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Direct observation of coal–gas interactions under thermal and mechanical loadings

Chunguang Wang [a,d], Jili Feng [b], Jishan Liu [c], Mingyao Wei [d,e], Changsheng Wang [a], Bin Gong [a]

[a] State Key Laboratory of Mining Disaster Prevention and Control Co-founded by Shandong Province and the Ministry of Science and Technology, Shandong University of Science and Technology, China
[b] State Key Laboratory for GeoMechanics and Deep Underground Engineering, School of Mechanics and Civil Engineering, China University of Mining and Technology, Beijing, China
[c] School of Mechanical and Chemical Engineering, The University of Western Australia, Australia
[d] Institute of Rock and Soil Mechanics, Chinese Academy of Science, Wuhan, China
[e] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, China

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ABSTRACT

In this study we directly observe the multi-physical process of coal–gas interaction induced by thermal impacts through a specially designed facility. This facility can be used to measure the evolution of coal deformation and migration of originally existing gas in coal. Tests were conducted through three stages, i.e., heating, uniaxial loading, and re-heating stage. In the first-stage, heating triggers two concurrent effects, coal expansion and gas migration. It was found that both the coal deformation and gas flow firstly increase with the rise of coal temperature. When the coal temperature is in isothermal equilibrium, the volume of coal is either recovered or maintained unchanged approximately. In the course of the process, the gas flow begins to peak off by a relatively low flow rate. The results at the uniaxial loading showed that the gas migration is significantly controlled by the progressive deformation of the stressed coal under isothermal conditions. From the relationship between the coal deformation and concurrent gas flow, the direction of gas migration depends upon the development of cracks. It consequently leads to either sucking of gas to the opening of cracks/fractures, or discharging of gas to the closure of cracks and pores. The re-heating at the last stage can accelerate gas discharge. The concentrations of released gas species increase proportionally with the coal temperature. In order to quantify the thermodynamic characteristics of gas migration, the concentration of desorbing gas is defined as a function of temperature by using the Arrhenius equation. The results statistically showed that CO_2 has a stronger affinity for the coal than CH_4. It was also revealed by the results that the deformation evolution of the heated coal is related to the competition between thermal swelling of solid coal and shrinking by gas desorption. Finally, it was indicated by the present tests that the complex deformation potentially makes it possible to deteriorate in the mechanical properties of coal. This work can help to understand the mechanism of coal–gas interaction induced by multi-physical fields including thermal-induced coal deformation, residual gas desorption and adsorption, and coal shrinkage.

1. Introduction

Mining activity and fluid injection or recovery inevitably enable to disturb the geothermal equilibrium of coal masses, among which thermal effect that can definitely be produced triggers a complex interaction between coal and gas. Such interaction that is a multi-physical process deals with gas desorption with corresponding shrinking of coal, gas expansion with corresponding pore pressure change, and coal matrix deformation against porosity change. Among this process, the extent of coal deformation is the dominating factor due to its dominant effect on coal permeability and its mechanical behavior. A comprehensive understanding of the multi-physical process is consequently crucial for the enhanced coalbed methane (ECBM) production and assessment on the stability of coal mass under particularly mining-induced stress and temperature conditions. However, the emergence of coupling between solid deformation and gas migration indeed makes coal permeability not easily predicted.

It is well known that solid coal not only features the mechanical behavior of porous medium, but also exhibits the swelling behavior as a result of the uptake of gas and supercritical fluids, and shrinkage as a result of gas release (Harpalani and Chen, 1997; Karacan, 2003, 2007; Larsen, 2004; Mavor and Gunter, 2006; Mazumder et al., 2006). Based on the numerous field and laboratory observations, the coal permeability model is generally defined as a function of external stress and pore pressure. For example, Palmer and Mansoori (1998) regarded coal permeability as a function of effective stress and matrix shrinkage. Shi and Durucan (2004) presented a cleat permeability model for coalbed under an assumption of only horizontal stress controlling the cleats. Cui and Bustin (2005) also proposed a stress-dependent

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permeability model. However, the coal permeability models mentioned briefly above were all derived on the isothermal assumptions.

It is widely believed that solid materials are to thermally expand due to temperature increase. The inhomogeneous deformation between minerals, due to different thermal expansion coefficients, will contribute to damage of porous structure of rocks like micro-cracking (Heuze, 1983; Wong and Brace, 1979), which can change the mechanical behaviors of the heated rocks. Besides the thermal-induced solid deformation, the pore fluid within coal is sensitive to pressure–volume–temperature conditions. At higher temperature gas migration is to be accelerated due to the increase of gas diffusion and desorption (Charrière et al., 2010; Deishad et al., 2009). The increasing amount of newly-generated free gases continuously fills the cleat system, which raises the pore pressure as well. Furthermore, the onset of gas desorption is concurrent with shrinking of coal matrix, which enables to widen the aperture of the cleat system and further influence the magnitude of expansion deformation of coal. Recently, Zhu et al. (2011) and Qu et al. (2012) successively proposed that the coupled permeability models are associated with coal deformation, gas transport, thermal transport and influence of temperature on sorption capacity. They found that the change in temperature that results in thermal expansion and sorption-induced swelling can significantly affect coal permeability.

Although the various coupled permeability models above were examined and developed, the relevant experimental work has only been focused on individual process from the standpoint of either mechanical behaviors or the evolution of coal permeability (Gentzis et al., 2007; Hobbs, 1964; Medhurst and Brown, 1998). For example, Macrae and Mitchell (1957) and Shoemaker et al. (1977) presented that both the strength of the British coal and Pittsburgh coal were increased to 120 °C due to the weaker secondary forces of the van der Waals-type between structural units. However, their works ignored the gas adsorption/desorption-induced deformation.

In the present work, we perform a series of thermal–mechanical impacts on intact coal to observe the response of coal–gas, instead of directly measuring the coal permeability under varied temperature. Although the temperature of mining face will decrease due to ventilation and coal recovery, it is possible to appear alternative change of temperature. For example, it is also likely that coal spontaneous combustion that is caused by the exothermic reaction between coal and oxygen enables to release thermal energy, and in turn to definitely increase the temperature of surrounding rocks (coal). Therefore, the intact coal samples were tested by means of heat in our present study rather than decreasing their temperature. In addition, numerous works suggested that one of the mechanisms of rock failure (i.e. borehole breakout and rockburst) near free surface is characterized by compressive failure, which is caused by tensile (or splitting) fractures (Fairhurst and Cook, 1966; Germanovich and Dyskin, 2000; Horii and Nemat-Nasser, 1985). It was also found by these studies that these fractures tend to propagate sub-parallel to the free surface and parallel to the direction of maximum principal stress. From these experimental results and in situ observation, we simplified the bio-axial stresses into uniaxial compressive loading in order to interpret failure mechanism of coal near the surface of an opening. The associated procedure on experimental test is divided into three steps. The first is to heat intact coal up to a prescribed temperature to obtain the evolution of solid deformation of the coal and the concurrent gas flow. The second is that uni-axial compression is applied on the heated coal, in which the gas discharge and the coal deformation are measured. The third is that the deformed coal is reheated to study the thermodynamic characteristics of adsorbed gas. The aim of the present study is to better understand the evolution mechanism of coal permeability and its strength associated with the micro-flow of porous gas and the solid deformation by means of the thermal-induced feedbacks of intact coal under unconfined loading conditions.

2. Method of test

2.1. Testing setup

The testing system shown in Fig. 1 that was successfully used to investigate the desorption behavior of adsorbed gas in coal (He et al., 2010) is composed of two parts, that is, thermal–mechanical and gas measurement units. The former is equipped with a hydraulic serve-control system and an electric-controlled heater soaked in a hydraulic-oil of triaxial cell. A platinum-thin sensor of HERAEUS (PT-100) attached on the outer surface of coal is to feed the coal temperature back into the heater in order to control the temperature of hydraulic-oil in the cell. The latter is made up of a high-accuracy transducer of gas pressure connected by two gas flow-meters, whose outlet is atmospheric. The gas-pressure transducers used in the present tests are from TRAFAG in Switzerland. Their precision is ±0.3% of full scale from −2000 to +2000 Pa. The gas compositions are detected by a gas chromatography (GC). The gas detector of the GC is equipped with

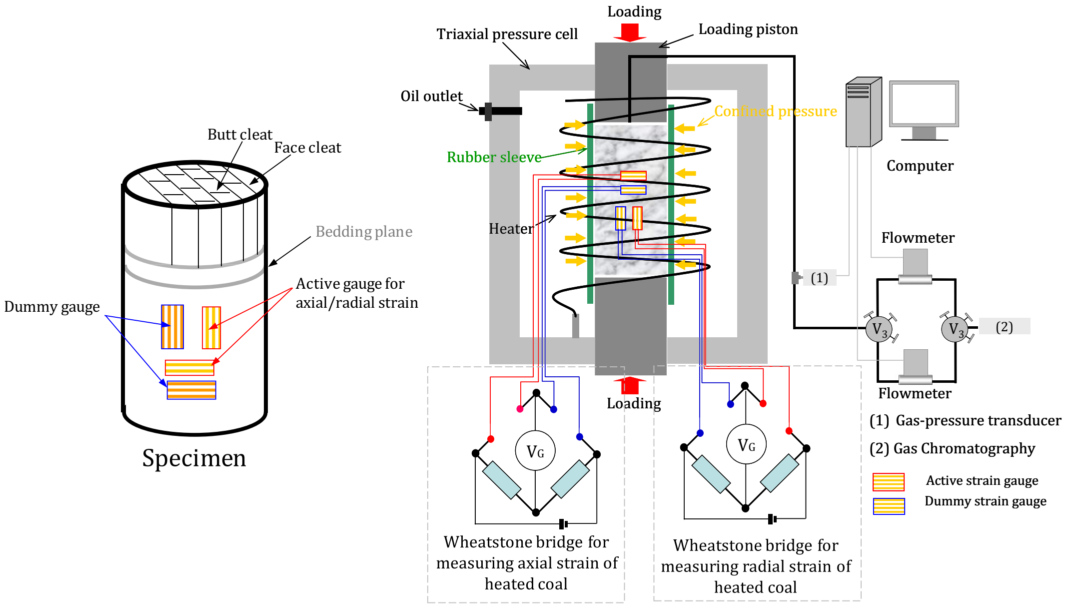

Fig. 1. Schematic setup of testing apparatus and Wheatstone bridge circuits measuring deformation of the coal core with varied temperature.