An experimental investigation of the roles of water content and gas decompression rate for outburst in coal briquettes

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Abstract: The coal and gas outburst has become a worldwide challenge and is still not fully understood. In this study, an experimental investigation was carried out for outburst evolution. Coal briquettes were fabricated based on less than 0.6 mm pulverized coal particles of Tunliu Coal Mine. CO_2 was used to simulate outbursts by saturating coal briquettes in varying gas pressures (0.2, 0.4 and 0.6 MPa). The outbursts of coal briquettes were induced when rapid gas decompression was performed. The results indicate the outbursts depend on the gas pressure, water content and the rate of gas decompression. The differential pressure between the gas inside and outside the coal briquette is essential to outbursts and varies for different water contents while other parameters affect the initiation and intensity of outbursts as well. The higher gas pressure the more intense outburst occurs. It is worth noting that low rate of gas decompression cannot activate any outburst in the experiments even for a high gas pressure. The water content affects the outburst strongly. The critical minimum gas pressure in the coal briquettes with high water content becomes much higher than that in the coal briquettes with low water content. The major energy of the outbursts in the experiments is the expansion energy of the free state gas inside the coal briquettes. This study clearly demonstrates the progressive fragmentation of outbursts due to gas decompression.

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1 Introduction

Coal and gas outbursts are well known as the sudden and violent energy release of coal and gas that results from a comprehensive function of gas pressure, in-situ stress, coal strength, etc. The first coal and gas outburst accident was reported in France in 1843 and led to two fatalities. Since then, over 30,000 coal and gas outbursts occurred in China, Russia, Poland, Turkey, etc. [1, 2]. For instance, on 20th October 2004, Daping coal mine in Henan Province, China, occurred a methane explosion due to a coal and gas outburst, resulted in 148 deaths (Xinhuanet). Moreover, as mining depth increases, underground mining and tunnelling have to face more severe situations, especially in terms of outbursts when gases are involved.

Coal is a porous material containing various pores and voids, thus these pores and voids can be filled with gases during their formation at depth, e.g. methane (CH_4) and carbon dioxide (CO_2). As investigated, there is a large number of gases storing inside the coal seam. The gas can have high pressure after formation at depth. The gases with pressure occupies the microvoids of coal and can result in instantaneous coal and gas outburst accidents. The gases inside coal are not only free state in coal but mostly adsorbed on pore surface [3]. The adsorbed gas typically accounts for 98% of total stored gas in the coal seam, which varies with the adsorbed pressure [4]. The adsorbed state gas has the potential becoming free state gas as gas pressure, temperature or in-situ stress change. The free and adsorbed gases can result in alterations of physical (e.g. swelling) and mechanical behaviours (e.g. strength) [5-8]. High-pressure gases of coal induce severe consequences and high outburst proneness. In particular, an outburst has been recognised that gas pressure is one of the key factors. When the gases run out, an outburst could be less likely to occur. The gases with pressure will escape because of gas pressure gradient and release expansion energy. Therefore, the role of gas acting on outbursts is rather significant for the mechanism of outbursts, however, there is still no clear understanding of the effects of gas during the process of outburst, which is briefed below.

The mechanism of outbursts has been studied since outburst occurred [9-11]. Though the proposed mechanisms can address some aspects of the outburst process, there is still a lack of full and clear understanding of the complete process. In the early 1950s, the extensive efforts have been made [12-14] with consideration of the mechanisms of sorption/desorption of gas and stress in the generation of outbursts. Outbursts involve many factors, e.g. gas pressure, physical and mechanical of coal. Some authors have also considered outbursts as gas-involved rockbursts which are another severe hazard in underground mining and tunnelling [15, 16]. Experimental studies on outbursts have been conducted [17-19] which involved the factors of gas pressure, in-situ stress, and coal strength. As involved with a large number of gases, more violent and wide damage will take place in the accidents. Undoubtedly, the gases with pressure must play a key factor for the severe results. Only a few studies have experimentally conducted on the how the gas acts on outbursts [20-22]. It has been shown that outbursts are a gas-driven explosive eruption phenomenally and gases alone can lead to a violent eruption. Valliappan and Wohua [23] analysed the gas energy during outbursts and found that both free gas and desorbed gas contribute to outbursts, and the major energy is from the desorbed gas in the coal. An experimental study on the energy release from Yang et al. [24] indicates the first 10 seconds of gas release is significant to the occurrence of outbursts. The role of gas expansion energy during the outburst is still remained to be understood. Therefore, a better understanding of the mechanism of outbursts is urgently required to resolve the serious consequences of outbursts [1, 9, 11, 25].

The present work concentrates on the experimental simulation of outbursts considering gas pressure, the rate of gas decompression, and water content. This study aims to study the evolution of outbursts and how the internal gas of coal acts on outbursts based on a comprehensive experimental investigation. The energy components that contribute to the outburst were analysed and compared.

2 Experimental

2.1 Experimental apparatus

An experimental apparatus was designed to investigate the effects of high pressure gas on outburst phenomenon. It mainly consists of a compression test machine, a transparent acrylic cell, two end plates and a gas tank. The experimental apparatus is similar to that in Guan et al. [22], which have been validated for simulating coal outburst with CO_2 and implying magma fragmentation of volcanoes. The overview of the experimental apparatus is illustrated in Fig. 1. The cell has an inner diameter of 120 mm and a height of 330 mm. There are two outlets in the bottom plate. One is for injecting gas and the other one is for recording the pressure of the gas in the cell. The gas is supplied by a gas tank and its pressure is controlled by a regulator.

In the experiments, CO_2 is used in the experiments instead of CH_4. One reason is that CO_2 has no chemical explosion such that it is much safer than CH_4. Another reason is that the adsorption capacity of CO_2 is larger than CH_4 in coal for pure gases [26]. Thus, CO_2 has the ability to cause outbursts easier than CH_4. There could be more violent and severe consequences of outbursts if CO_2 is involved. It is significant to use CO_2 for outburst mechanism investigation.

2.2 Sample preparation

Our experimental setup is designed based on the triaxial test setup in soil mechanics. The transparent cell has the pressure limitation of 1.0 MPa. The regulator of the CO_2 tank can provide only ~ 1.2 MPa for the experiments. However, based on the test results of the raw coal, the raw coal samples have much higher UCS (12.14 MPa) and tensile strength (1.05 MPa) than the briquette samples. Accordingly, the experimental setups must resist higher pressure of saturated gas for longer time which depends on the permeability and adsorption capacity. Moreover, the laboratory safety is also considered, a new setup cannot be used before safety evaluation. Consequently, the briquettes were used instead of raw coals in the experiments. The briquettes are made of pulverized coal, and they can have similar properties to those weak raw coals. Previous studies also indicated that coal briquettes possess similar properties to a physically altered coal such as mylonite, which can be found near the "outburst zones" [27]. They can be a representative of the coal and be used to investigate outbursts. In this study, the coal samples are collected from Tunliu Coal Mine in Taiyuan, China. According to the coal proximate analysis of the coal, the used coal is a high-rank coal and has volatile matter content V_{daf} of 11.8 %. After being pulverized, less than 0.6 mm coal particles and employed to fabricate coal briquettes. The capability of CO_2 adsorption/desorption of the pulverized coal particles can be referred to the tests of Li et al. [28].

The coal briquettes are made of pulverized coal particles and water under compaction. Excess water will be expelled due to compaction. The compaction of about 20 MPa is held for 1 hour. Although excess water is expelled during the compaction, the fresh coal briquettes still have high water content. Fresh coal briquettes can become dry coal briquettes after 2-day air-drying.

The uniaxial compressive strengths (UCS) of the two coal briquettes are notably different. The fresh coal briquette with high water content (14.82 %) has a higher UCS than the dry coal briquette with low water content (1.09 %), i.e. 0.36 MPa vs. 0.22 MPa. In terms of failure strain, the high water content coal briquette (2.26 %) presents higher than the low water content coal briquette (1.97 %). Therefore, the coal briquette with high water content indicates ductile failure while the coal briquette with low water content shows brittle failure. Slight larger Young's modulus is found by comparing with the two stress-strain curves, i.e. 19.50 MPa vs. 13.38 MPa. Brazilian disc tests were also performed to determine the tensile strength of the coal briquettes based on the suggested methods of the ISRM [29, 30]. The tensile strengths are 0.018 and 0.012 MPa for the high water content and low water content coal briquettes respectively.

2.3 Experimental procedure

Prior to injecting CO_2 into the cell, a coal briquette is placed into the cell and the two end plates are fixed to make sure the plates and cell are sealed well. By adjusting the compression machine such that the plates are pressurised to a specified load, e.g. 0.5~1.0 MPa, to prevent high pressure gas escaping from the cell during the experiments. Because of the low permeability of coal samples, the penetration of the gas is slow. A specified saturation duration for gas penetration and adsorption is determined. As a result, the adsorbed pressure of the gas reaches the same value of the pressure of the saturated gas. The saturation duration of CO_2 is estimated from $t = r^2/D$ where t is time, r is the radius of coal specimens, and D is CO_2 diffusivity of coal [31]. For the fabricated coal briquettes, their diffusivity is larger than that of raw coal. Therefore, a sufficient saturated duration is kept at 10 hours in the experiments. In the saturation process, the CO_2 tank continually supplies gas to keep the saturated pressure be constant. The gas detector is set to 0 for the atmospheric pressure. Thus the value of the gas detector is the differential pressure between inside and outside gas.

Thereafter, decompression of saturated gas is performed after a coal briquette completes CO_2 infiltration and adsorption. The pressure of saturated gas drops down and approaches to the atmospheric pressure. But the gas inside the coal briquette cannot run out during the outside gas decompression, and then the differential pressure between inside and outside gas is formed. The differential pressure results in the gas expansion potential and generating tension against coal briquettes. During the gas decompression, the gas pressure in the cell is measured to figure out the process of gas acting on outburst.

3 Results and discussion

3.1 Experimental observation

Typical nine coal briquettes were performed to investigate the mechanism of outburst. Table 1 presents the parameters of coal briquettes in the experiments. Not all coal briquettes occurred outburst due to insufficient conditions. As concluded, there are three different phenomena occurring in the coal briquettes: Case 1: coal briquettes were still intact after gas decompression; Case 2: obvious fractures were found in the coal briquettes; Case 3: so-called outbursts occurred.

Case 1 (Intact coal briquettes) means only degassing occurred and the adsorbed gas and free gas diffused towards the outside. The internal gas pressure is lower than the critical pressure such that no damage happened in the coal. Case 2 (The fractures of coal briquettes) results from the propagation of cracks and fissures due to the internal gas. However, the growth of fractures depends on the various parameters, e.g. gas pressure and the strength of coal briquettes. Fracture growth stops if the gas pressure and contents are insufficient. Finally, fractures but no fragmentation occur in coal briquettes. Fig. 2(a)-(c) shows the fracture results of coal briquettes after gas decompression under varying gas pressures. When the saturated gas pressure is 0.2 MPa, only a few and small fractures were found in the coal briquette. For 0.4 MPa saturated gas, there were more and larger fractures in the coal briquette. As improved to 0.6 MPa of saturated gas, more fractures were found in the coal briquette. Furthermore, small fragments were separated from the main body of the coal briquette. This observation indicates the outburst occurs in the coal briquette when the saturated gas pressure exceeds 0.6 MPa after rapid gas decompression (Case 3).

Compared with the coal briquettes with high water contents, low water content coal briquettes are liable to occur outburst (Case 3). The outburst fragments in Fig. 2(d)-(f) demonstrate the outburst phenomena of coal briquettes after gas decompression. Intact coal briquettes became fragments due to growth and coalescence of the gas induced fractures. It is observed that the fragment size decreased as gas pressure increased. The saturated pressure of CO_2 of 0.2 MPa resulted in a slight degree of fragmentation while considerable fragmentation was found if the CO_2 pressure increased to 0.4 and 0.6 MPa.

In terms of the process of the outburst, the outburst only takes several microseconds, see Fig. 3. Fracture initiation takes place in the microstructure of coal briquettes. It depends on the growth velocity of cracks which is relied on gas pressure and contents. Once the fracture coalescence completes, fragmentation is formed such that undissipated free gas and desorbed gas act on these fragments. As a result, the fragments will be ejected at a specific velocity resulted from the pressure and content of the gas.

3.2 Intensity of outbursts

As experimental results show, the intensity of outburst depends on gas pressure, gas decompression rate and water content of coal briquettes. To describe the intensity of coal and gas outburst, the degree of fragmentation is introduced. The degree of fragmentation is defined as the mass ratio of the residual fragment to total mass [22]. Therefore, the normalised intensity of outburst f is calculated by the following equation and shown in Table 1:

$$f = \frac{m_t - m_r}{m_t} \times 100\% \tag{1}$$

where m_t and m_r are the total mass and the largest fragment of coal briquettes after outbursts.

3.3 Effect of gas pressure on outbursts

The main energy of outbursts comes from the release of gas. It is obviously known that outbursts must occur only when gas pressure reaches a threshold. The critical gas pressure is significant to evaluate the risk in underground mining engineering. The outbursts have been experimentally studied in terms of high pressure gas [20, 22]. Critical values of gas pressure have been realised for outburst-prone assessment [32], they are 0.15, 0.74 and 1.00 MPa in Czech, China and Russian respectively. It indicates that outbursts can occur even for low-pressure gases of coal.

According to the results shown in Figs. 4-5, an outburst will not occur until a critical gas pressure is reached. The critical gas pressure of coal briquettes for outbursts could be lower than 0.2 MPa since the strength of the coal briquettes is low. The normalised outburst intensity increases dramatically as gas pressure increases. At the gas pressure of 0.4 MPa, the normalised intensity *f* is improved to 67 %. A normalised intensity of outburst of 89 % arrives when the gas pressure reaches 0.6 MPa. In contrast, the higher gas pressure is required to generate outburst of the coal briquettes with higher strength.

3.4 Effect of water content of coal briquettes on outbursts

In the experiments, two different coal briquettes showed different critical gas pressures accordingly. The coal briquettes with high water content and high strength (average water content of 14.08 % and UCS of 0.36 MPa) were difficult to occur outbursts until the high gas pressure of 0.6 MPa was reached. In comparison, the critical gas pressure decreased to 0.2 MPa in terms of the coal briquettes with low water contents and low strength (average water content of 1.09 % and UCS of 0.22 MPa), as shown in Fig. 4(a). The higher water content of coal briquettes corresponds to the weaker intensity of outbursts. Water occupies the micropores and voids of the coal and prevention of gas flow, which results in the reduction of gas in the coal. The effective permeability of gas in coal will decrease as the increase of water content [33]. Less gas is involved in the outburst process, consequently, the intensity of coal can be weakened. The experimental result agrees with the analysis of prior studies [17, 34] and field observation [35].

3.5 Effect of rate of gas decompression on outbursts

In our experiments, the rate of gas decompression is indicated as a key factor to induce outbursts. Since the limitation of the experimental apparatus, the rate of gas decompression is difficult to be controlled continuously. Only two different rates of gas decompression were conducted in the experiments, e.g. 0.60 and 6.23 MPa/s. Coal briquettes were employed in the outburst experiments. According to the results, the rate of gas decompression affects the outburst of coal briquettes, see Fig. 4(b). For the high rate of gas decompression, 6.23 MPa/s, outbursts occurred at the gas pressure of 0.2 MPa. However, under the low rate of gas decompression of 0.60 MPa/s, there was no outburst occurring even the gas pressure was increased to 0.60 MPa. Therefore, a critical rate of gas decompression is essential to the occurrence of outbursts in the experiments. The rate of gas decompression can correspond to the permeability and emission of gas in the coal seam.

3.6 Evolution of outbursts

3.6.1 Gas adsorption/desorption process from coal

The gas in the micropores of coal are divided into free state gas and adsorbed state gas [3]. The adsorbed state gas has the potential becoming free state gas when gas pressure and gas content decrease and temperature increases [36].

Under the isothermal condition, the absorbed gas volume V_m is evaluated by Langmuir isotherm model, given as:

$$V_m = \frac{pV_L}{p + p_L} \tag{2}$$

where p is the equilibrium gas pressure, V_L and p_L are the Langmuir Volume and Langmuir Pressure representing the maximum gas storage capacity and the gas pressure at half Langmuir Volume, respectively. For the coal samples, V_L= 34.98 mL/g and p_L= 1.15 MPa [28].

For intact coal samples, the sizes of pores can be assumed as uniform. Based on this assumption, a unipore model was developed [37] in order to describe the kinetics of gas adsorption on coal. The diffusion model can be described as [38]:

$$\frac{V_t}{V_m} = 1 - \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp(-D_e n^2 \pi^2 t) \tag{3}$$

where V_t is the total volume of the diffusing gas that has desorbed at time t, V_m is the total desorbed gas volume in infinite time, and D_e is the diffusion coefficient of gas from coal.

In particular, for short time (< 600 s) and the desorbed fraction is less than 0.5, the diffusion of gas in coal $V_{des}(t)$ can be simplified approximately as below [38, 39]:

$$\frac{V_{des}(t)}{V_m} = \frac{6}{\sqrt{\pi}}\sqrt{D_e t} \tag{4}$$

It is well known the statistical duration of outbursts usually in the range of 3~96 s [40]. In particular, an outburst occurred on 25 April 2009 in Haizi Coal Mine lasted about 10 seconds based on the record of the micro-seismic monitoring system [41]. The gas decompression process of the present experiments is recorded in Fig. 5. The gas pressure decreases slowly when the compression test machine starts destressing at first. As the compression test machine running, the end plates for sealing purpose suddenly separate from the cell, therefore, a sudden drop of gas pressure occurs. During the sudden drop of gas pressure, the coal briquette initiates fracturing and even fragmentation. The duration of the drop of gas pressure is about tens of microseconds. Compared with the decompression process with coal briquettes in the cell (outburst occurred), no abundant desorbed gas could be detected according to Fig. 5.

The so-called outbursts in our experiments occurred within tens of microseconds, here we suppose the outburst duration is 40 ms. By assuming D_e to be 10^{-5} s^{-1} [38], only about 0.2 % adsorbed gas can be desorbed during the outburst process from Eq. (3). It is possibly observed that the outburst initialises when cracks propagate, starts at the fragmentation occurrence, and finally breaks out as coal fragments ejection with the gas flow. The fracture growth velocity is rather much faster than the desorption rate. Thus, the fracture is induced by free gas, and the ejection of coal fragments is contributed by the desorption of gas [23].

3.6.2 Progressive fragmentation of coal

Adsorption in coal is classified as chemical adsorption and physical adsorption. In chemical adsorption, the adsorbate is bound to the solid surface by a direct chemical bond, and in physical adsorption, adsorption occurs mainly due to van der Waals and electrostatic forces between the adsorbate molecules and the atoms composing the adsorbent surface [36]. As a result, coal swelling results from CO_2 adsorption. Experimental investigations have been carried out that gas adsorption can weaken the strength of coal. According to the previous experimental results, the

UCS of coal samples decreases with increasing saturated gas and the volumetric strain decreases as well [42, 43].

The gas behaviours (e.g. CH_4, CO_2) such as diffusion, emission, adsorption and desorption are complex processes resulting in physical and chemical behaviours of gas-solid interaction. These gas behaviours in coal depend on many factors of coal including microstructures, grades, and water contents. Initially, the inside and outside gas of coal briquettes are at equilibrium when the coal is saturated in gas, see Fig. 6(a). Suddenly, the rapid decompression of CO_2 takes place. Since the permeability of coal is not high enough to let the internal free gas of coal flow promptly. The internal free gas of coal has a potential expansion power which can split the coal matrix near the tips, see Fig. 6(b). The fracture initiation is observed as the initiation of outburst. The criterion of outburst can be taken as the criterion of fracture initialisation. It should be worth noting that fragmentation is the result of sufficient fracture growth, see Fig. 6(c). At the moment of the fragmentation of coal, the residual gas including undissipated free gas and desorbed gas contributes to the ejection of fragments.

Thus, a criterion for the crack initiation in the coal is introduced as [42]:

$$\Delta p_g \geq \frac{K_c}{\sqrt{\pi a}\left(1-\sqrt{\rho/a}\right)} \tag{5}$$

where Δp_g is the differential pressure between the gas pressures inside and outside the coal briquette, a is the half length of the crack, K_c is the fracture toughness of the coal filled with gas, and ρ is the radius of the curvature of the crack tip.

From Eq. (5), it can be understood that the crack initiation depends on the crack length, the fracture toughness of coal, and the geometry of crack. The gas inside the coal briquettes is dominant in the outburst occurrence, there is no any initiation of fracture without the differential gas pressure. The differential pressure is essential for the occurrence of outbursts.

3.6.3 Energy components during an outburst

The progress of the outburst can be further understood according to the analysis of energy release during an outburst. The energy components involved in outbursts are the energy generated by free gas W_f and desorbed gas W_{de} and the dissipated energy E_f for fracturing and fragmentation of the coal.

For an adiabatic process, the total expansion energy of the free gas in coal W_f can be written as [44]:

$$W_f = \frac{(p_g + p_0)V_f}{\kappa - 1}\left[1 - \left(\frac{p_0}{p_g + p_0}\right)^{\frac{\kappa-1}{\kappa}}\right] \tag{6}$$

where p_g is the differential pressure between internal gas and atmospheric pressure, V_f is the volume of the free gas, κ is the adiabatic coefficient of CO_2, 1.30, and p_0 is the atmospheric pressure, 0.1 MPa.

Given that the adsorbed gas in coal, replace the volume of free gas with the volume of adsorbed gas volume from Eq. (1), then the total expansion energy of the adsorbed gas in coal W_{ad} is:

$$W_{ad} = \frac{(p_g + p_0)^2 V_L}{(\kappa - 1)(p_g + p_0 + p_L)}\left[1 - \left(\frac{p_0}{p_g + p_0}\right)^{\frac{\kappa-1}{\kappa}}\right] \tag{7}$$

However, only a portion of the adsorbed gas is involved in the progress of outbursts since the duration of the present experimental outburst is tens of microseconds, t_0. The desorbed gas takes part in outbursts can be given by:

$$W_{de} = \frac{6}{\sqrt{\pi}}\sqrt{D_e t_0}\frac{(p_g + p_0)^2 V_L}{(\kappa - 1)(p_g + p_0 + p_L)}\left[1 - \left(\frac{p_0}{p_g + p_0}\right)^{\frac{\kappa-1}{\kappa}}\right] \tag{8}$$

In general, fragmentation occurs along with outbursts, the energy is from the gas because there is no other loading applied on the coal briquette. It is worth noting that the more energy dissipated in the fracturing process, the higher fragmentation degree occurs. We consider a simple model to evaluate the relationship between the energy dissipated for fracturing and the fragmentation degree. Then, assumptions are made that the energy acting on fracturing is proportional to the fracture area at a ratio of the specific surface energy and the all energies from free gas and desorbed gas can act on fracturing. The shape of fragments is taken as spherical particles with a mean diameter of d. The total volume of the coal briquette V_{coal}. Then the area of the fracture surface is:

$$A_f = \frac{6}{d} V_{coal} \tag{9}$$

Thus, the total energy dissipated by the fragmentation E_f can be:

$$E_f = \gamma A_f \tag{10}$$

where γ is the specific surface energy of the coal. Since the UCS and tensile strength of the coal briquettes are very low, the specific surface energy is assumed to be 10^{-4} J/m^2 [45].

Based on the above analysis, the energy components involved in the expriemental outbursts can be calculated and the results are shown in Fig. 7. For the calculation, the porosity of the coal briquette is assumed to be 0.15 based on the water content. As gas pressure increases in the coal, the energy release of free gas and desorbed gas participated in the outburst increase. The saturated gas pressure of 0.2 MPa in the coal briquette contains the energies of free gas of 2.3×10^{-6} J and desorbed gas of 2.6×10^{-7} J during outbursts. Those energies can only result in no smaller than 20 mm of the mean diameter of fragments. As the gas pressure increases to 0.4 MPa, the free gas and desorbed gas energies become 5.2×10^{-6} J and 4.1×10^{-7} J. A mean diameter of about at least 7 mm of fragmentation can occur. When the saturated gas pressure is 0.6 MPa, more energies released from free gas and desorbed gas can lead to more violent fragmentation. The energy release of free gas is much larger than the energy release of adsorbed gas. The free gas is highly possible the main energy for the outburst, but no sufficient evidence can indicate how much of the free gas and adsorbed gas contribute to the outburst. Valliappan and Wohua [23] calculated the energy components during outbursts and found the energy releases of free gas and desorbed gas were larger than the energy dissipation of fragmentation. It also can be observed that the energy dissipation of the fragmentation and outburst required increases as the intensity increases. Only slight fragmentation and outburst occurs if the energy release of free gas and adsorbed gas of the outburst is not sufficient enough.

4 Conclusions

We have performed experiments to investigate the effects of internal gas in coal on outbursts. So-called outbursts were observed clearly in the experiments, which demonstrated the gas cause. Based on the experiments, the progress of outburst and the roles of water content, decompression rate as well as energy components during outbursts were examined. The main findings are concluded as follows:

(1) Coal briquettes of high quality and CO_2 gas were experimented using a designed apparatus to investigate the mechanism of outburst. The coal briquettes were validated to be practicable for outbursts. Evident outbursts were observed due to the gas decompression. Critical minimum gas pressure exists for the outburst occurrence, more violent outbursts can occur as gas pressure increases.

(2) The water content of coal briquettes can significantly affect the initiation of outbursts. For coal briquettes have higher water content, more water can occupy the micropores of coal, which can reduce the gas content and coal brittleness, and increase the coal fracture

roughness. The expansion energy releases from the gas may not be enough to cause the fragmentation of coal briquettes when they have higher water content. So, only fractures appear in the coal briquettes with higher water content. However, violent outbursts can occur in the coal briquettes with lower water content at the same saturated gas pressure and rate of gas decompression.

(3) The rate of gas decompression is a second key factor to cause the outburst of coal briquettes. If the rate of gas decompression is lower than the critical minimum rate, the internal gas can flow and seep out as the coal briquette is an intrinsic porous material. The coal briquettes can only degas safely if the rate of gas decompression is below the threshold. The rate of gas decompression corresponds to the gas desorption and gas emission in the coal briquettes. The coal briquettes can occur fragmentation and outburst if the rate of gas decompression is above the threshold. The threshold value increases as the water content increases. Further studies will be conducted to figure the threshold function with the water content in the coal briquette, which will be presented in the future publications.

(4) The evolution of outbursts was identified and discussed. An outburst is the consequence of the coal fracture and fragmentation mainly caused by the internal gas. Energy components, i.e. energy release of free gas, desorbed gas, and energy dissipation of fragmentation, were quantitatively analysed for the experimental outbursts. Free gas possibly contributes mainly to the outbursts in the experiments, which can be useful to the actual outbursts in coal mining.

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