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A numerical model for outburst including the effect of adsorbed gas on coal deformation and mechanical properties

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ABSTRACT

The complexity of the interactions between coal and gas is an obstacle to creating a quantitative description of the outburst mechanism. In addition to free gas acting in the form of pore pressure for the coal mass, the adsorbed gas can also induce coal deformation and changes in the mechanical properties of coal. To analyse the effect of gas desorption on outburst initiation, a model is established for gas migration and mechanical processes during excavation. The permeability is significantly changed during excavation and is zonally redistributed. The coal mass near the coal wall undergoes stress release and cracks develop, which creates a sharp increase in permeability. Behind this area, the permeability of stress-concentrated coal mass drops quickly, causing a steeper pressure gradient and therefore creating greater potential for an outburst initiation. The mechanical behaviour of the coal mass is influenced not only by the free gas but also by the absorbed gas, which affects the coal deformation and mechanical properties in gas emission. To analyse the effect on outburst initiation, the results obtained consider the desorption-induced shrinkage and mechanical changes and are compared with those obtained with consideration of the effect of only free gas. This comparison demonstrates that desorption-induced shrinkage affects the stress state of the coal mass and that this influence becomes increasingly obvious as the desorption proceeds. The plastic area and the maximum plastic strain of the coal mass are also altered. The increase in strength due to the decrease of adsorbed gas decreases the plastic area and the maximum plastic strain of the coal mass; it also minimises the tendency towards coal collapse, thus enabling convergence with higher gas pressure. This result indicates that the effect of adsorbed gas on the mechanical behaviour of the coal mass is non-negligible. The effects of coal-seam depth, gas pressure and strength on outburst are analysed using this model.

1. Introduction

Coal and gas outburst is a dynamic failure in which a coal mass containing high-pressure gas collapses and the destroyed coal is ejected by turbulent gas flow. The violent eruptions of coal and gas, and particularly the potential gas explosion, pose a serious threat to miner safety and coal production. Although many explanations and hypotheses for the outburst mechanism have been proposed in previous research, they are only able to qualitatively describe the outburst gestation, initiation, and development.

The quantitative investigation of this phenomenon is continuously progressing with the deepening understanding of coal gas storage and migration laws, the effect of adsorbed gas on coal deformation and mechanical properties, and the permeability evolution law of a coal seam together with the development of better numerical calculations. Litwiniszyn [1] suggested that a shock wave propagates in the coal mass prior to the outburst initiation, which causes the coal gas to transform from a liquid into a gaseous state, and the high gas pressure created by this phase transformation leads to the failure of the coal skeleton, which is followed by an outburst. In contrast, Paterson [2] proposed that an outburst represents a structural failure of the coal caused by the gas pressure gradient generated in gas migration and that outbursts could be eliminated by reducing this gas pressure gradient. In later models established by Choi and Wold [3,4], Xu et al. [5], and Xue et al. [6], the gas pressure gradient as the main cause of coal mass failure and collapse is a critical topic in outburst research. The Choi and Wold model considered the effect of damage evolution on the mechanical processes and provided an initial estimate of the coal-fragment particle size. Using RFPA2D-GasFlow, the Xu et al. model considered the heterogeneity of coal and rock and the

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Nomenclature

b	impact factor of coal volumetric stress on permeability
C	cohesion
c_m	free gas density of coal matrix
c_f	free gas density in fracture
$\bar{c}_m$	average gas density of coal matrix
D	diffusion coefficient
E	elastic modulus
f	volume force
G	shear modulus
I_1	first stress invariant
J_2	second invariant of the deviator stress
k	coal seam permeability
k_0	initial coal seam permeability
k_{DP}	material constant estimated by cohesion and friction angle
K	bulk modulus of coal mass
K_m	bulk modulus of coal matrix
K_s	bulk modulus of coal skeleton without pores
M	molar mass of coal gas
p	pore pressure
p_0	atmospheric pressure
p_L	Langmuir pressure constant
p_L^s	Langmuir pressure of adsorption-induced strain
q	gas diffusion velocity from coal matrix
Q_a	amount of adsorption gas
Q_f	amount of free gas respectively
R	gas constant
T	gas temperature
u	unit displacement
V_L	Langmuir volume constant
V_m	volume of coal matrix

Greek letters

α	reduction factor of the coal mechanical parameter
α_M	maximum reduction of the coal mechanical parameter
α_{DP}	material constant estimated by cohesion and friction angle
α_s	shape factor
γ_m	effective stress coefficient of matrix
γ_f	effective stress coefficient of fracture
γ^p	softening parameter
γ^{p^*}	transition value of the softening parameter from which the residual behaviour begins
δ_{ij}	Kronecker delta
ε_{Lv}^s	maximum adsorption-induced volume strain
ε_1^p	first principal plastic strain
ε_2^p	second principal plastic strain
ε_3^p	third principal plastic strain
Θ	volumetric stress
λ	Lamé constant
μ	gas viscosity coefficient
ρ	bulk density
υ	Poisson ratio
φ_m	matrix porosity
φ_f	fracture porosity
φ_{f0}	initial fracture porosity
ϕ	friction angle
σ	stress
σ'	effective stress
τ	adsorption time of coal matrix
ξ	jump coefficient of permeability

Subscript

0	initial value of the variable
m	matrix
f	fracture
c	coal
r	rock

increased gas permeability induced by damage and further analysed the entire process of coal and gas outbursts. By linking and executing FLAC3D and COMET3 sequentially, the Xue et al. model computed the mechanical process and gas migration in order and incorporated the coal and gas coupling by transferring the calculation result between the two codes.

In all the above models, coal mass failure is caused by coal gas combined with stress. However, only free gas is considered for analysis of the mechanical effect of coal gas in the effective stress principle. Adsorbed gas is treated as the source term of gas migration only, and its effect on coal mass deformation and mechanical properties is ignored.

Due to interactions between coal and gas, coal swells after gas adsorption, and its mechanical properties change as well. Experimental studies of coal deformation via gas adsorption proved that the deformation is proportional to the adsorption [7–9]. The effect of adsorbed gas on coal deformation relative to that of free gas is obvious. The results from George and Barakat [10] showed that the deformation caused by the effective stress change was less than the shrinkage caused by gas desorption and that the desorption-induced shrinkage is 2.5 (10) times greater than the deformation caused by the change in gas pressure for CH_4 (for CO_2). With respect to the effect of gas adsorption on coal strength, Ettinger and Lamba [11] reported that coal was hardened after gas desorption in coal recovery and confirmed the strength reduction by gas adsorption using the mechanical pounding method. The same conclusion was obtained based on the crushing resistance results of Czapliński and Holda [12] and the drillability analysis of Aziz and Ming-Li [13]. Recent research shows that CO_2 adsorption reduces the uni-axial compressive strength and elastic modulus of coal [14,15], but no obvious change in the tri-axial strength is observed [14]. The acoustic emission test found differences between saturated and natural coal samples [15,16]. Perera et al. [15] suggested that the early crack initiation of saturated coal was due to the CO_2 adsorption-induced swelled layer as well as early crack damage and failure points due to lower surface energy. Comparison of coal before and after exposure to CO_2 indicated the formation of micro-fractures induced by heterogeneous swelling [17] and rearrangement of the coal structure [18–20].

In addition, unlike coal-bed methane exploitation, excavation has an enormous effect on the stress state, gas pressure distribution and migration of coal mass ahead of the excavation face [21]. Stress redistribution could result in a great change in permeability due to the susceptibility of fractures to stress [22–25], and the fracture development in the coal failure process will alter the permeability as well [21,26], leading to a strong effect on the gas migration and distribution. Coal gas pressure distribution is a key factor in outbursts, and it is necessary to consider the effects of excavation for a more practical simulation of such a phenomenon.

This work analyses the evolution of porosity and permeability during excavation and creates a model for coal gas migration, mechanical processes during excavation, together with their coupling. To assess the effect of adsorbed gas, the model is applied to analyse the coal mass mechanical behaviour, including the