Fuel 219 (2018) 223–238

Contents lists available at ScienceDirect

Fuel

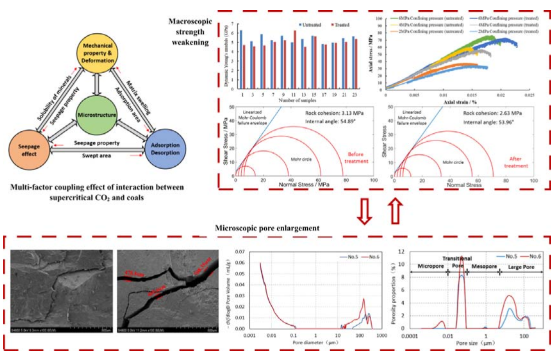
journal homepage: www.elsevier.com/locate/fuel

Experiment study of mechanical properties and microstructures of bituminous coals influenced by supercritical carbon dioxide

Meng Meng[a,*], Zhengsong Qiu[b]

[a] Department of Petroleum Engineering, The University of Tulsa, Tulsa, OK, USA
[b] Institute of Petroleum Engineering, China University of Petroleum (East China), Qingdao, China

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Supercritical CO_2
Coal
Mechanical properties
Microstructures
Microscopic mechanisms

ABSTRACT

The injection of CO_2 into deep coal seams can not only increase the recovery of CH_4 but also contribute to the geological sequestration of CO_2. In deep coal seams, CO_2 can easily become the supercritical state when the pressure is over 7.38 MPa, and the temperature is over 31.04 °C. It can influence both the physical and chemical properties of coals, especially weakening the mechanical strength, which could compromise the long-term integrity and stability of the deep coal seams. Through acoustic emission experiment and triaxial compression experiment, the results show that after the treatment of supercritical CO_2, the mechanical parameters of coals, including dynamic Young's modulus, static Young's modulus, rock cohesion, and peak strength, decrease significantly. It demonstrates that supercritical CO_2 can reduce the mechanical strength of coals. This macroscopic phenomenon can be explained by the mechanism of the enlargement of microscopic pore spaces of coals, and this mechanism has not been studied thoroughly yet. Therefore, several microscopic quantitative experiments are comprehensively conducted, including scanning electron microscope (SEM), mercury injection porosimetry (MIP) and nuclear magnetic resonance (NMR). The results of these three tests are relatively consistent, and they show that after treatment of supercritical CO_2, not only the diffusion space consisting of micropore and transitional pore but also the percolation space involving large pores and even cracks has been enlarged and expanded. This can be a significant underlying microscopic mechanism to effectively explain the weakening of the mechanical strength of coals. The pore space enlargement, together with the swelling of coal matrix, and the theoretical explanation of fracture mechanics and thermodynamic theory are all underlying mechanisms to explain the weakening behavior of coals influenced by the supercritical CO_2.

* Corresponding author at: The University of Tulsa, McDougall School of Petroleum Engineering, North Campus 211D, USA.
E-mail address: mem282@utulsa.edu (M. Meng).

https://doi.org/10.1016/j.fuel.2018.01.115
Received 5 November 2017; Received in revised form 6 January 2018; Accepted 26 January 2018
0016-2361/

1. Introduction

The injection of CO_2 into coal seams can not only be used to improve the recovery of coal seams methane but contributes to the geological sequestration of CO_2 [1–3]. The interaction between CO_2 and coal seams is a complex process that consists of several physicochemical phenomena, including the change of microstructure, the adsorption/desorption of CO_2 and CH_4, the seepage effect of CO_2 and CH_4, the deformation of coal matrix and the changing of the mechanical strength of coal seams. These processes are closely related and coupled with each other. When CO_2 is injected and flows in the deep coal seams, it can easily become the supercritical state ($P > 7.38$ MPa, $T > 31.04$ °C). Then it will change the pore pressure and effective stress in the coal seams. Within the affected area, CO_2 can displace CH_4 through competitive adsorption. As time pass by, the pressure of CO_2 will dissipate gradually, and desorption will happen. The desorption of CH_4, adsorption of CO_2 and finally desorption of CO_2 could cause a variance of mechanical properties and volume deformation of coals. The physical parameters of the coal, such as porosity and permeability will also be changed. All these, in turn, will affect the seepage properties of CO_2 in the coal seams. Therefore, we can see that the injection of CO_2 into deep coal seams is a complex process with different mechanisms coupled with each other and the whole process is shown in Fig. 1.

Up till now, many researchers have paid enough attention to the adsorption, seepage, and volume swelling behavior of supercritical CO_2 on coals. However, researchers have not paid enough attention to the variance of mechanical properties and microstructures of coal under the influence of supercritical CO_2. There is only a few literature related to this area, and unfortunately, most of them are limited to the subcritical or gas state of CO_2. Ranjith [4] used acoustic emission methods to study the effect of CO_2 saturation on mechanical properties of coal and showed that the sorption of CO_2 could cause a reduction in strength of the coal samples. But he didn't provide the detailed study of the actual underlying mechanisms. Perera [5] studied the influence of mechanical property of coals influenced by CO_2 and N_2. He concluded that CO_2 saturation could weaken the mechanical strength of coals, but N_2 saturation could slightly increase the mechanical strength and delays crack propagation. Masoudian [6] studied the effect of CO_2 on the mechanical properties of coal under in-situ stress conditions and he suggested that the adsorption of CO_2 changes Young's modulus and the strength of coal sample and these effects are reversible. It shows that the Young's modulus of coal decreases up to 19% and the strength of coal reduced by 20%.

For the influence of supercritical CO_2, Perera [7] used uniaxial compression test to investigate the effects of gaseous and supercritical

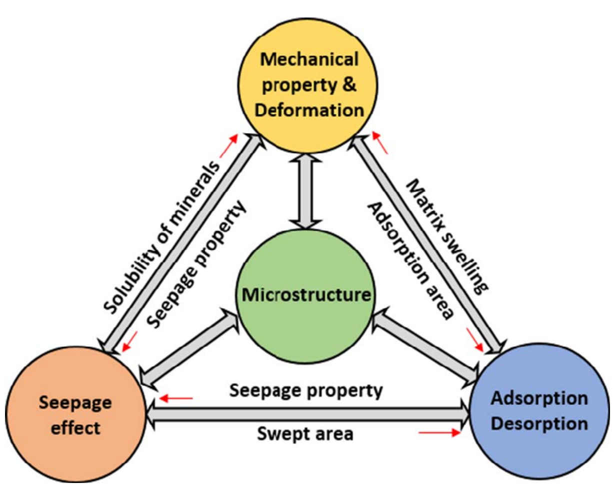


Fig. 1. Multi-factor coupling effect of interaction between supercritical CO_2 and coals.

CO_2 on coal strength. He concluded that the supercritical CO_2 has a greater influence in weakening coal strength and Young's Modulus. Ranathunga [8] used the unconfined compressive strength tests, acoustic emission system and optical 3D deformation analysis to study the mechanical property alterations of coal. He found that supercritical CO_2 has a greater ability to reduce the coal strength because supercritical CO_2 has a greater adsorptive potential, which eventually creates greater coal matrix swelling. Later, Ranathunga [9] studied the influence of supercritical CO_2 on coal seams during CO_2 adsorption under in-situ stress conditions by conducting tri-axial compression tests. The results show that the strength reduction in coal with the CO_2 injection under field conditions is significantly less than that expected based on uniaxial compression tests.

Among these limited publications, the weakening of the coal strength after its interactions with supercritical CO_2 is a consensus. The macroscopic phenomenon is the overall effect of the microscopic properties, and the variance of microscopic properties can effectively explain macroscopic phenomena. There are three possible mechanisms to explain the weakening effect. First, supercritical CO_2 could expand the pore space of coals. Second, the adsorption of supercritical CO_2 could cause the swelling of the coal matrix [8]. Thirdly, the theory of fracture mechanics and thermodynamic theory could be used to explain the weakening behavior [10]. The last two mechanisms have been studied by former researchers. However, to the best of our knowledge, there is not enough work that thoroughly investigates the microscopic mechanism of pore space enlargement and its relation to the weakening of coal strength. Hol, S. [11–13] analyzed the microstructure of coal under exposure of supercritical CO_2 and mentioned that microfractures formed and propagated through the coal samples as a result of the exposure to CO_2. However, under in-situ conditions adsorption and swelling cannot cause any auto-cracking and the new microfractures should occur during the CO_2 injection process or because of the extraction ability of the supercritical CO_2. Masoudian [6] also mentioned that the changes in the microstructures of coal could be expected to cause changes in the mechanical properties of solid coal. He used Scanning Electron Microscopy method and found that CO_2 appeared to change the macromolecular structure of the coal. Since the coals are fractured materials with cleats and various pore structures [14], the variance of the microstructures and the change of spatial fracture arrangement can strongly affect the strength of coals. Therefore, all of these former work shows that quantitative description of the variance of microstructures of coal after interaction with supercritical CO_2 is necessary and significant.

During the study of the variance of mechanical properties of coal, many researchers [9,11–13] has mentioned the importance of measurements during in-situ conditions. For the measurement of microstructures, it is extremely hard to do this under in-situ conditions because of experimental technology limits. However, in reality, the injection of CO_2 into coal seam can be cyclic. After each cycle of injection, the desorption of CO_2 will inevitably happen because of CO_2 pressure diffusion and dissipation in the coal seam. Therefore, it is also very meaningful to measure the mechanical property, and microstructure variance before and after displacement of supercritical CO_2. The current experimental methods to measure microstructure of rocks includes mercury injection porosimetry (MIP), low-field nuclear magnetic resonance (LFNMR), scanning electron microscopy (SEM), transmission scanning electron microscope (TEM), small angle scattering (SAS), computed tomography method (CT), and gas adsorption method. All of these methods have their advantages and disadvantages [15]. The MIP is widely used in characterizing the distribution of pore structures, but it is a destructive method. The LFNMR is a recent emerging method in the petrophysical characterization of different rocks, including coals. NMR transverse relaxation (T_2) distributions strongly relate to the coal pore structures [16]. The methods of SEM, TEM, and SAS could show the surface of the microstructures of rocks, but they are limited to the local area. The CT method is a more direct method to restore the whole