Fuel 235 (2019) 551–557

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Expansion energy of coal gas for the initiation of coal and gas outbursts

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ARTICLE INFO

Keywords:
Coal and gas outburst
Gas expansion energy
Coal damage

ABSTRACT

The study of coal and gas outburst mechanisms is necessary for the safety and efficiency in mining. Gas expansion energy is a major factor in outburst initiation. However, the amount of coal gas participating in outburst initiation is hard to estimate. In this study, considering the effect of coal damage and the environmental pressure change for desorption, a method to calculate gas expansion energy for outburst initiation is provided. Due to the reduction of the diffusion path, new fractures caused by coal damage can obviously affect gas expansion energy during outburst initiation. A peak zone of gas expansion energy during outburst initiation exists in front of the working face that belongs to the failure zone in coal mining and the zone of high gas pressure gradient. The peak zone is the risk source of the outburst and is the reason for the slabbing characteristic of the outburst. In outburst initiation, the variable pressure environment for gas desorption from the coal matrix has a limited effect on gas expansion energy for the outburst. Thus, the approximation of gas desorption with atmospheric pressure in the previous gas energy calculation is practicable. Gas conditions can affect the gas distribution in a coal mass and then obviously affect the gas expansion energy for an outburst initiation. Meanwhile, fracture development or the sorption time of the coal matrix has an obvious effect as well. It means tectonic coal could contribute much more gas expansion energy than primary-structure coal, causing high frequency and large power outbursts in tectonic regions. Unlike the effect on elastic energy accumulated in the coal mass, the increase of coal seam depth only broadens the peak zone of gas expansion energy and has little effect on the peak magnitude.

1. Introduction

Coal and gas outburst is a dynamic failure in which lots of gas is released rapidly and the destroyed coal is ejected by turbulent gas flow, causing casualties and economic loss. Due to the complexity of the physical process, the mechanism of coal and gas outbursts could only be described qualitatively until now. Difficulties in the research are various. On the one hand, the target material is complex because of the anisotropism of the coal mass and the polymorphism found in the existing state of coal gas. On the other hand, the target process is complex because the mechanical processes and energy release of dynamic instability are hard to describe. However, to predict and prevent outburst disasters, we should conduct fundamental research on the outburst mechanism [1].

Usually, coal and gas outbursts can be divided into four stages, including preparation, initiation, progress, and termination. The three essential elements for an outburst—coal gas, physico-mechanical properties of coal, and stress—influence each other and play different roles during the four stages.

The predamage of the coal mass and the formation of gas pressure gradients proceed in the first stage, and dynamical instability failure triggers disaster in the second stage. Research into the two stages are combined frequently for coal and gas outburst control. Towards the understanding of outburst preparation, Paterson analyzed the gas flow and stress distribution of two-dimensional coal seams in 1986, convincing the role of high gas pressure gradients [2]. Later, many numerical models were established [3–9]. For the initiation of the outburst, it is common to judge whether one or several parameters reach the critical values. From the angle of force and deformation, evolutions of damage parameter [6,7], deformation of the coal mass [8–10], and plastic strain [11] were used as instability criterion in most numerical models. In addition, analysis of the energy's evolution is also important for understanding the instability mechanism. An energy hypothesis proposed by the former Soviet Union scholar BB Ходот may be the earliest accepted theory, which showed energy and stress conditions for outbursts [12]. Coal gas expansion energy is the primary source of

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https://doi.org/10.1016/j.fuel.2018.07.132
Received 22 April 2018; Received in revised form 3 July 2018; Accepted 29 July 2018
0016-2361/

energy for an outburst [13], and the release of gas energy by methane desorbed from the coal matrix to the pores was believed to be the major cause of the occurrence of outbursts [14].

The vital effect of coal gas expansion energy had been verified by laboratory work on coal and gas outburst study as well. Gas expansion energy is the main dynamic source to throw and grind the coal [15]. Gas pressure in coal had a nearly liner relationship with the outburst intensity, and outbursts would not happen in the experiments when the gas pressure was at or below the threshold value [16]. Initial desorption characterization of coal gas was studied by experiments, showing the initial expansion energy of released gas can reflect the risk of outbursts [17,18]. Minioutburst experiments by Sobczyk verified that the efficiency of accumulated gas-releasing processes seemed to determine the minioutburst initiation [19]. To convey outburst coal, the rapid desorption of coal particles with small sizes within a short period is an essential condition for the development of an outburst [20]. The expansion energy of coal gas is also a focus for the evaluation of the impact damage in the progress stage [21–23].

According to the dual pore structure of coal seams, coal gas in fractures and the coal matrix contributes to expansion energy in the initiation and progress stages. Gas in fractures is deemed to fully contribute to the outburst initiation, owing to the direct connection with the outer space, while gas in the coal matrix must desorb and diffuse out in order to participate in the outburst. Ian Gray [24] measured the released gas energy and the volume of released gas from a unit volume of coal under adiabatic and isothermal conditions and found that there was a linear regressive relationship between the desorbed gas energy and the volume of desorbed methane in a unit volume of outburst coal. The result indicated that the calculated formula in thermodynamics for gas expansion energy is usable, but the participation amount of desorbed gas is hard to estimate and was calculated according to the desorption time by the desorption model [14,19].

However, conditions for gas desorption are not changeless and were affected by the coal mass damage and the environmental pressure change. Through experimental simulations of coal and gas outbursts, it was found that the number of acoustic emission events gradually increased until an outburst occurred [25]. This result demonstrates that coal mass damage is increasing before outburst initiation. Moreover, gas desorption from the coal matrix is not under atmospheric pressure. Through the pressure sensors prefabricated in the coal mass for outburst experiments, it was discovered that compared to stress, gas pressure in fractures had a linear continuous reduction process [26]. Gas pressure also decreased sharply in the initial time and then leveled off [18]. In addition, from the investigation of the flow state and transport mechanism of coal and gas in the progress stage, it was deduced that the front of the outburst was gradually exposed to air [23]. These findings of desorption condition changes for gas from coal matrix were ignored in the previous study. This paper presents a calculation method for gas expansion energy during outburst initiation considering coal damage and environment pressure change for desorption. The numerical analysis is shown to illustrate the influence of various factors on the gas energy release during outbursts.

2. Calculation method of gas expansion energy for outburst initiation

2.1. Impact assessment of the coal mass damage on gas desorption

It is obviously well known that new fractures generated by mining-induced stresses would affect coal mass permeability [27]. On the other hand, new fractures would cut the coal matrix, affecting the gas diffusion path. However, unlike permeability, the effect of coal damage on gas desorption from coal matrix has a lack of experimental research. In this case, indirect assessment is applied in this paper.

Fracture description is important for the mechanical and flow properties study. Porosity of fractures is an usual parameter for the overall description of fractures in coal. Porosity of fractures is affected by loading stress obviously, hardly to show the spatial distribution change independently. The concept of fractals was a useful way of describing the statistics of fractures in rock mechanics [28]. Fractures and pores in coal show self-similarity in geometrical morphology and could be quantitatively characterised using fractal theory [29–32], as well as the evolution of fracture network [33]. Using the fractal theory, fracture distribution in the sections of coal mass could be expressed as [29]

$$N(r) = Ar^{-D_f} \tag{1}$$

where N represents the amount of fractures longer than r, r represents the statistical length in m, D_f represents the fractal dimension of fractures, and A represents the proportionality coefficient. D_f is often expressed by box-counting dimensions, which chooses one section of coal mass to analyze the fracture distribution using the gridding method. If the overall length of fractures in one section is L, it could be expressed using the fractal rule as

$$\begin{aligned} L &= \int_{R}^{r_0} r dN(r) = \int_{r_0}^{R} rD_f Ar^{-D_f-1} dr \\ &= \frac{AD_f}{D_f-1}\left(r_0^{1-D_f} - R^{1-D_f}\right) \end{aligned} \tag{2}$$

where r_0 represents the minimum size of fractures in m and R represents the maximum size of fractures in m. The dimensions of fractures in the coal mass are dramatically different, reaching several orders of magnitude. Therefore r_0 is much smaller than R, and Eq. (2) could be simplified as

$$L = \frac{AD_f}{D_f-1} r_0^{1-D_f} \tag{3}$$

At present, the coal mass is usually deemed as a dual porous structure composed of the quadrate coal matrix and mesh-type fractures. Spontaneously, gas exchanged between fractures and the coal matrix can be simplified by treating the coal matrix as homomorphic units. Similarly, fracture evolution or the size of the coal matrix is uniformly simplified, as shown in Fig. 1. Taking the section parallel to the coal matrix surface, the overall length L can be related to the side length of the coal matrix by

$$L = 2nl \tag{4}$$

where n represents the amount of the coal matrix in the section and l represents the side length of the coal matrix in m.

Influenced by mining, fractal dimension of fractures increases from D_{f0} in the original coal mass to D_f in the damaged coal mass, overall length of the fractures increase from L_0 to L, the side length of the coal matrix reduces from l_0 to l, and the amount of the coal matrix in the

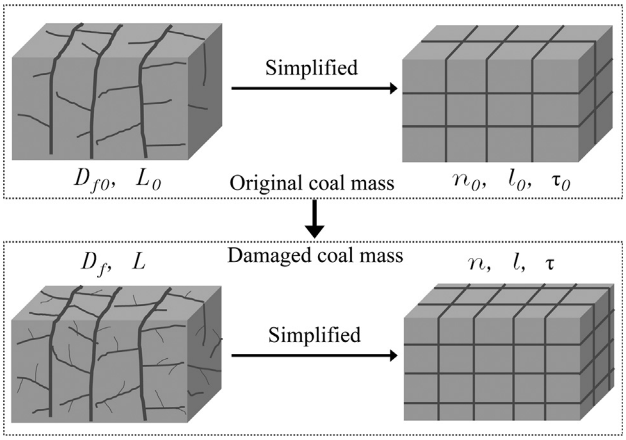

Fig. 1. Fractures change in coal mass as a dual porous structure.