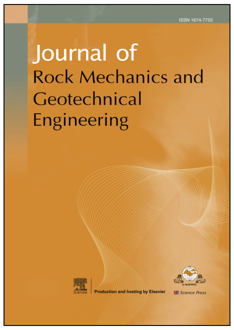

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Rapid decompression and desorption induced energetic failure in coal

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Abstract: In this study, laboratory experiments are conducted to investigate the rapid decompression and desorption induced energetic failure in coal using a shock tube apparatus. Coal specimens are recovered from Colorado at a depth of 610 m. The coal specimens are saturated with the strong sorbing gas CO_2 for a certain period and then the rupture disc is suddenly broken on top of the shock tube to generate a shock wave propagating upwards and a rarefaction wave propagating downwards through the specimen. This rapid decompression and desorption has the potential to cause energetic fragmentation in coal. Three types of behaviors in coal after rapid decompression are found, i.e. degassing without fragmentation, horizontal fragmentation, and vertical fragmentation. We speculate that the characteristics of fracture network (e.g. aperture, spacing, orientation and stiffness) and gas desorption play a role in this dynamic event as coal can be considered as a dual porosity, dual permeability, dual stiffness sorbing medium. This study has important implications in understanding energetic failure process in underground coal mines such as coal gas outbursts.

Keywords: rapid decompression; gas desorption; energetic failure; gas outburst; coal

1. Introduction and background

The sudden and violent ejection of coal and gas from a working face and surrounding strata in an underground coal mine is known as a gas outburst and represents a major coal mining hazard. In the last 150 years, more than 30,000 outbursts have occurred in the coal mining industry worldwide (Lama and Bodziony, 1998). The largest recorded outburst in a coal mine that occurred in Gagarin Colliery, Donetsk Basin in Ukraine, ejected 14,500 t of coal with 600,000 m^3 of gas (Beamish and Crosdale, 1998; Lama and Bodziony, 1998). The most disastrous mine outbursts resulted in 187 deaths in the Piast area of Nowa Ruda Colliery in the Lower Silesian coal basin in 1941 (Lama and Bodziony, 1998), and 214 deaths in the Sunjiawan coalmine in Fuxin, China, in 2005 (Li et al., 2007). As mines progress into deeper and gassier coalbeds, the prediction and prevention of these low-probability/high-consequence events are of utmost importance for the coal mining industry worldwide (Wang et al., 2013a, b).

Scientific research on the mechanism of gas outbursts has been conducted for more than a century. Some of the earliest studies on this phenomenon were reported by Taylor (1853). The properties of coal, gas pressure, and gas emission were considered as the basic factors to describe sudden emissions of gas and outbursts. Thereafter until 1950, numerous Russian scientists introduced the role of stress and mechanical energy in outburst theory. Since 1950, extensive research on gas outbursts has been reported by Khristianovich (1953) who considered the role of sorption/desorption of gas in the generation of outbursts, and who also developed the crushing wave theory and considered the outburst process as a complex function of tectonic stress, induced stress, and free gas presented in the pore space. The differential gas pressure across the face of the crushing wave, which is the pressure difference between the high pressure inside the coal and the low pressure outside of the coal, should be equal to or greater than the tensile strength of the coal to result in splitting of the coal. Kidybinski (1980) proposed the presence of three zones ahead of the mining face and conditions under which outbursts occur: degassed zone, high gas pressure zone, and abutment pressure zone. Gray (1987) suggested two gas-initiated coal failure mechanisms: tensile failure of unconfined coal and piping of sheared material. Later a model proposed by Litwiniszyn (1985) was based on a three-phase medium model describing the initial phase of the phenomenon of gas outbursts in hard coal. In this model, the skeleton of coal consists of the solid body, the condensed liquid, and the gaseous substance. Ryncarz and Majcherczyk (1986) defined outburst as a gas-geodynamic phenomenon, which may be instantaneous or may last over several minutes. Paterson (1986) assumed that an outburst is the structural failure of coal due to excess stress resulting from body forces on the coal. Williams and Weissmann (1995) emphasized gas pressure gradient and gas desorption rate existing ahead of the working face. Valliappan and Zhang (1999) numerically studied the role of gas energy during coal outbursts, which included the stored strain energy and the internal gas energy due to desorption and expansion of methane gas in coal seams. Wold et al. (2008) investigated the role of spatial variability in coal seam parameters on gas outburst behavior during coal mining. Guan et al. (2009) categorized coal gas outburst as a gas-driven explosive eruption. However, only high-gas pressure in coal was postulated as the controlling parameter in their analysis. The role of gas desorption in driving the explosive eruption was not mentioned, which may be even more important in accelerating the eruption process. The work was reported by Chen (2011) who developed a model combining fracture mechanics and gas dynamics and identified the effect of fracture properties on failure process.

Gas is stored primarily by sorption into the coal (Hol et al., 2011; Wang et al., 2011, 2012). This usually accounts for 98% of the methane within a coal seam depending on the gas pressure (Gray, 1987), which leads to the significant difference between energetic failure of coal and that of other rock types. So far the following factors are believed to play a dominant role in gas outbursts (Wang et al., 2013a, b): (1) geological structures: particularly steeply dipping seams, faults, dykes, and mylonite; (2) gas in coal related to: (a) composition, (b) pressure, (c) content, (d) sorption capacity, and (e) desorption rate; (3) stress level

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and stress state at the mining face associated with: (a) development of cracking and crushing of coal; (b) changes in permeability of coal seams and redistribution of gas pressure; (c) transfer of pressure from the static phase into a dynamic phase as a result of destruction of the coal seam; and (4) properties and structures of coal seams: (a) strength, (b) porosity, and (c) permeability (Harpalani, 1985; Durucan and Edwards, 1986; Ates and Barron, 1988; Cyrul, 1992; Beamish and Crosdale, 1998; Lama and Bodziony, 1998; Aziz and Li, 1999; Cao et al., 2001; Xu et al., 2006; Wold et al., 2008; Diaz Aguado and Gonzalez, 2009; Vishal et al., 2013a, b, 2015).

Although various models and theories have been proposed, the mechanisms of the energetic failure remain to be poorly understood for either the flow phenomena or the rupture processes. Among many parameters that contribute to the initiation of outbursts, gas desorption rate in conjunction with the gas pressure gradient ahead of the face is thought to be the important one (Williams and Weissmann, 1995). Heading advance creates a situation of atmospheric conditions at the working face with much higher virgin gas pressures only a short distance ahead. Encountering any coal seam weakness or disruption therefore can be catastrophic, as confinement of the coal seam is seriously diminished (Beamish and Crosdale, 1998). The purpose of our study is to investigate the effect of rapid gas decompression and desorption due to pressure gradient on the dynamic failure of coal in order to improve the understanding of these processes. In this study, we address the mechanisms of energetic failure of coal by conducting experiments using a shock-tube apparatus. We saturate coal specimens in the shock-tube apparatus for a certain period and then suddenly decompress the specimens. We find that the gas decompression and desorption can drive coal to energetic failure. It is not the intent of the paper to address all mechanisms related to coal gas outbursts. This study is best applicable to coal gas outbursts that occur right after new mining faces are exposed.

2. Experimental method

To investigate the fragmentation of coal induced by rapid gas decompression and desorption, we perform fragmentation experiments in a vertical shock tube apparatus designed by Alidibirov and Dingwell (1996) for simulating volcanic eruptions and coal explosions (Guan et al., 2009). Fig. 1 shows the schematic of the shock tube apparatus. It mainly consists of a high pressure stainless steel vessel and a rupture disc. The volume of the vessel is 617.78 cm^3. Pressurization of the pressure vessel is applied from a high pressure CO_2 tank and the subsequent depressurization is regulated by the rupture disc that beaks at a defined pressure. The gas pressure in the vessel is measured by using a pressure transducer. The rupture disc, also known as a burst disc or burst diaphragm, is a non-reclosing pressure relief device that, in most uses, protects a pressure vessel or equipment from overpressurization. A rupture disc, made out of metal used in this work, fails at a predetermined pressure. The rupture disc provides instant pressure release (within milliseconds) to an increase in the pressure vessel, but once the disc has ruptured it will not reseal. Cylindrical specimens drilled from coal blocks are glued at the bottom of the vessel and pressurized with CO_2 to a desired pressure. The reason to use CO_2 instead of methane is because CO_2 is safer to work with in the laboratory. The difference between using CO_2 and using methane is that the amount of gas adsorbed in the coal specimen is different. Generally, the molar mass of adsorbed CO_2 is greater than that of methane for a coal specimen (Wang et al., 2011). The glue is only applied to the bottom of the specimen, and is just strong enough to hold the specimen in place against the pressure difference between its top and bottom surfaces when the specimen is decompressed. For tests without glue, the entire specimen is propelled upwards by the decompressed gas ejected from the base of the vessel. After a saturation period, rapid decompression of the coal specimen is triggered by the controlled failure of the rupture disc, producing a rarefaction wave that travels downwards through the specimen. If the resulting pressure differential (ΔP) is larger than the tensile strength (σ_T) of the specimen, the specimen fragments in a brittle manner (Alidibirov and Dingwell, 1996; Guan et al., 2009) and the mixture of gas and solid particles are ejected upwards rapidly. If the resulting pressure differential is lower than the tensile strength of the specimen or the specimen is too permeable, only degassing of the entire specimen occurs. Fig. 2 shows a schematic of this process.

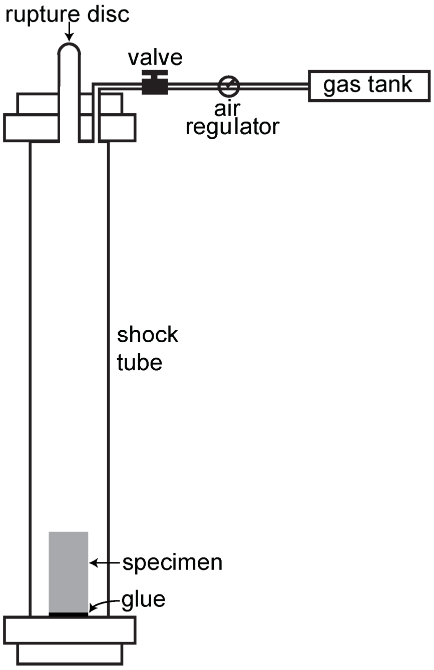

Fig. 1. A schematic showing the shock tube apparatus.

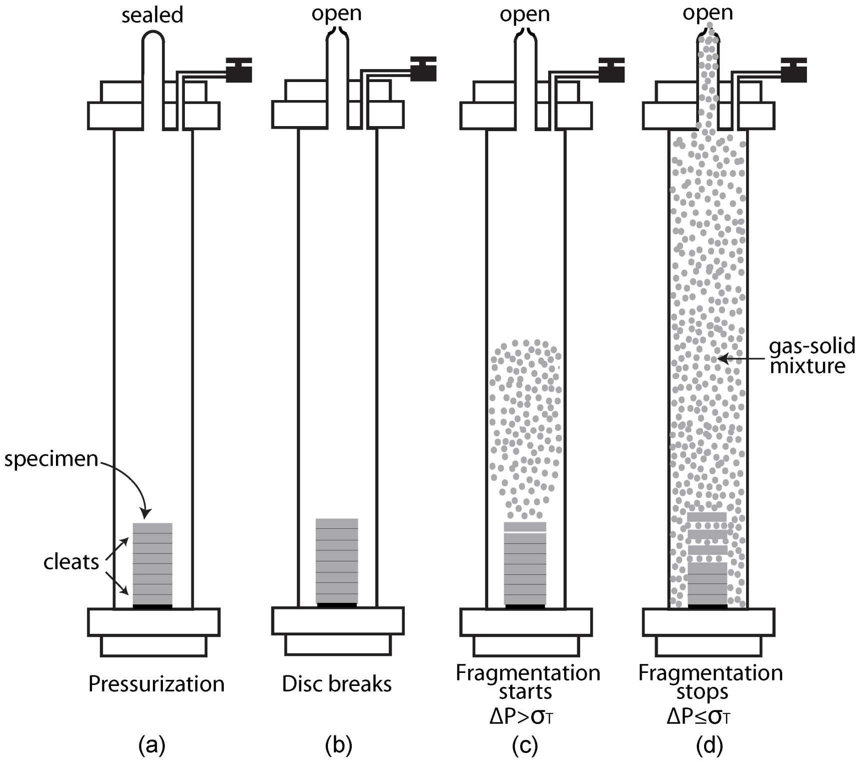

Fig. 2. A schematic showing the fragmentation experiment. (a) The specimen is saturated at a certain pressure for 4 d; (b) A pressure exceeding the rupture disc limit is used to break the rupture disc; (c) Fragmentation starts when the differential pressure across the face is larger than the tensile strength of the specimen; and (d) Fragmentation stops when the differential pressure across the face is lower than the tensile strength of the specimen.

We use specimens obtained from the Upper B seam, Colorado, USA. Table 1 summarizes the properties of the coal as received. The permeability and porosity measurements presented in the table are recovered from a standard triaxial apparatus arranged for flow-through or pulse permeability testing. Permeability is measured using CO_2. A triaxial core holder capable of accepting membrane-sheathed cylindrical samples and of applying independent loading in the radial and axial directions is used. The cylindrical sample is sandwiched within the Temco core holder between two cylindrical stainless steel loading platens with through-going flow connections and flow distributors. The sample and axial platens are isolated from the confining fluid by a rubber jacket. The end-platens are connected to two low-volume stainless steel gas reservoirs through tubing and isolating valves when the pressure transient method is applied to measure permeability. The gas-pressurized upstream reservoir is discharged through the sample to the downstream reservoir with equilibration time defining permeability of the sample. The mass of gas sorbed into the coal samples is calculated from mass balance. Please see Wang et al. (2011) for the experimental details on the permeability and porosity, and adsorption measurements.

Table 1. Properties of the used Colorado bituminous coal.

Proximate analysis (%)			Ultimate analysis (%)				Mean maximum vitrinite reflectance (%)	Density (kg m^{-3})	Porosity (%)	Permeability (m^2)
Fixed carbon	Volatile matter	Ash	Carbon	Hydrogen	Nitrogen	Oxygen				
65.98	24.08	9.94	86.96	5.61	1.97	5.46	1.39	1132	5	3.3×10^{-17}

3. Experimental observation

Table 2 summarizes the results of the suite of experiments. Permeability is measured at a pore pressure of 5 MPa and a confining stress of 10 MPa. After the permeability measurement, each specimen is saturated with CO_2 for 4 d and followed by the fragmentation experiment. Among these 20 experiments, 7, 10, and 3 tests are performed at initial applied gas pressures of 4 MPa, 5 MPa, and 6 MPa, respectively. Thirteen out of these 20 specimens are fragmented. In this series of experiments, three types of phenomena are observed after the rapid decompression and desorption. The fist type is degassing without significant fragmentation. However, small particles off the specimens are observed for all these specimens. This indicates that the rapid decompression and desorption can still burst the loose and soft parts of the specimen, if not able to explode the specimen completely. These particles are found to come from the regions in the vicinity of cleats. Table 2 lists the initial permeability and tested gas pressures of all the tested specimens. Among the seven samples that are not fragmented, one is tested at a gas pressure of 4 MPa, four at 5 MPa, and two at 6 MPa. All these seven samples have a relatively large permeability, compared with those fragmented. This indicates the significant role of permeability in controlling the decompression process, either to be just transient flow or dynamic coal gas burst.

Table 2. Experimental details for the suite of experiments. Coal samples are recovered from the Upper B seam, Colorado and permeability is measured using CO_2.

Specimen number	Length (cm)	Permeability (m^2)	Pore pressure (MPa)	Degree of fragmentation (%)

1	5.11	1.10×10^{-17}	6	62.65
2	4.93	4.20×10^{-17}	5	0
3	5.03	1.24×10^{-17}	5	34.11
4	5.06	1.93×10^{-17}	5	15.68
5	4.77	6.33×10^{-17}	5	0
6	4.89	3.17×10^{-18}	4	75.64
7	4.32	1.99×10^{-15}	6	0
8	5.29	9.86×10^{-17}	5	0
9	5.04	4.20×10^{-17}	5	39.71
10	5.67	3.99×10^{-19}	4	63.78
11	4.11	2.45×10^{-18}	4	52.94
12	4.66	3.01×10^{-17}	5	0
13	5.08	7.39×10^{-18}	4	51.22
14	4.77	3.06×10^{-18}	4	39.07
15	4.37	5.97×10^{-18}	4	28.67
16	4.9	1.07×10^{-17}	5	39.92
17	5.03	3.29×10^{-16}	6	0
18	5.41	9.00×10^{-18}	4	0
19	4.31	4.20×10^{-17}	5	9.45
20	3.93	5.22×10^{-17}	5	42.19

The second type is the vertical fragmentation after the rapid decompression. Fig. 3 shows a representative specimen before and after the decompression for this type. Horizontal bedding planes are observed in the original coal specimen (Fig. 3a). Pictures after the experiments suggest that the fragmentation/explosion begins from these weak bedding planes. The third type is the horizontal fragmentation. Fig. 4 shows a representative specimen of this type before and after the rapid decompression. This is also consistent with the fracture network of the original specimen, where a series of pre-existing vertical fractures are observed. If coal fragments, the degree of fragmentation increases with the initial gas pressure. The degree of fragmentation, *F*, is defined as (Guan et al., 2009)

$$F = \frac{M_0 - M_1}{M_0}$$

where M_0 and M_1 are the initial mass and the mass of the largest coal piece remained after the experiment, respectively. Fig. 5 shows the relationship between the degree of fragmentation and permeability for the suite of experiments. For the fragmented specimens, the degree of fragmentation is negatively correlated with the permeability of the specimen. Although there is little information regarding the linkage between permeability and fragmentation in coal, substantial laboratory studies are reported on verification of this correlation in the research area of magma fragmentation in volcanic conduits. And we believe fundamental similarities exist in these two rapid decompression induced dynamic fracturing processes.

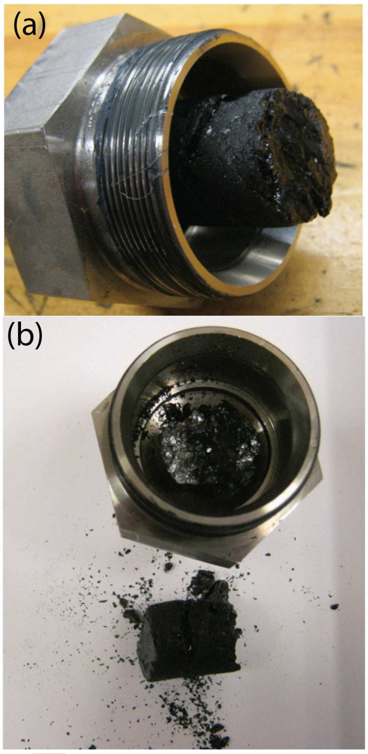

Fig. 3. (a) Endcap and the glued coal specimen before the test. (b) The specimen after rapid decompression showing vertical fragmentation. The applied pressure is 4 MPa.

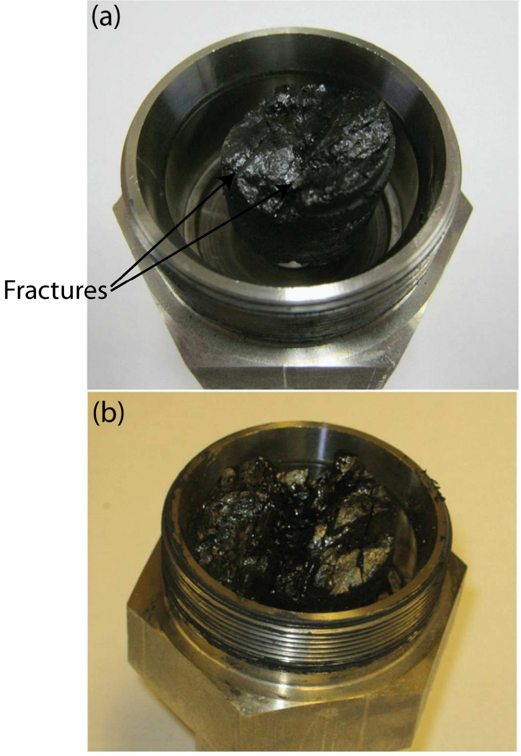

Fig. 4. (a) Endcap and the glued coal specimen before the test. (b) The specimen after rapid decompression showing horizontal fragmentation. The applied pressure is 5 MPa.

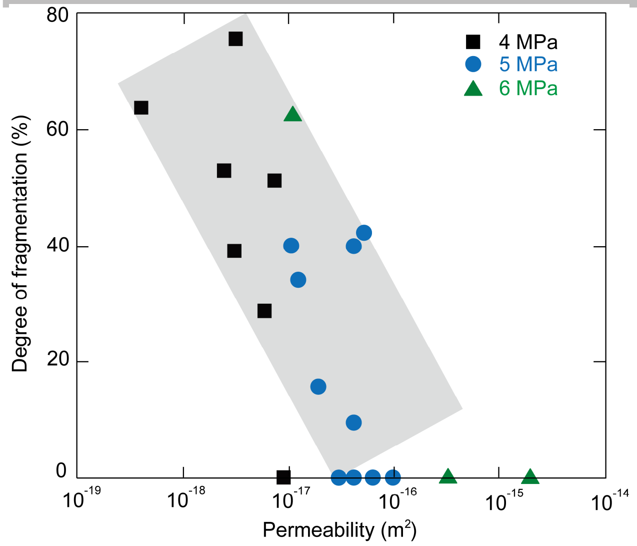

Fig. 5. The relationship between the degree of fragmentation and permeability for the suite of experiments. For the fragmented specimens, the degree of fragmentation is negatively correlated with the permeability of the specimen.

4. Comparison and discussion

Shock wave theory as a potential mechanism accounting for gas outburst was first proposed by Khristianovich (1953) and Litwiniszyn (1985, 1990). Guan et al. (2009) reported rapid decompression experiments using coal-CO_2 system and they stated that for coal pressurized in CO_2 at high pressure for some long duration, sudden decompression often leads to significant coal fragmentation. Thus, coal outbursts may be regarded as a type of gas-driven eruption. From their results, coal specimens are pulverized when decompressed from 3.2 MPa for anthracite and 4 MPa for bituminous. They found no single threshold pressure for fragmentation to occur. The pressure threshold depends on the type of coal and can be variable even for the same type of coal. The variability of the fragmentation threshold is attributed to heterogeneity of coal specimens. Thus, the coal/gas outburst threshold is expected to depend on crack abundance and distribution in coal (Guan et al., 2009), making it difficult to predict. No porosity, permeability, information related to sorption/desorption capacity/rate data are reported in their study. Fig. 1 in Guan et al. (2009) shows that the coal specimen has an initial length of 90 mm and the degree of fragmentation is 21.5%. This means that a piece of coal of 19.35 mm (90×21.5%=19.35) in length is fragmented in their tests. From the six continuous frames of video camera recording presented in their paper, it can be observed that the specimen stays intact in frame 2 and fragments in frame 3. Therefore, the fragmentation process lasts for less than 0.033 s. This in turn yields a fragmentation speed larger than 0.58 m/s. However, this 5 frame per second recording rate seems too low to capture the real fragmentation time, which means that the real fragmentation speed from this test may be much larger than 0.58 m/s.

The purpose of this work is to explore the dynamics of such an event. Our study is based on the hypothesis that the coal is internally pressurized, as previously postulated to explain the high gas pressure driven eruption phenomena (Guan et al., 2009). High gas pressure is found in coal seams as high as 6 MPa (Li and Hua, 2006; Sang et al., 2010). If the coal fails and fragments, the gas will be released, together with any fine-grained particles generated during the fragmentation process. The purpose of the experimental work is to validate that rapid decompression and desorption can indeed induce coal failure, which has been proven in Section 3.

In the fragmentation process we described above, the fragmentation criterion is assumed to be the tensile strength criterion. If the gas pressure differential after rapid decompression is larger than the tensile strength of the coal, the fragmentation occurs until the pressure differential across the fragmentation front is less than the tensile strength. Coal specimen exhibits a lower permeability magnitude in the range of 10^{-21}–10^{-13} m^2 (Wang et al., 2011). The coal specimens in this study show a permeability of ~10^{-17} m^2. The influence of permeability on this dynamic explosion of coal may require a comprehensive model to identify. The weakening role of gas desorption has been shown through drained and undrained laboratory experiments (Wang et al., 2013a). It is found that gas desorption can reduce the strength of coal even at a much lower gas pressure (1 MPa). Thus, we believe that the rapid gas desorption following the rapid decompression will accelerate the rupture process and that in turn will lower the explosion threshold, as suggested by our experimental results. Studies have shown that the sorption and swelling processes in coal are heterogeneous (Karacan, 2003; Pone et al., 2010; Izadi et al., 2011; Liu et al., 2011; Wu et al., 2011; Hol et al., 2012; Vishal et al., 2013a, b, 2015), thus the gas desorption process should also occur heterogeneously, depending on the characteristics and properties of the cleat network. This anisotropic desorption feature will influence the dynamic failure behavior through weakening localization in the vicinity of cleats.

5. Conclusions

In summary, we conduct laboratory experiments using a shock tube apparatus to examine the energetic explosion behavior related to underground coal gas outbursts. Bituminous coal specimens recovered from Colorado at a depth of 610 m are used in this study. CO_2 is used for the permeability measurement and for the sorption/desorption tests. Three types of behaviors are observed in coal after rapid decompression, i.e. degassing without fragmentation, horizontal fragmentation, and vertical fragmentation. We clearly find that rapid decompression and desorption can cause energetic failure in coal. Furthermore, the rupture behavior is to some degree controlled by the pattern of the fracture system, especially the orientation. The characteristics of fracture network (e.g. aperture, spacing, orientation and stiffness) and gas desorption play a role in this dynamic event, as coal can be considered a dual porosity, dual permeability, dual stiffness sorbing medium. This study bears important implication for understanding energetic failure processes in underground coal mines.

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 significant financial support for this work that could have influenced its outcome.

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