kg · m$^{-3}$</td>
</tr>
<tr>
<td>Mean gas flow speed/m · s$^{-1}$</td>
</tr>
<tr>
<td>Coal flow speed/m · s$^{-1}$</td>
</tr>
<tr>
<td>Mass conservation</td>
</tr>
<tr>
<td>Empirical</td>
</tr>
</tbody>
</table>

Fig. 6. Ejection velocity variation with the applied gas pressure.

Fig. 7. Critical pressure estimation in the Zhongliangshan outburst.
were noted at 2.5 s, 3.5 s, and 4.0 s. From 9.0 s to 19.5 s, a sound of strong wind blowing was heard followed by another series of crashing sounds. Because of the long history of data and its non-repeatability, we set the following parameters from literature or experience according to the actual situation in the Zhongliangshan outburst.

By introducing the parameters above into Eq. (5), (8), (9) and (12), we can obtain the speed of flow and its solid-gas ratio in the Zhongliangshan outburst using the method of energy conservation and mass conservation, as listed in Table 2. The greatest flow speed calculated for gas/coal is 12.2 m/s, and the solid-gas ratio is 382 kg/m³.

4. Analysis and discussion

4.1. Physical air knife of outbursts

Hodot [13] first noted that an outburst can be regarded as a coal particle ejection process using gas, which was followed by several ejection experiments conducted by Guan et al. [11] and Wang [34,35]. If this ejection can be finished, a gas piston must be required, thus the fragmentation speed needs to be greater than the declining speed of the gas pressure [13]. When the stress status of the coal seams changes suddenly, the fragmentation begins immediately. The total surface area of coal increases dramatically with the decreasing particle size. A high fragment rate expands the area that the gas pressure can affect and significantly increases the desorption rate of the gas. Thus, a gas piston is formed and pushes the front solid aggregations forward.

For a micro-body of outburst coal, to achieve fracture’s tension failure, the gas pressure difference between inside and outside should meet the following relation [12,16,22,32]:

$$P_f - P_0 \geq K_{fc}\sqrt{\pi/(2\sqrt{c_l})}$$  \hspace{1cm} (13)

where $P_f$ and $P_0$ are the pressure in the fracture and the roadway, respectively, MPa; $K_{fc}$ is the fracture toughness, MPa·m⁰.⁵; $c_l$ is the initial length of coal fracture, m.

When the pressure gradient satisfies the demand of the ejected coal, i.e., Eq. (13), a spallation will be formed and the coal will be ejected with a sudden decrease in the gas pressure. Then, an influx of gas from other areas increases the pressure, thus the coal will be ejected again. Usually, the coal will be ejected in a spherical shell-shape, parallel to the outburst front [17,18]. The thickness of the spherical shell will experience a negative variation with the gas gradient, leaving a series of fracture textures, as indicated in Fig. 5. This fracture texture both occurred in the outburst experiments conducted by Jiang [17] and Guo [12], which confirms the correctness of the periodic dynamic variation of gas pressure. Similarly, the gas pressure before and after the coal plug should meet the requirements of Eq. (13) as well.

From the analyses above, it is not difficult to conclude that there is a gas piston behind the outburst coal. Similar to the air knife in a plug flow, this piston is a periodic physical knife that can cut the outburst coal part by part and push the coal plug along the roadway. This characteristic is convenient for forming a plug flow of coal-gas outbursts.

4.2. Gas pressure in outbursts

The gas pressure is the primary power source for the outbursts. Several countries have regarded this as an index for evaluating the outburst risk. Since the 1970s, an increasing number of studies investigated the minimum outburst pressure. For most of the studies, the pressure was primarily obtained from statistical data. For different coal samples from different mining areas and various firmness coefficients, coal ranks and geological conditions, the outburst pressure shows different values.

Table 3

<table>
<thead>
<tr>
<th>No.</th>
<th>Mine</th>
<th>Date</th>
<th>Size/t</th>
<th>Gas released/m³</th>
<th>Outburst pressure/MPa</th>
<th>Depth/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dayong</td>
<td>1967/01/12</td>
<td>2000</td>
<td>1,300,000</td>
<td>1.72</td>
<td>295</td>
</tr>
<tr>
<td>2</td>
<td>Mugang</td>
<td>1971/03/26</td>
<td>1700</td>
<td>180,000</td>
<td>1.47</td>
<td>330</td>
</tr>
<tr>
<td>3</td>
<td>Sanhui</td>
<td>1975/08/08</td>
<td>1278</td>
<td>1,400,000</td>
<td>0.69</td>
<td>500</td>
</tr>
<tr>
<td>4</td>
<td>Luling</td>
<td>2002/04/07</td>
<td>8729</td>
<td>930,000</td>
<td>2.6</td>
<td>600</td>
</tr>
<tr>
<td>5</td>
<td>Daping</td>
<td>2004/10/20</td>
<td>1894</td>
<td>249,501</td>
<td>2</td>
<td>612</td>
</tr>
<tr>
<td>6</td>
<td>Dashucun</td>
<td>2007/04/29</td>
<td>1270</td>
<td>93,000</td>
<td>0.96</td>
<td>573</td>
</tr>
<tr>
<td>7</td>
<td>Pingyu</td>
<td>2010/10/16</td>
<td>2547</td>
<td>150,000</td>
<td>0.95</td>
<td>519</td>
</tr>
<tr>
<td>8</td>
<td>Jiulishan</td>
<td>2011/10/27</td>
<td>3246</td>
<td>291,000</td>
<td>1.74</td>
<td>364</td>
</tr>
<tr>
<td>9</td>
<td>Xiangshui</td>
<td>2012/11/24</td>
<td>490</td>
<td>45,000</td>
<td>1.65</td>
<td>203</td>
</tr>
<tr>
<td>10</td>
<td>Bailongshan</td>
<td>2013/09/01</td>
<td>868</td>
<td>84,130</td>
<td>1.57</td>
<td>500</td>
</tr>
<tr>
<td>11</td>
<td>Yangmeng</td>
<td>2014/05/14</td>
<td>325</td>
<td>11,354</td>
<td>0.48</td>
<td>800</td>
</tr>
</tbody>
</table>

Note: I. The data were provided by the State Administration of Work Safety, China. II. The gas released here is the gas amount involved in outbursts, including the effective gas (high speed, able to carry outburst coal powders) and ineffective gas (low speed, unable to carry outburst coal powders).

Fig. 8. Triaxial outburst simulation apparatus and distribution of the outburst coal.
Yu analyzed the data in 26 outbursts, and established a formula determining the minimum outburst pressure with a firmness coefficient and a volatile proportion as follows [27]:

$$P_{\text{min}} = A(0.1 + BCVf)$$

(14)

where $P_{\text{min}}$ is the minimum outburst pressure, MPa; $f$ is the firmness coefficient of the coal; $CV$ is the volatile proportion of coal, %; $A$ and $B$ are two fitting parameters, which are 5 and 0.017 for his collections, respectively.

Additionally, Hua obtained an empirical formula to describe the relationship between the minimum pressure and the coal’s firmness coefficient based on the outburst data of Hu and Wen, which can be expressed as follows [27]:

$$P_{\text{min}} = 3.994(f_{\text{min}} - 0.1)^{0.6}$$

(15)

where $f_{\text{min}}$ is the minimum firmness coefficient of the soft coal seam in the mines.

The outburst pressure head in the Zhongliangshan outburst is 0.3–0.6 MPa, and the pressure drop per hundred meters is 120–299 KPa/ hm ($\Delta P = 0.2–0.5$ MPa). Table 3 lists the outburst pressure in 11 coal mines in China. For these cases, the pressure is all below 3 MPa. In the Outburst Prevention Provisions set by the Chinese government, 0.74 MPa (relative pressure) is considered to be the minimum outburst pressure. The mines should use particular drainage approaches to ensure that the gas pressure is less than this value. If we assume this pressure to be the flow head and the outburst length to be 200 m, the pressure drop over a hundred meters is 370 KPa/hm. By comparing it to the loss in the dense-phase (50–600 KPa/hm) or the dilute-phase (10–100 KPa/hm), we find that these pressures are considerably greater than the pressure needed in the dilute-phase. Thus, the flow has a greater likelihood of being transported in the dense-phase state.

4.3. Flow speed and solid-gas ratio of outbursts

Using the calculation results of the Zhongliangshan outburst, we can obtain a slow flow with a gas/coal speed of approximately 10 m/s and a high solid-gas ratio of approximately 400 kg/m³. These characteristics
significantly expand the capacity of transporting the outburst coal. Wang [34,35] used a shock tube apparatus designed by Alidibirov and Dingwell [1] to test the ejection process of cylinder briquette coal powered by CO2. Although a few simplifications were obtained, compared to the outbursts, a guiding value of these results deserves to be admitted. The ejection velocity of the coal-gas mixture is presented in Fig. 6. From the figure, we can determine that if the ejection velocity is sped up to the sound velocity, a high pressure will be needed to supply such large amounts of power; however, under normal geological circumstances, such high pressure is impossible. Therefore, the outburst ejection flow is more likely to continue at a low speed, which is similar to a plug flow.

4.4. Explanation of crash sounds occurring in outbursts

Pulse-shaped crash sounds of outbursts were also noted in one outburst experiment in Red October Mine (Donbass coalfield, Ukraine) [7]. Sun et al. [31] provided an explanation for the generation of this kind of crash sounds. It was believed that when the flow speed reached the sound velocity, a choking phenomenon would occur, and the outburst would stop for a short period, leading to a loud sound. Although this explanation is reasonable to a certain degree, we should ensure that the choking phenomenon that occurs in the critical state is not an actual blockage. The most noticeable difference is the flow velocity. Choked flow occurs when gas velocities become sonic, while blockage is a stationary stop. Because the choked flow cannot speed up any more, it is regarded as a dynamic choke. Although certain characteristics are superficially the same as blockage, they are truly not. Additionally, once a flow wants to reach the sound velocity, it needs a strict condition, such as a special nozzle configuration, which is not always easy to fulfill.

However, if we use the plug flow theory to explain this sound mechanism, a more reasonable answer can be achieved. A plug flow is a flow state that holds a similar characteristic to the blocking state. In industrial applications of plug flow pneumatic conveying, workers often find that transport pipes are easily congested by powders under improper operations. Blockages have to be drenched using the high pressure of gas, which leads to loud sounds in the pipes. Similarly, in an outburst, blockages may occur frequently and gas may help dredge the congestion, which forms a deafening sound.

This dredging pressure is termed as the critical pressure of the plug flow. Furthermore, Takeshi Kano thought that it had a relationship with the plug length, as shown in Eq. (16) as follows [38]:

\[ \Delta p_i = \left( \sin \alpha + \frac{8}{3\pi^2} \mu \cos \alpha \right) \rho_b g l_i \]

where \( \Delta p_i \) represents the pressure drop between the front and the back of a single plug, MPa; \( \rho_b \) is the natural bulk density, m\(^3\)/kg; \( l_i \) is the length of a single plug, m.

Using the parameters presented in Table 1, we can obtain the outburst pressure drop, 0.49 MPa, for a plug of 167 m (ignoring the width of air knife, as shown in Fig. 7), which is in the range of the measured pressure drop, 0.2–0.5 MPa. This result provides reliable evidence for the outburst of the plug flow.

4.5. Distribution of outburst coal on the ground

Guo [12] used a triaxial outburst simulation apparatus to perform outburst simulations several times, as indicated in Fig. 8. He collected 20 kg of coal powder of less than 0.25 mm and placed them in a 25 cm \( \times \) 25 cm \( \times \) 31 cm cavity for pressing. Then, he applied different CO2 pressure and stress values to the cubic briquette coal sample and waited for equilibrium. When all of these steps were completed, he opened the outburst hole and observed the entire outburst process.

Based on the photographs of the experiments (Fig. 8), we can easily observe a wave-shape distribution of the coal powders, particularly in the middle area. Several stripes of coal are apparent followed by a certain length of blank. Guo [12] thought this distribution was because of the purging of the gas behind, but did not mention the existence of plug flow. He also analyzed the mass distribution characteristics of the coal powders along the ejection direction, as indicated in Fig. 9(a). In various distances from the outburst hole, the coal mass being ejected also expresses a wave-shape distribution. Certain bulges exist in this line, which indicates that a mass aggregation lies in this distance range, which is similar to the mass distribution of the plug after collapsing in the pipes.

Ideally, without considering the air resistance, the distribution of the ejected powders can be thus determined by the initial horizontal velocity. From the theory of horizontal projectile motion, we can obtain

\[ h = \frac{1}{2} g t^2 \]  
\[ S = v_0 t \]

where \( h \) is the height of the outburst hole, m; \( S \) is the outburst length, m; \( t \) is the flying time of the objects, s; \( v_0 \) represents the ejection velocity, m/s.

During the crushing phase, the fragment velocity is larger than the decreasing rate of gas pressure [13]. Thus, the gas pressure can be assumed to be constant in the moment that the coal is ejected. From the perspective of momentum conservation, we know that the ejection speed of the coal powder in an outburst front can be expressed as


follows:

\[ P\Delta t = \Delta m_c \cdot v_0 \]  

(19)

where \( \Delta m \) represents the coal mass of an outburst front, kg; \( \Delta t \) is the duration of the gas pressure applied on an outburst front, s.

Therefore, the ejection distance of an outburst front can be expressed as follows:

\[ S = \frac{P\Delta t}{\Delta m_c} \sqrt{\frac{2h}{g}} \]  

(20)

Under ideal conditions, if the coal obtains the same initial ejection velocity for one ejection, a mass aggregation will occur on the ground; after several ejections, with the pressure's decrease, a wave-shape distribution will be found. According to the Fig. 9, it was noticed that if different gas pressures were applied, the location and the number of bulges did not remain the same. The higher the gas pressure, the lesser the number of bulges. This result most likely occurs because a continuous ejection is hard to achieve in small-scale experiments. With an increase in the gas pressure, the thickness of the outburst front will increase along with the mass \( \Delta m \). Because the total mass of the coal in a closed cavity is limited, the number of ejections will decrease inevitably. Additionally, a higher pressure indicates a shorter duration of the outburst, which leads to a higher homogeneity of the ejection velocity. Furthermore, the number of bulges decreases along the ejection direction.

When an outburst occurs, it is difficult to maintain a horizontal ejection because of dips in the roadways and the location of the outburst hole. A majority of outburst coal will lie on the floor with a trapezoid shape. The space near the outburst hole will be filled with coal powders while the further area from the hole will form a slope with a dip angle smaller than the natural rest angle. However, certain outbursts will show a wave-shape distribution. As indicated in Fig. 10, an outburst occurring in the Xinxing coal mines in the Heilongjiang Province of China on November 21st, 2009 was an actual case with this type of distribution. From the figure, we can easily find a fluctuation in the heights along the roadway. For coals with lower intensity, the powders will be easier to form, thus the wave-shape distribution is more apparent. Large coals or rock lumps are difficult to be transported by gas and can hardly express a characteristic of the gas-solid flow.

5. Numerical simulation verification for the plug flow of the outbursts

Based on the calculation results of the Zhongliangshan outburst, we conducted a numerical simulation using ANSYS software to prove the possibility of the plug flow existing under the calculated flow speed and solid-gas ratio. We set a 20 m × 2.5 m rectangle area as the assumed roadway. Then, we input a 10 m/s methane velocity and a 3.5 m/s coal velocity (the mean fragmentation rate of coal) into the left boundary and maintained the pressure of the right boundary to be 0.1 MPa. The entire running time is 2.5 s, and the constitutive model is a typical Eulerian model. To achieve the cutting process of the air knife, the left boundary is set to a dynamic boundary moving intermittently to the right side. As it moves, the moving velocity is greater than the influx velocity of the coal but smaller than that of methane so that only methane can enter the simulated area, which forms an air knife. When it stops, a solid phase starts to appear, and the plug forms. The dynamic boundary is used to form a blank air area, and it only determines the length of the solid plug. Similar results are expected to be obtained with a fixed boundary and an intermittent flow. Figs. 11 and 12 depict the coal volume fraction distribution in the roadway when the first, second and third air knife appears, and that at point (15, 2.5), respectively. It is apparent that certain cross sections are filled with coal, and a solid plug appears gradually, which is the primary characteristic of the plug flow.

Because of the influence of gravity, the density of the upper area is smaller than that of the bottom area. When the gas pressure reaches the outburst pressure, a methane passageway initially forms at the top of the plug. The sudden break in the plug leads to a high transport speed of methane, which blows the coal powders away. At the same time, the plug begins to topple, forming a horizontal wavy distribution, as described previously. The formation and breaking process of a single plug is depicted in Fig. 13.

6. Conclusions

The plug flow has a high probability of transporting the gas-solid outbursts, as indicated in Fig. 14.

I. Based on the formation conditions of the plug flow, the gas-solid flow of outbursts has similar characteristics, i.e., high pressure and a high solid-gas ratio. In the development stage of the outbursts, the gas gradient behind the outburst front acts as a periodic physical knife that cuts the outburst coal part by part and pushes the coal plug along the roadway.

II. Based on the transport velocity of the plug flow, the gas-solid flow of the outbursts is a flow at low speed, approximately 10 m/s, similar to the plug flow. Significant damage to the
roadways is attributed to the large mass of outburst, not the high flow speed.

III. Based on the distribution of powders when the plug flow stops, the gas-solid flow of the outbursts holds a wave-shape distribution of the coal powders in both the experiments and the actual outburst accidents, which fits the features of the plug flow.

IV. Based on the sound formation in the plug flow, it is more reasonable for the gas-solid flow to produce loud sounds when dredging the blockages.

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