Journal of Rock Mechanics and Geotechnical Engineering 8 (2016) 93–112

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Review

Multiphysics of carbon dioxide sequestration in coalbeds: A review with a focus on geomechanical characteristics of coal

Mohsen S. Masoudian*

School of Civil Engineering, University of Sydney, Darlington, Australia

ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form
7 August 2015
Accepted 17 August 2015
Available online 21 September 2015

Keywords:
Coalbed geosequestration
Carbon dioxide (CO_2)
Reservoir geomechanics
Elasticity
Rock failure

ABSTRACT

To reduce the emissions of carbon dioxide (CO_2) into the atmosphere, it is proposed to inject anthropogenic CO_2 into deep geological formations. Deep un-mineable coalbeds are considered to be possible CO_2 repositories because coal is able to adsorb a large amount of CO_2 inside its microporous structure. However, the response of coalbeds is complex because of coupled flow and mechanical processes. Injection of CO_2 causes coal to swell, which leads to reductions in permeability and hence makes injection more difficult, and at the same time leads to changes in the mechanical properties which can affect the stress state in the coal and overlying strata. The mechanical properties of coal under storage conditions are of importance when assessing the integrity and safety of the storage scheme. On the other hand, the geomechanical response of coalbed will also influence the reservoir performance of coalbed. This paper provides an overview of processes associated with coalbed geosequestration of CO_2 while the importance of geomechanical characteristics of coalbeds is highlighted. The most recent findings about the interactions between gas transport and geomechanical characteristics of coal will be discussed and the essence will be delivered. The author suggests areas for future research efforts to further improve the understanding of enhanced coalbed methane (ECBM) and coalbed geosequestration of CO_2.

1. Introduction

1.1. Global warming and carbon sequestration

Global warming is the average increase in temperature of the atmosphere, which can lead to changes in global climate patterns. This is primarily caused by increases in greenhouse gases in the Earth's atmosphere. Changes in climate patterns mean that extreme weather events such as heat waves, floods, storms, droughts and bushfires will become more frequent, more widespread or more intense (Hansen et al., 1981; Dai, 2011). Lashof and Ahuja (1990) reported that 57%–72% of the greenhouse gas effect on global warming is due to the CO_2 emissions. The increase in the global surface temperature over 50 years from 1956 to 2005 is 0.13 °C per decade and eleven of the twelve years between 1995 and 2006 rank among the twelve warmest years since 1850 (Pachauri and Reisinger, 2005). The Kyoto Protocol is an international agreement that has been ratified by 178 countries, committed to specific emission targets. However, it is believed that the Protocol failed to meet its goals during its first commitment period, as there was no noticeable impact on global emissions (Helm, 2012). Most European countries have been successful in reducing their emissions while the others have failed to reach their designated targets.

In order to reach the emission targets, scientists have suggested several ways to decrease the amount of greenhouse gas emissions. Carbon dioxide (CO_2) capture and storage (CCS) is considered as one of the options for reducing atmospheric emissions of CO_2 from human activities (IPCC, 2005). Different formations may be used for CO_2 storage as illustrated in Fig. 1. CO_2 can be injected into depleted oil or gas reservoirs (option 1), or it can be used to enhance the production of oil or gas from an active hydrocarbon reservoir (option 2), or it can be injected into deep saline aquifers to reside in the aqueous environment (option 3). Alternatively, it can be injected into deep coal seams to enhance the production of methane (option 5). When CO_2 is used for enhanced oil or gas recovery or enhanced coalbed methane (ECBM) recovery, the produced hydrocarbons contribute to offset the CCS cost. The estimated capacities of CO_2 storage for geological storage options are listed in Table 1 (IPCC, 2005).

1.2. Coalbed geosequestration

1.2.1. Techno-economic advantages of coalbed sequestration

Coalbeds are interesting because they have naturally stored methane which can be displaced by injecting CO_2 and can help to

---

* Corresponding author. Tel.: +61 2 9351 5155.
E-mail address: mohsen.masoudian@gmail.com.

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2015.08.002

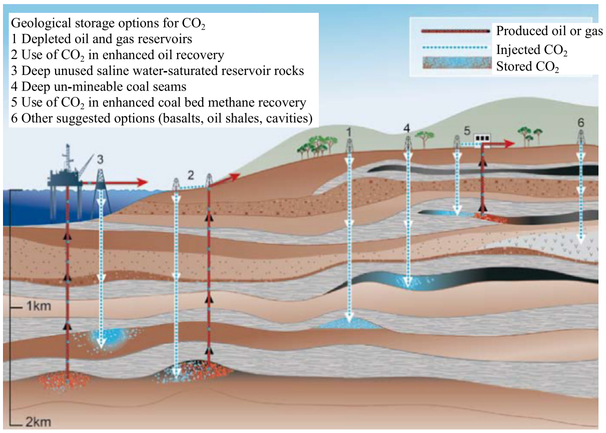

Fig. 1. Methods for storing CO_2 in deep underground geological formations. Two methods may be combined with the recovery of hydrocarbons: enhanced oil recovery (EOR) (option 2) and ECBM (option 5) (IPCC, 2005).

Table 1
Global storage capacity for several geological sequestration options (IPCC, 2005).

Reservoir type	Storage capacity (Gt CO_2)	
	Lower estimate	Upper estimate
Oil and gas fields	675[a]	900[a]
Un-mineable coal seams (ECBM)	3–15	200
Deep saline formations	1000	Uncertain, but possibly 10,000

[a] These numbers would increase by 25% if undiscovered oil and gas were included in this assessment.

produce a relatively clean and valuable hydrocarbon that can partly offset the sequestration expenses. Thus, it is also called CO_2-ehanced coalbed methane (CO_2-ECBM) recovery. The economic feasibility of CO_2 sequestration into coal seams in some areas and formations has been investigated by several authors and it has been suggested that this option might be economically viable (Gentzis, 2000; Yamazaki et al., 2006; Robertson, 2009; Shimada and Yamaguchi, 2009).

Coalbeds contain a mixture of gases of which methane makes up 80%–99% and the remainder is composed of minor amount of CO_2, nitrogen (N_2), hydrogen sulphide, and sulphur dioxide (Flores, 1998). Coalbed methane (CBM) is now viewed as a promising gas resource in many regions (Yalcin and Durucan, 1991; Levy et al., 1997; Flores, 1998; Markowski, 1998; Narasimhan et al., 1998; Yao et al., 2009). As an example, coalbed gas production in the United States totalled nearly 54×10^9 m^3 (1.9 Tcf) in 2010, which provided about 8% of total natural gas production in the United States (EIA, 2012).

Coalbed gas is mainly stored as adsorbed gas on the surface of micropores in the matrix of coalbeds (Flores, 1998). Injection of CO_2 enhances the production of methane from the coal seam since CO_2 generally has higher adsorption capacity than methane and hence displaces the methane. Thus, the injection of CO_2 in coalbeds can enhance the production of CBM, as well as provide a safe solution for sequestration of CO_2 (ECBM). Additionally, many power plants are located near coal seams, and sequestering would reduce the transportation costs. The flue gas itself or a captured stream of concentrated CO_2 can be injected into a coal seam. Because the oxidant commonly used in coal-fired power plants is air, only about 10%–14% of the flue gas is CO_2; the majority of the remaining flue gas is N_2. Thus, in most cases, CO_2 will be captured from the flue gas and injected into the coal seams as concentrated CO_2 (Ozdemir, 2004).

The depth range of suitable coal seams for CO_2 sequestration purposes can be defined based on the economic feasibility of the coal mining and/or CBM production, which is a function of time, and the efficiency and safety of the storage. Gale (2004) stated that considering the CBM value only, the suitable depth window for CO_2-ECBM projects can be 300–1500 m. Bachu (2003) stated that the optimum depth for coalbed geosequestration is the depth at which the storage capacity is maximised while, at the same time, the cost of drilling and injection is minimised. Using this approach, Bachu (2003) suggested that the optimum storage depth window can be 800–1000 m for cold basins (where CO_2 density decreases with depth) and 1000–1500 m for warm basins (where CO_2 density increases with depth). Other researchers have suggested that the maximum storage depth may be up to several kilometres depending on characteristics and sealing efficiency of the basin (e.g. Li and Fang, 2014).

A number of pilot/demonstration projects of CO_2 injection into coalbeds have been undertaken in the United States, Europe and Asia since 1990's. Study results have been reported from these tests and interested readers are referred to these reports and reviews (Reeves, 2001; van Bergen et al., 2006; Yamaguchi et al., 2006; Wong et al., 2007; Botnen et al., 2009; Steadman et al., 2011; Sheng et al., 2015). The one common problem observed in these tests is the loss of gas injectivity due to swelling and permeability reduction around wellbore. For further information on the technology, storage capacity, and potential of methane recovery from coal seams, extensive review and reports can be found in the literature (e.g. Gale and Freund, 2001; White et al., 2005).

1.2.2. *Processes associated with coalbed geosequestration*

Numerous processes are associated with geological storage of CO_2 in coalbeds that need to be well understood. These processes can be classified in three types of behavioural categories: reservoir, adsorption and geomechanical behaviours (Fig. 2). Based on today's knowledge, when CO_2 is injected into deep coal seams, the gas flows through the cleats, a process that is usually described by Darcy's law, and diffuses into the microporous matrix where it is absorbed by the coal matrix, in which the major part of the stored gas resides (Parkash and Chakrabartty, 1986). The diffusion process that controls the CO_2 movement is usually described by Fick's law.

It should be noted that these behaviours interact with each other as the arrows indicate in Fig. 2. CO_2 injection changes the pore

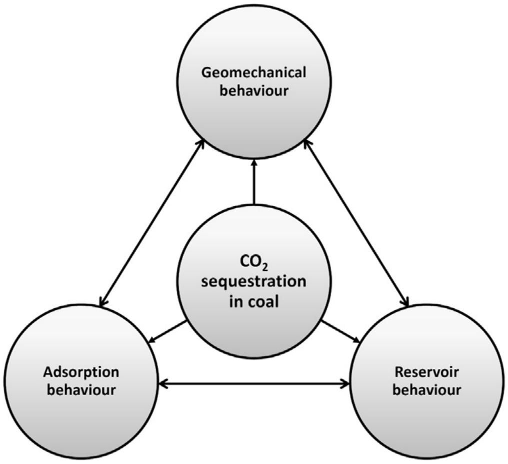

Fig. 2. Different aspects of CO_2 sequestration in coalbeds and their interactions.