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Review

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

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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

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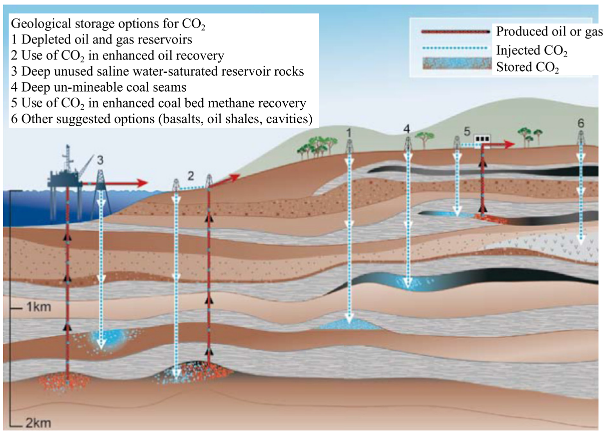

Fig. 1. Methods for storing CO_2 in deep underground geological formations. Two methods may be combined with the recovery of hydrocarbons: enhanced oil recovery (EOR) (option 2) and ECBM (option 5) (IPCC, 2005).

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

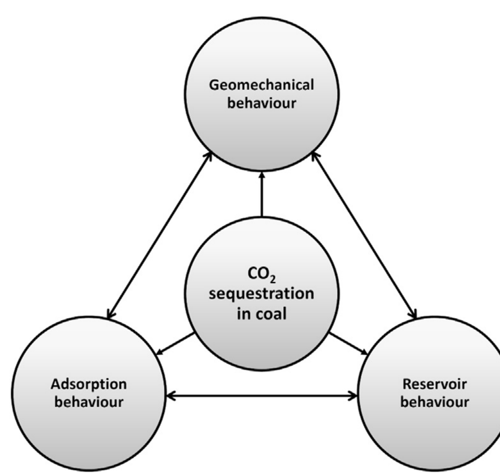

Fig. 2. Different aspects of CO_2 sequestration in coalbeds and their interactions.

pressure and consequently the stress state within the coal seam, which results in mechanical deformations in the reservoir and possibly the rock mass above it. The reservoir behaviour of coal seams can also influence the adsorption process since it determines the pressure distribution of gas within the reservoir, and since the amount of adsorbed gas is related to the pressure and temperature.

On the other hand, the mechanical behaviour can affect the other two aspects. The injection-induced mechanical deformations can change the aperture of the fractures and hence the permeability of the coal seam. Although the effects of stress on the diffusivity and adsorption have received little study, Hol et al. (2011) suggested that adsorption decreases with increasing effective stress. Nevertheless, it is known that the adsorption of CO_2 is accompanied by changes in volume of the coal matrix, i.e. coal swelling. Swelling influences the ease with which the fluid flows within the fractures, i.e. permeability. In addition to the effects of the adsorption of CO_2 and desorption of methane on matrix swelling, it has also been shown that there are accompanying reductions in stiffness and strength (Viete and Ranjith, 2006; Wang et al., 2013a; Masoudian et al., 2013a, 2014; Vishal et al., 2015).

This paper provides an overview of different processes associated with sequestration of CO_2 in coalbeds. Many publications have discussed the reservoir and adsorption behaviours of coalbeds and many papers have reviewed the findings related to them. However, very little studies have taken the geomechanical aspects into account or considered the importance of geomechanical processes in coalbed geosequestration. There exist some review papers discussing the multiphysics of coalbed sequestration and the coupling of different processes in reservoir modelling of coal (Liu et al., 2011; Shukla et al., 2010), but these discussions have neglected some important geomechanical aspects that may compromise the safety and viability of coalbed sequestration (e.g. Li et al., 2014; Fei et al., 2015). Thus, the three different processes depicted in Fig. 2 are discussed in this paper, while special attention is given to those geomechanical processes. The main purpose of this paper is to provide a unified platform for coupled analysis of coalbed sequestration from a geomechanical perspective. Another aim of this study is to highlight the significance of induced geomechanical processes and the role of geomechanical characteristics of coal seams. In order to achieve these, this paper succinctly discusses the petrology of coal and the adsorption behaviour of coal. Then, mechanisms of flow in coalbeds are discussed to provide a unified approach in reservoir modelling for researchers with geomechanical background. Then the geomechanical characteristics and processes in coalbeds are extensively discussed, while their interactions with reservoir and adsorption behaviours are highlighted. Then, the significance of induced geomechanical response of ground to CO_2 injection will be discussed both qualitatively and quantitatively. Finally, a series of research gaps has been identified to provide a map of research direction for the research efforts in this area.

2. Petrology of coal

Coal is an organic sedimentary rock that contains varying amounts of carbon, hydrogen, and other elements including mineral matter. In other words, coal is composed of a number of organic and inorganic substances: macerals and minerals, respectively. There are three basic groups of macerals. Vitrinite is usually the main maceral in coal and derived from coalified woody tissues and it is known to be always anisotropic (e.g. Bustin et al., 1986). The anisotropy of vitrinite increases with carbon content of coal (van Krevelen, 1993). Liptinite is derived from the resinous and waxy parts of the plants, and intertinite is derived from charred and biochemically altered materials of the plants (Sereshki, 2005; Pashin, 2008). The inorganic materials mostly appear as filling materials inside the fractures.

Coal can be considered as a polymer of a certain molecular weight (Ward and Suárez-Ruiz, 2008) with a structure composed of an accumulation of aromatic macro-molecular chains which are inter-linked to form a body of solid material. The molecular structure of coal depends on the origin and rank of a particular coal (Kabe et al., 2004), and a number of different models have been proposed (Nishioka, 1993). For carbon contents greater than 85%, many properties of coal can be related to the molecular size of the structural units. According to the ASTM classification, coal is classified into four classes: lignite, subbituminous, bituminous, and anthracite. In general, as coalification proceeds, coal rank increases in the order of lignite, subbituminous, bituminous, and anthracite (Kabe et al., 2004).

Coal is a porous material with a wide range of pore sizes, which includes many micropores resulting in a large internal surface area (Pashin, 2008). The range of pore sizes and their interconnectedness influence mechanical properties, gas storage and flow and have been of interest to researchers in coal science for many years (Alexeev et al., 1999; Hall et al., 2000). In general, coal has significant pore volume with porosities varying significantly with carbon content. The porosity is generally considered to comprise of nanopores or micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm) in which fluids can be stored and flow (Harris and Yust, 1976; Balek and de Koranyi, 1990; Radlinski et al., 2004; Sereshki, 2005; Pashin, 2008).

To date, many techniques and methods have been used to observe and measure the porosity of coal matrix, and this has resulted in an ongoing debate about the interconnectedness of the pores. Some assume that coal matrix has an interconnected network of pores (Harris and Yust, 1976; Harpalani and Zhao, 1991; Radovic et al., 1997; Pan et al., 2015), while others believe that pores are isolated from each other. An understanding of the molecular structure and the nature of the pores, which affect the mechanical response, and the gas flow and storage, is required in CO_2 sequestration and ECBM applications. Studies have shown that the transport properties of coal can be predicted by investigating the micro- and nano-structure of coal and therefore provide fundamental understanding on geological processes that may play roles in site selection and determining suitable coal seams for sequestration purposes (e.g. Yao et al., 2014; Liu et al., 2015; Pan et al., 2015). However, when considering the flow and mechanical behaviour, there does not appear to be any advantage from considering micropores and mesopores separately and hence the term micropores is used for all pores less than 50 nm. A major part of the stored gas resides in the micropores (Parkash and Chakrabartty, 1986). The nature of the porosity varies with carbon content and rank, with macropores (primary porosity) predominant in the lower carbon (lower rank) coals, whereas higher carbon (higher rank) coals contain predominantly micropores (Gan et al., 1972). The porosity of coal tends to decrease with carbon content until reaching a minimum at approximately 89% carbon content, and then increases with further carbon content increase (Speight, 2005).

A system of natural orthogonal fractures, also known as cleats, forms the vast majority of the macropore space in coal (Pashin, 2008). Cleat formation is controlled by intrinsic tensile forces, fluid pressures, and tectonic stresses (Gamson et al., 1993; Su et al., 2001). Most cleat surfaces are perpendicular to the bedding. The major set is variously termed the primary, main, face, or master cleats, and the minor set named the secondary, butt, back, cross, or bord cleats (Spears and Caswell, 1986). The secondary cleats end at intersections with through-going primary cleats and are believed to have formed later (Laubach et al., 1998). In some coals, a third cleat set is present which is commonly curvi-planar, very short in length and not aligned with either primary or secondary cleats (Gamson et al., 1993). Transport of gas through coal depends primarily on the spacing and aperture of the cleats (Laubach et al., 1998). Cleat spacing is usually sufficiently close (millimetres to centimetres) that numerous visible fractures are present in coal cores (Laubach et al., 1998). Cleat spacing tends to increase with increasing mineral content (Spears and Caswell, 1986), and decreases with porosity so that cleat spacing reduces with rank reaching a minimum for medium volatile bituminous coals, where porosity is a minimum, and then increases for higher carbon contents (Laubach et al., 1998). Cleat apertures range from hairline fractures narrower than one micron to major fractures wider than 20 mm (Pashin, 2008). Some minerals may fill the cleats and affect the permeability of coal (Pashin, 2008). These minerals in the cleats constitute a significant fraction of total mineral matter in the coal (Spears and Caswell, 1986).

3. Adsorption behaviour of coalbeds

Gas adsorption and desorption or simply sorption is a process in which gas molecules interact with a surface (Sereshki, 2005; Pashin, 2008). Molecules can attach themselves onto surfaces in two ways: physisorption and chemisorption. In physisorption, there is a reversible weak Van der Waals attraction of the adsorbate to the surface. Chemisorption is an irreversible process where gases are held on the surface of coal by chemical forces in contrast with physisorption (Ozdemir, 2004; Pashin, 2008). Physisorption can occur alone, but chemisorption is always accompanied by physisorption (Dollimore et al., 1976).

The mechanism of gas sorption in coal is still not completely understood (Melnichenko et al., 2009). However, it is usually described by one of three models: Langmuir, BET (Brunauer–Emmett–Teller) and Dubinin (Dutta et al., 2008). Amongst them, Langmuir is the simplest model where it is assumed that under constant pressure and temperature, there is a dynamic equilibrium between sorbed and non-sorbed phases and sorption is limited to a single layer (Langmuir, 1918). Langmuir's equation is given as

$$V = \frac{V_L P}{P_L + P} \quad (1)$$

where P is the equilibrium gas or vapour pressure, V is the volume of gas adsorbed, V_L is the Langmuir monolayer volume (maximum monolayer capacity), and P_L is the Langmuir pressure corresponding to $0.5V_L$. The BET model is an extension of the Langmuir model that accounts for the formation of multilayers (Ozdemir, 2004). The Dubinin theory likens the sorption to a mechanism of volume filling and two equations have been developed based on this theory: Dubinin–Radushkevich (D–R) and Dubinin–Astakhov (D–A) equations (Rand, 1976; Clarkson et al., 1997). In addition to these models, some other isotherm models have been proposed such as the semi-empirical models used by Bae and Bhatia (2006) (The Toth model) or the 2D-EOS model based on equation of state (EOS) of the gas mixture (e.g. Pan and Connell, 2009).

When sequestrating in deep coal seams, the in-situ pressure P and temperature T can be high enough so that CO_2 is in supercritical state ($T > 31$ °C and $P > 7.38$ MPa). In this case, care should be taken when choosing the model for sorption. Many studies have investigated the sorption of CO_2 and multi-component gas mixtures (containing CO_2) on coal under below-critical conditions (Laxminarayana and Crosdale, 1999; Busch et al., 2003a; Jodłowski et al., 2007; Saghafi et al., 2007; Prusty, 2008) and supercritical conditions (Busch et al., 2003b, 2006; Yu et al., 2008) using the Langmuir model. The application of the BET equation to supercritical fluid sorption cannot be justified physically as multilayer formation is considered unlikely (Clarkson et al., 1997). Studies have shown that both Langmuir and Dubinin (D–A and D–R) models may not fit the experimental data, especially under supercritical conditions, underestimating the supercritical CO_2 sorption capacity of coal by around 30% (Sakurovs et al., 2007). However, Sakurovs et al. (2007) introduced modified D–R and Langmuir equations (Henry Hybrid) that showed a good fit with the supercritical CO_2 adsorption data. As discussed, a wide range of isotherm models have been developed for gas adsorption on coal but what seems necessary for geotechnical engineers and geomechanics researchers is to focus on the balance of accuracy of sorption and implementation in reservoir simulators.

The adsorption capacity of coal and the stability of the adsorbed CO_2 can be affected by a number of factors, including those related to coal composition, i.e. rank and moisture content of the coal, and those related to the environmental variables, i.e. temperature, pressure, change in pH value. These factors have been investigated for a long time and comprehensive information is available in the literature. A summary of parameters affecting gas adsorption capacity of coal is provided in Table 2. However, one should bear in mind that many of the compositional parameters are inter-related (e.g. rank and carbon content, porosity) and it may not be possible to investigate the effect of each parameter without interference by the others.

There are a significant number of studies concerning the parameters influencing the sorption capacity of coal seam under different compositional and environmental factors as reported in this table. The discussion in this paper is to only provide first-hand understanding of adsorption mechanisms and contributing factors to the geotechnical engineers and rock mechanics specialist. More rigorous and comprehensive reviews are readily available in the literature, providing in-depth discussions on gas sorption in coal (Dutta et al., 2008; Mazzotti et al., 2009; Busch and Gensterblum, 2011; Wang et al., 2011).

4. Gas flow in coalbeds

4.1. Gas flow mechanisms

When CO_2 is injected into a coal seam, the gas flows inside the fractures where the flow is assumed to be laminar and viscous, then it moves inside the coal matrix blocks where it is adsorbed on the internal surface area of the microporous space within the matrix blocks (see Fig. 3). Thus, there are at least two distinct scales for fluid flow: a fracture-scale flow that considers the flow of fluid in cleats, and a matrix-scale that considers the flow of gas inside the coal matrix blocks. The viscous and diffusive mechanisms of gas flow in coal seams are explained below. Although there may be some other mechanisms associated with the flow and transport of gas in coal seams (Klinkenberg effect, Forchheimer effect, etc.) (Webb, 2006; Wei and Zhang, 2010), they are not discussed in this paper due to insufficient evidences on their significance in coalbed geosequestration.

4.1.1. Gas flow in cleats/fractures

It is generally assumed that flow of gas through cleats is a laminar viscous flow. The viscous flow is usually described by Darcy's law. Darcy's law states that velocity of gas, u, is directly proportional to the pressure gradient, ∇P, and the gas-phase permeability, k, as illustrated below:

Table 2
A summary of parameters affecting the gas adsorption capacity of coal.

Studied parameter		Relationship with sorption capacity	Reference(s)
Coal composition factors	Maceral type	Vitrinite-rich coals have higher sorption capacity, generally a little influence	Ceglarska-Stefańska and Brzóska, 1998; Laxminarayana and Crosdale, 1999
	Carbon content	U-shape trend with minimum at around 85%–90% total carbon	Day et al., 2008a
	Ash content	The higher the ash content, the less the adsorption capacity	Laxminarayana and Crosdale, 1999; Katyal et al., 2007
	Coal rank	U-shape trend with minimum in medium to low volatile bituminous coal	Laxminarayana and Crosdale, 1999; Siemons and Busch, 2007; Day et al., 2008a; Zhang, 2008; Wang et al., 2015; Weishauptová et al., 2015
	Porosity	The higher the porosity, the higher the adsorption capacity	Day et al., 2008a; Prusty, 2008
Environmental factors	Temperature	The higher the temperature, the lower the adsorption capacity	Yang and Saunders, 1985; Azmi et al., 2006; Zhang, 2008
	Pressure	The higher the pressure, the higher the adsorption capacity	Daines, 1968; Yang and Saunders, 1985; Krooss et al., 2002; Busch et al., 2003a; Day et al., 2008c; Pone et al., 2009b
	Moisture content	Sorption capacity decreases as moisture content increases to a critical value (40%–80% of relative humidity). Further increases in moisture content after the critical value do not change the sorption capacity	Day et al., 2008c; Joubert et al., 1973, 1974; Krooss et al., 2002; Siemons and Busch, 2007; Weishauptová et al., 2015
	Gas composition	Higher adsorption selectivity of CO_2 is generally accepted. However, this selectivity is dependent on other parameters such as temperature, pressure and moisture content, and sometimes higher selectivity of methane occurs	Clarkson and Bustin, 2000; Krooss et al., 2002; Busch et al., 2006; Brochard et al., 2012
	pH value	The less the pH value (acidic), the higher the adsorption capacity	Schroeder et al., 2001; Azmi et al., 2006
	Effective stress	The adsorption capacity reduces with increasing effective stress	Hol et al., 2011, 2012a

$$u = -\frac{k}{\mu}(\nabla P - \rho g \nabla z) \tag{2}$$

where μ is the gas viscosity, ρ is the density of gas, and g is the gravity acceleration. It should be noted that this velocity is not the true velocity of the gas in pores, v, but $v = u/\phi_f$ (Webb, 2006), where ϕ_f is the fracture porosity. The mass balance equation can be presented as (Aziz and Settari, 1979):

$$\frac{\partial(\phi\rho)}{\partial t} = -\nabla\cdot(\rho u) + Q \tag{3}$$

where Q is a sink/source term. This form of flow equation considers the compressibility of the gas which can be described by an equation of state (i.e. $\rho = f(P, T)$) such as Peng–Robinson used by Henderson et al. (2005). They also considered the relationship among gas viscosity, pressure, and temperature using an empirical equation. It should be noted that supercritical gas, immediately above the critical point, is still compressible and therefore, the compressibility must be considered in this situation. Many models developed so far neglect this fact and assume the supercritical gas is an incompressible or slightly compressible fluid (e.g. Connell and Detournay, 2009; Masoudian et al., 2013b).

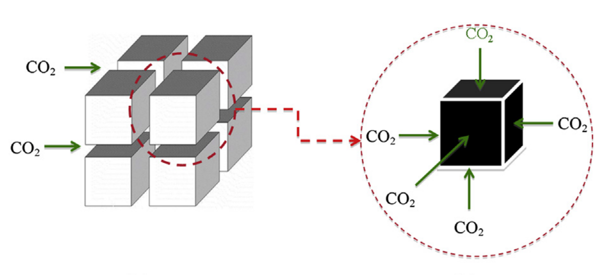

Fig. 3. Gas injection into a dual porous medium: CO_2 flows inside the fractures (a) and it diffuses into matrix blocks and is adsorbed on the internal surface area (b).

4.1.2. Gas flow in matrix blocks

Diffusion is the process of fluid movement in microporous matrix blocks of rocks due to the concentration gradient. There are different kinds of gas diffusion mechanisms occurring in porous media but it is generally assumed that continuum diffusion is the dominant mechanism in CBM recovery (Cui et al., 2004). Diffusion processes in porous media are conventionally described by Fick's first and second laws: first for steady and second for unsteady flux. The Fick's first law has been extended to multicomponent gas and it is called the Maxwell–Stefan formulation. The Fick's first law can be written as

$$q_d = -D^e \nabla c \tag{4}$$

where q_d is the diffusive flux, D^e is the effective diffusion coefficient, and ∇c is the concentration gradient. The Fick's second law is the same but with the second derivative of concentration which reflects the unsteady diffusion (Kokes and Long, 1953):

$$q_d = -D^e \nabla^2 c \tag{5}$$

The Fick's second law is more important when short-term estimations are needed, while the Fick's first law is favourable for long-term modelling or experiments in which the steady diffusive flow is maintained. However, some recent studies have tried to use other equations for diffusion of gas in coal. For example, Wang et al. (2009) used Smoluchowski equation to describe the gas diffusion in carbon nano-tubes for the ECBM application, but due to insufficient experimental evidences, it will not be discussed here.

4.2. Reservoir properties of coalbeds

4.2.1. Permeability

The permeability of coal seams has been investigated by a number of authors and a wide range of values has been published. The permeability in mining applications is usually in the range of 0.1 mD to 100 mD (9.87×10^{-14} m^2 to 9.87×10^{-11} m^2) (Sereshki, 2005). For sequestration, low values can be expected because the target coal seams are significantly deeper, and the elevated stress levels will cause smaller cleat apertures. For example, Pinetown et al. (2008) reported that permeability of coal in the Sydney Basin varied from 0.1 mD to 50 mD, decreasing for deeper seams so that permeability was commonly less than 1 mD below 400 m in depth. Also, due to the anisotropic nature of coal and the different continuities and apertures of face and butt cleats, horizontal permeability (parallel to bedding) is typically in an order of magnitude larger than the vertical permeability (Gash et al., 1993).

Permeability is influenced by the intrinsic properties of coal. Several studies (Smyth and Buckley, 1993; Clarkson and Bustin, 1997; Robertson and Christiansen, 2005) have shown that permeability is affected by coal rank in a similar manner to porosity, reaching a minimum for medium volatile bituminous coals and increasing for higher and lower rank coals. However, an exception is lignite which can have very low permeability despite a relatively high porosity due to the lack of a well-developed and interconnected cleat system (Botnen et al., 2009). Although there have been studies that considered the effect of coal matrix permeability in reservoir modelling (e.g. Thararoop et al., 2012), there are only a few studies that have analysed this parameter of coal matrix (e.g. Gensterblum et al., 2014). The permeability of the intact coal matrix blocks is reported to be considered very small (e.g. 0.04–0.7 mD (Flores, 2004) and 1×10^{-5} mD (Thararoop et al., 2012)).

4.2.2. Diffusivity

The value of effective diffusion coefficient depends on the coal rank and type, gas type, porous network, and environmental conditions (pressure and temperature). For many coals, the effective diffusivity of methane ranges from 2.9×10^{-11} m^2/s to 3.7×10^{-9} m^2/s (Olague and Smith, 1989). The diffusivity of CO_2 is usually higher than that of methane by a factor of 2–3 for dry coal and 5–6 for moist coal (Busch et al., 2004). It has been suggested that the relative difference between diffusion of methane and CO_2 is due to the different behaviours of CO_2 and methane (Charrière et al., 2010), and the role of gas molecule size and pore space structure (Cui et al., 2004). Larsen (2004) stated that CO_2 has a more favourable interaction enthalpy than hydrocarbons (such as methane) which results in faster diffusion into coal.

Environmental conditions can also affect the rate of diffusion. For example, increase in moisture content decreases the diffusivity of both methane and CO_2 (Clarkson and Bustin, 1999) because water molecules can block the pathways of gas molecules inside the coal matrix. Increasing temperature has a positive effect on the rate of diffusion (e.g. Krooss et al., 2002; Busch et al., 2004; Charrière et al., 2010) due to the fact that at higher temperature, gas molecules have higher energy and tend to move faster. Moreover, Cui et al. (2004) reported that increase in gas pressure continuously decreases the apparent diffusion coefficient; however, the influence of pressure on the effective diffusivity is not well established.

4.3. Multi-scale flow modelling

According to Wei et al. (2005), there are three types of CBM reservoir models that may be used for coal seam gas and CO_2 sequestration in coalbeds. The most primitive type is the conventional black oil and compositional model in which diffusion is assumed to be instantaneous and thus cannot fully describe the gas flow processes in coal seams (Wei et al., 2005). The second type is the most widely used for CBM simulations in which a non-equilibrium diffusion process is modelled with a dual porosity system comprised of fractures and microporous matrix blocks. The third type of CBM simulator includes improved CBM/ECBM models such as the bidisperse pore diffusion model, and the triple porosity model. These latter types of models consider a more complicated porous network for the matrix blocks (Wei et al., 2005) or more accurate approaches to estimate the diffusive flux. It was explained earlier that gas-phase flow in porous media consists of viscous and diffusive components and that coal is a naturally fractured medium, usually characterised by a dual porosity system composed of matrix blocks and fractures. Despite the fractured nature of the coal, it is usually assumed that each of fracture-scale and matrix-scale flows is continuous, i.e. a multicontinuum system (Rutqvist et al., 2002). These scales are coupled to each other through a sink/source term that represents the mass transfer between macro- and micro-scales, also known as the matrix-fracture transfer function. This section briefly discusses the fundamentals of the fracture flow and two distinct models for the matrix-fracture transfer function.

4.3.1. Fracture-scale modelling

To model single-phase flow of a gas within the fractures/cleats, the Darcy's equation (Eq. (2)) is substituted in the mass balance equation (Eq. (3)), which leads to the following equation:

$$\frac{\partial\left(\phi_{\mathrm{f}}\rho\right)}{\partial t} - \nabla\cdot\left[\rho\frac{k}{\mu}(\nabla P - \rho g\nabla z)\right] = Q \tag{6}$$

where ∇ denotes the gradient operator in fracture continuum (macro-scale) whose spatial derivatives are performed with respect to spatial coordinates in the fracture continuum $\boldsymbol{X}_{\mathrm{f}} = \{x_{\mathrm{f}}, y_{\mathrm{f}}, z_{\mathrm{f}}\}$.

However, in reality there usually exist more than one phase and more than one gas species in coal seams. The underground coalbeds usually contain both water and gas before CO_2 injection and hence a two-phase (gas and water) and multicomponent model is usually required to model the flow of gas within coalbeds. For such two-phase, multicomponent (N_{g} gas species) fluid system, the macro-scale flow equation can be rewritten below (Lu and Connell, 2010):

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\phi_{\mathrm{f}}S_{\mathrm{w}}\rho_{\mathrm{w}}\omega_{\mathrm{w}i} + \phi_{\mathrm{f}}S_{\mathrm{g}}\rho_{\mathrm{g}}\omega_{\mathrm{g}i}\right) - \nabla\cdot\left[\rho_{\mathrm{w}}\frac{k\kappa_{\mathrm{rw}}}{\mu_{\mathrm{w}}}(\nabla P_{\mathrm{w}} - \rho_{\mathrm{w}}g\nabla z)\right.\\&\left.+\rho_{\mathrm{g}}\frac{k\kappa_{\mathrm{rg}}}{\mu_{\mathrm{g}}}\left(\nabla P_{\mathrm{g}} - \rho_{\mathrm{g}}g\nabla z\right)\right] = Q_i\end{aligned} \tag{7}$$

where S represents the saturation; κ_{rw} and κ_{rg} are the relative permeabilities of water and gas, respectively; $\omega_{\mathrm{w}i}$ and $\omega_{\mathrm{g}i}$ are the mass fractions of the i-th component in the water and gas phases, respectively. Note that here the subscripts "w" and "g" represent water and gas phases with water indexed by $i = N_{\mathrm{g}}+1$ and gas species are indexed by the rest $i = 1, 2, \ldots, N_{\mathrm{g}}$. In order to solve this set of equations, some supplementary equations are needed including capillary pressure equation to relate water and gas partial pressures to each other, and the relative permeability equations (e.g. van Genuchten, 1980). Eq. (7) is usually solved using numerical methods such as finite difference, finite volume, and finite element methods (Liu and Smirnov, 2008; Ozdemir, 2009), but discussion on numerical schemes is beyond the scope of this paper.

In order to take into account the effect of fracture deformation on the pressurisation of fluid within the fractures, one can follow Detournay and Cheng (1993) which leads to a term on the right side of the flow equations as follows:

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\phi_{\mathrm{f}}S_{\mathrm{w}}\rho_{\mathrm{w}}\omega_{\mathrm{w}i} + \phi_{\mathrm{f}}S_{\mathrm{g}}\rho_{\mathrm{g}}\omega_{\mathrm{g}i}\right) - \nabla\cdot\left[\rho_{\mathrm{w}}\frac{k\kappa_{\mathrm{rw}}}{\mu_{\mathrm{w}}}(\nabla P_{\mathrm{w}} - \rho_{\mathrm{w}}g\nabla z)\right.\\&\left.+\rho_{\mathrm{g}}\frac{k\kappa_{\mathrm{rg}}}{\mu_{\mathrm{g}}}\left(\nabla P_{\mathrm{g}} - \rho_{\mathrm{g}}g\nabla z\right)\right] = Q_i - \left(\phi_{\mathrm{f}}S_{\mathrm{w}}\rho_{\mathrm{w}}\omega_{\mathrm{w}i} + \phi_{\mathrm{f}}S_{\mathrm{g}}\rho_{\mathrm{g}}\omega_{\mathrm{g}i}\right)\frac{\partial\varepsilon_{\mathrm{v}}}{\partial t}\end{aligned} \tag{8}$$

where ε_{v} is the total volumetric strain, which is a function of time and fracture-scale coordinates. The added term couples the flow equation in fracture-scale to the mechanical deformation of reservoir. The mechanical deformation mechanisms and their formulations will be discussed later in this paper.

4.3.2. Matrix-scale modelling

As stated earlier, Q in Eqs. (6) and (7) is a sink/source term which can relate the fracture-scale flow to the matrix-scale flow. The term Q is the mass rate of gas diffusing into and/or out of matrix blocks and is known as the matrix-fracture transfer function. Note that Q is a function of time and macro-scale coordinates:

$$Q\left(X_{\mathrm{f}},t\right) = -\frac{\partial q_{\mathrm{ave}}\left(X_{\mathrm{f}},t\right)}{\partial t} \tag{9}$$

where q_{ave} is the mean value of the gas concentration inside the coal matrix and is determined by integration over the volume of the matrix block:

$$q_{\mathrm{ave}}\left(X_{\mathrm{f}},t\right) = \frac{1}{V_{\mathrm{m}}}\int_{V_{\mathrm{m}}} q\left(t,X_{\mathrm{m}},X_{\mathrm{f}}\right)\mathrm{d}V \tag{10}$$

where V_{m} is the volume of matrix block; and q is the gas concentration which is a function of time, t, global fracture coordinate, X_{f}, and local matrix coordinate, X_{m}. According to this equation, in order to find the matrix-fracture transfer function, we need to first find the concentration distribution in the coal matrix, q. The concentration inside the matrix blocks can be determined using the Fick's second law, which is re-written below:

$$\frac{\partial}{\partial t}q\left(t,X_{\mathrm{m}},X_{\mathrm{f}}\right) = D^{\mathrm{e}}\nabla^2 q\left(t,X_{\mathrm{m}},X_{\mathrm{f}}\right) \tag{11}$$

In many applications, this equation and the gas flow equation can be simultaneously solved using a numerical method. However, in reservoir engineering, because of the large scale of the dimensions, this is not computationally feasible. Therefore, an analytical or a semi-analytical solution must be used to solve the equation of diffusion while the gas flow equation is solved numerically. There are different approaches to find the analytical approximation for the diffusion equation, of which two techniques are explained below.

(1) Quasi-steady approach

The most widely used and simplified approach to approximate the matrix-fracture transfer function is to consider a quasi-steady state approach (Warren and Root, 1963) in which no attempt is made to solve the diffusion equation within each block. The main disadvantage of this method is the inaccuracy of the short-term predictions which can also influence the long-term results significantly. In this approach, Q is assumed to be directly proportional to the difference between the gas concentration in the fracture and the matrix block. The quasi-steady matrix-fracture transfer function for gas species of a multicomponent mixture is given below:

$$Q_i\left(X_{\mathrm{f}},t\right) = \pi^2 D_i^{\mathrm{e}}\left(\frac{1}{l_x^2}+\frac{1}{l_y^2}+\frac{1}{l_z^2}\right)\left[q_{\mathrm{avg}\,i}\left(X_{\mathrm{f}},t\right)-q_i^{\mathrm{s}}\left(X_{\mathrm{f}},t\right)\right] \tag{12}$$

where l_x, l_y and l_z are the length of rectangular parallelepiped matrix blocks (cleat spacing) in x, y, and z directions, respectively; and q^{s} expresses the concentration of the gas on the walls of the fractures. This concentration is the boundary condition for the diffusion equation, which also shows the maximum or the minimum concentration that the gas can have inside the matrix blocks at a specific time. The value of q^{s} can be determined by using an adsorption isotherm (e.g. Langmuir's equation).

(2) Transient approach

To improve the short-term predictions, a solution for the transient diffusion of gas into coal matrix blocks is required. Lu and Connell (2007) solved the Fick's second law for which the concentration in the fractures provides a boundary condition. The solution for rectangular matrix blocks is given below (Lu and Connell, 2010, 2011):

$$Q\left(t,X_{\mathrm{f}}\right) = -\frac{8}{\pi^2}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\sum_{p=1}^{\infty}\frac{H_S^2(m,n,p)[D^{\mathrm{e}}]}{(m\,np)^2}\left(\frac{m^2}{l_x^2}+\frac{n^2}{l_y^2}+\frac{p^2}{l_z^2}\right)\cdot \int_0^t \mathrm{e}^{-[D^{\mathrm{e}}]\left(m^2/l_x^2+n^2/l_y^2+p^2/l_z^2\right)(t-\tau)}\frac{\partial}{\partial\tau}\left[q^{\mathrm{s}}\left(\tau,X_{\mathrm{f}}\right)\right]\mathrm{d}\tau \tag{13}$$

where $[D^{\mathrm{e}}]$ is the matrix of diffusion coefficients with $N_{\mathrm{g}}\times N_{\mathrm{g}}$ dimensions, and H_{s} is defined as

$$H_{\mathrm{s}}(m,n,p) = [1-\cos(m\pi)][1-\cos(n\pi)][1-\cos(p\pi)] \tag{14}$$

The main advantage of this model over the quasi-steady state model is the accuracy of the predictions in the short term. This can have a significant improvement on the reservoir simulation results as explained by Lu and Connell (2007) and Connell and Lu (2007). However, this method is computationally expensive and requires significant computational developments to successfully implement it in the numerical model as explained by Connell and Lu (2007) and Masoudian et al. (2013b).

4.3.3. Other modelling approaches

Many attempts were dedicated to improve the modelling of gas flow within coal seams mostly by developing models that represent the matrix-scale flow better, e.g. bidisperse pore diffusion models (Shi and Durucan, 2003), triple porosity models. The bidisperse models take into account the three porosity scales within the matrix (macropores, mesopores, and micropores) and consider different diffusion mechanisms in them: surface diffusion in the micropores and pore diffusion in the mesopores and macropores (e.g. Shi and Durucan, 2003). However, it has been discussed that one of the main issues with these models is the need for a comprehensive knowledge and models of the porous structure of coal matrix (see Wei et al., 2005). In addition, some other models can be found in the literature in which the interaction of different gas species on matrix diffusion (counter-diffusion) is considered. Some other models have considered that gas diffusivity can be dependent on the concentration or even pressure. A review of these models can be found in the literature (e.g. Wei et al., 2005).

Another approach that can improve the modelling of gas flow in coal seams is the way that the fracture-scale and matrix-scale fluxes are combined. For most viscous-diffusive flow studies, gas fluxes due to viscous flow and diffusion are calculated separately and then simply added together, and this approach has been widely used in the area of ECBM and geosequestration. This approach is easy and needs a low level of computational effort and is therefore more favourable. However, some studies have shown that such an approach in some porous media may lead to inaccuracy (an example is given in Webb (2006)) and have recommended the use of the dusty gas model (DGM) which is the most widely used mechanistic model to combine gas viscous and diffusive flows in porous media at the present time. DGM includes the effect of porous media as a dusty gas component of the gas mixture whose velocity is zero compared to the gas molecules (Webb, 2006).

5. Geomechanical behaviour of coalbeds

5.1. Mechanical deformations in coalbeds during geosequestration

It is well known that coal swells in the presence of CO_2 (e.g. Reucroft and Patel, 1986; Stacy and Jones, 1986; Walker et al., 1988). In addition to the sorption-induced strain, gas injection or production can lead to mechanical deformations of coalbeds due to the change in the stress state within the reservoir. Following the convention in geomechanics, the strain can be decomposed into an elastic (reversible) part, ε^{e}, and a plastic (irreversible) part, ε^{p}. When chemical/sorption-induced strains are involved, the elastic part itself is decomposed into mechanical $\varepsilon^{e,m}$ and chemical/sorption induced parts, $\varepsilon^{e,s}$, namely:

$$\varepsilon = \varepsilon^{e} + \varepsilon^{p} = \varepsilon^{e,m} + \varepsilon^{e,s} + \varepsilon^{p,m} \tag{15}$$

These three different types of deformations can then be estimated individually using analytical or numerical methods. In addition, rock may fail depending on the stress distribution within the reservoir. The principles of these concepts are explained below.

5.1.1. Sorption-induced swelling of coal

Many years ago, Marzec and Kisielow (1983) related the swelling to the osmotic pressure created by the higher concentration of coal molecules in the solutions inside the pores compared to the outside. They described that some pores have narrow entrances that do not allow coal molecules across while allowing smaller solvent molecules move frequently throughout the pore space. They suggested that this osmotic pressure supplies enough force to loosen the original packing of coal matter. However, later studies have suggested an alternative mechanism which is based on the polymeric nature of the coal structure. It has been shown that coal behaves as a glassy polymer at room temperature (Lucht et al., 1987; Green et al., 1991). In other words, the intermolecular interactions are greater than the available thermal energy (absorbed from environment) and therefore, the molecular structure of coal is "frozen" in place. The glassy state of a polymer is characterised by its glass transition temperature (for coal T_g = 580–623 K), the temperature at which a polymer changes from a glass to a rubber (Lucht et al., 1987). At this temperature, the thermal energy becomes greater than the intermolecular interactions and the molecular structure is "thawed" so that larger molecular motions are possible. However, the material retains its shape because the molecules are cross-linked. When gases and vapours (e.g. CO_2) are in contact with coal, it increases the coal's ability to rearrange to a new structure with a lower energy state and therefore the glass transition temperature decreases (Larsen, 2004). This transition from a glassy solid state to a rubbery state seems to be an appropriate explanation for the swelling process.

The earliest studies on the swelling of coal in the presence of CO_2 were dilatometric experiments on pencil-shaped samples (Reucroft and Patel, 1986; Walker et al., 1988). These studies reported that the increase in volume of samples ranged from 0.36% at low pressures to 1.9% at high pressure (up to 5 MPa). More recent studies have all used optical methods, such as scanning electron microscope (SEM) and X-ray, to measure the swelling of coal (Karacan, 2007; Day et al., 2008b; Pone et al., 2009a; van Bergen et al., 2009). For example, Day et al. (2008b) reported the maximum swelling of 1.7%–1.9% under high pressure and high temperature conditions.

It is expected that swelling is a function of the gas volume adsorbed onto the coal. Hence, the factors that affect the adsorption will affect the swelling as well. Day et al. (2008b) performed a comprehensive study on swelling of coal due to CO_2 adsorption and observed that swelling increased as a function of CO_2 pressure up to 8–10 MPa while further pressure did not increase the swelling. They showed that swelling was roughly proportional to the amount of adsorbed CO_2 under different temperatures. Studies showed that moisture reduces the amount of swelling (van Bergen et al., 2009). This is in agreement with the effect of moisture content on the adsorption capacity. Moreover, the mechanical properties of coal can also affect the extent of swelling. Durucan et al. (2009) reported that coals with higher Young's modulus yielded lower value of swelling. Also, swelling in the plane perpendicular to the bedding plane is always higher than that in the parallel direction (Day et al., 2008b). This can be related to the anisotropic nature of the vitrinite.

Many mathematical models have been used for volume change due to gas adsorption. These models are based on adsorption models such as Langmuir (Robertson and Christiansen, 2005; Pan and Connell, 2007; Mazumder and Wolf, 2008) and Dubinin (Day et al., 2008b). The Langmuir like equation for adsorption-induced swelling is given below:

$$\varepsilon_{v}^{s} = \frac{\varepsilon_{max}^{s} P}{P_{\varepsilon} + P} \tag{16}$$

where ε_{max}^{s} is the maximum volumetric swelling strain and P_{ε} is the Langmuir pressure for the Langmuir type swelling isotherm. It has also been repeatedly reported in the literature that the adsorption-induced swelling is fully reversible (e.g. Battistutta et al., 2010; van Bergen et al., 2011). In addition, it has been observed that swelling displays strong anisotropy for some coals with a larger swelling perpendicular to the bedding (e.g. Levine, 1996; Day et al., 2010).

It should be noted that when swelling coal is confined, the increase in volume of the coal matrix will decrease the cleat porosity of coal. The reduction in cleat porosity decreases the permeability. The reduction of permeability as a result of CO_2 injection has been observed in demonstration projects (Reeves et al., 2003; Wong et al., 2007). Further discussion on the permeability change will be presented later.

5.1.2. Elastic deformations

As Detournay and Cheng (1993) explained, two mechanisms play key roles in the elastic interaction between the fluid and the porous rocks. One mechanism is the pressurisation of the fluid as a result of compression of the rock and the other mechanism is the dilation of the rock as a result of an increase in pore pressure. The first mechanism is implemented in the gas flow equation in Eq. (8), where the effect of volumetric strain on the flow behaviour is taken into account. The second mechanism should be included in the mechanical deformation formulations.

It should be also noted that the mechanical strain of the soil and rock skeleton is induced by the effective stress defined as follows (Biot, 1941):

$$\sigma'_{ij} = \sigma_{ij} - \alpha P \tag{17}$$

where α is the Biot's effective stress coefficient, which denotes the influence of pore pressure on the solid matrix of porous media, and it is equal to 1.0 for soft sediments while it may be less than 1.0 for cemented soils and rocks.

The elastic stress–strain relationship is usually written as

$$\sigma'_{ij} = C_{ijkl}\varepsilon_{kl}^{e} \tag{18}$$

where C_{ijkl} is the elastic stiffness tensor (fourth rank tensor). Using the effective stress definition, the linear elastic constitutive equations can be defined as

$$E\varepsilon_{ij} = \sigma_{ij} - \nu\sigma_{kk}\delta_{ij} - (1-2\nu)\alpha P\delta_{ij} \tag{19}$$

where E is the elastic modulus, ν is the Poisson's ratio, and δ_{ij} is the Kronecker's delta (equals one when $i = j$, otherwise zero).

5.1.3. Failure and plasticity

In geomechanics, yield or failure is referred to the onset of inelastic behaviour (Davis and Selvadurai, 2002). Many failure criteria have been proposed over the years. The most widely used failure criterion is the Mohr–Coulomb one which is defined as below:

$$\tau = c' + \sigma'_{\rm n} \tan \varphi' \tag{20}$$

where τ and $\sigma'_{\rm n}$ are the shear and effective normal stresses with respect to failure plane, respectively; φ' is the effective angle of internal friction; and c' is the effective cohesion. The Mohr–Coulomb failure criterion can be described in terms of principal stress as follows (Davis and Selvadurai, 2002):

$$\sigma'_1 = \left(\frac{1+\sin\varphi'}{1-\sin\varphi'}\right)\sigma'_3 + \left(\frac{\cos\varphi'}{1-\sin\varphi'}\right)2c' \tag{21}$$

Another yield criterion is Hoek–Brown failure criterion, which is believed to be suitable for failure of coal (Gentzis et al., 2007). Hoek–Brown failure criterion is an empirical relationship between major and minor principal stresses as

$$\sigma'_1 = \sigma'_3 + \sigma_{\rm ci}\left(m\frac{\sigma'_3}{\sigma_{\rm ci}} + s\right)^a \tag{22}$$

where m, s and a are Hoek–Brown parameters and $\sigma_{\rm ci}$ is the uniaxial compressive strength of intact rock. It should be noted that the Hoek–Brown failure criterion has some advantages over the Mohr–Coulomb one when used for coal, which is the nonlinear normal-shear stress curve and has adaptability to include fractures.

It is usually assumed that the plastic deformation occurs once the failure takes place. In the plasticity theory in geomechanics, the plastic strain of rocks is generally defined by a flow rule which relates the plastic strain increment, $\dot{\varepsilon}^{\rm p}$, to the yield function, f, as follows (Davis and Selvadurai, 2002):

$$\dot{\varepsilon}^{\rm p} = \lambda_{\rm f}\frac{\partial f}{\partial \sigma} \tag{23}$$

where $\lambda_{\rm f}$ is the plastic multiplier, and f generally denotes the yield condition as a general function of components of stress matrix, such as Mohr–Coulomb and Hoek–Brown criteria. The plastic deformations can then be calculated with the help of the post-failure behaviour of the rock, e.g. strain softening and work hardening. The plastic deformations within the coalbeds are believed to play an important role in assessing the stress and strain around CO_2 injection or methane production wells (see Gentzis, 2009; Zhang et al., 2015).

5.1.4. Other geomechanical processes

In addition to the geomechanical response of coalbeds described above, there are other phenomena associated with fluid injection activities which can be related to the geomechanical behaviour of formations surrounding the coalbeds. As an example, fault reactivations induced seismic activities, and ground surface movements are known to be associated with fluid injection activities in oil and gas projects. These phenomena can greatly influence the feasibility of CO_2 storage projects but they have not been well investigated in coalbed geosequestration studies. The theory of these induced geomechanical processes will not be discussed in this paper although it should be noted that they can generally be described using elastic and plastic deformations and failure criteria explained above.

5.2. Geomechanical properties of coalbeds

5.2.1. Elastic modulus

Stiffness of coal varies with rank and carbon content, and the direction of loading relative to the bedding planes. Szwilski (1985) reported the elastic modulus of coals with different carbon contents and found that in general, larger carbon content results in higher elastic modulus although coals with carbon contents between 80% and 90% showed a decrease in elastic modulus with increasing carbon content.

When conducting mechanical tests on rock samples, the size of the specimen is important in the measured value of elastic modulus. It is generally believed that rock samples with larger diameters are more likely to contain more fractures and discontinuities which result in lower measured values of elastic modulus. Medhurst and Brown (1998) tested core samples with different diameters from 50 mm to 300 mm and their results showed that the elastic modulus of coal is lower in larger samples.

In addition, the direction in which the load is applied can influence the observed value of elastic modulus. Szwilski (1984) reported that the maximum value of elastic modulus can be measured when the load is applied in the direction perpendicular to minor cleats while its minimum can be measured when the load is applied perpendicular to the bedding plane. This anisotropic behaviour can be due to the difference between the apertures of different sets of fractures: narrower cleats have lower compressibility which results in larger elastic modulus measured perpendicular to its plane.

In addition to the coal's nature, environmental factors can affect the measured elastic modulus. Temperature can change the elastic modulus of coal but their relationship depends on the rank and carbon content of coal. It is known that as coal is heated the elastic modulus slightly decreases up to a temperature around 350 °C–375 °C, and as the temperature increases further the elastic modulus drops significantly. On the other hand, cooling this heated coal leads to a stronger and stiffer sample than the original coal (Krzesińska et al., 2006).

Another environmental factor is the confining stress that can affect the measured value of elastic modulus of rocks as studied by Brown et al. (1989). The influence of confining stress on elastic modulus of coal samples (3.75 cm in diameter) has also been investigated and the same effect has been observed by Gentzis et al. (2007). This can be explained by gradual closure of pores and fractures as the confining stress increases (Corkum and Martin, 2007). It can be seen that elastic modulus increases as the confining stress increases up to 5 MPa after which the modulus is practically constant. Also, results presented by Szwilski (1984) showed that confining pressure significantly increases the degree of anisotropy of elastic modulus which is believed to be mainly due to the frequency and orientation of microcracks created in the coal matrix during loading.

5.2.2. Mechanical strength

Mechanical strength of rocks is defined as the magnitude of the maximum principal stress at the yield point. Like stiffness, the mechanical strength of coal varies with rank and carbon content, and direction of loading. Medhurst and Brown (1998) observed that among medium rank coals, dull (higher ash content) coal has a higher strength than bright coal (lower ash content). They explained that bright coal contains more cleats while dull layers are blocky and hard. Similar to elastic modulus, the strength of coal is also affected by sample size because the larger samples contain more cleats and therefore the strength decreases significantly (Medhurst and Brown, 1998; Esterle, 2008).

Owing to the mode of deposition and cleat orientation, coal can be anisotropic and the strength is highest when the major principal stress is perpendicular to major cleats and it is lowest when the major principal stress is perpendicular to the bedding plane as depicted in Fig. 4 (Okubo et al., 2006).

The effect of confining stress on strength of coal is described by a failure criterion. Fig. 5 shows the fitted Mohr–Coulomb and Hoek–Brown failure envelopes over the triaxial data on Canadian Bituminous coals (Gentzis et al., 2007). Note that the values of cohesion, friction angle, and Hoek–Brown parameters presented in this figure are within the range for typical bituminous coals.

5.2.3. Poisson's ratio

Coal has a greater Poisson's ratio compared to other sedimentary rocks and it can be higher than 0.4 while it usually does not exceed 0.2 in sandstones and carbonated rocks (Yang et al., 2011). However, Poisson's ratio of coal is fairly variable as reported by a series of experimental data reviewed by Gercek (2007) where Poisson's ratio of Turkish coal ranged from 0.15 to 0.49. Poisson's ratio of Canadian Bituminous coal was reported to be between 0.28 and 0.48 (Gentzis et al., 2007). The reason for the considerable difference in the measured values of Poisson's ratio is not identified but it appears to be due to either carbon content and/or cleats. Peng et al. (2006) have suggested that the Poisson's ratio for coal

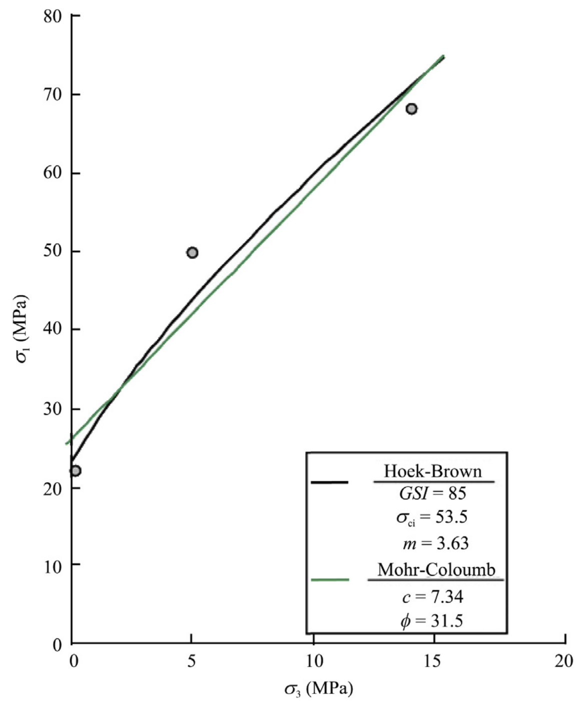

Fig. 5. Mohr–Coulomb and Hoek–Brown failure envelopes of coal samples (Gentzis et al., 2007).

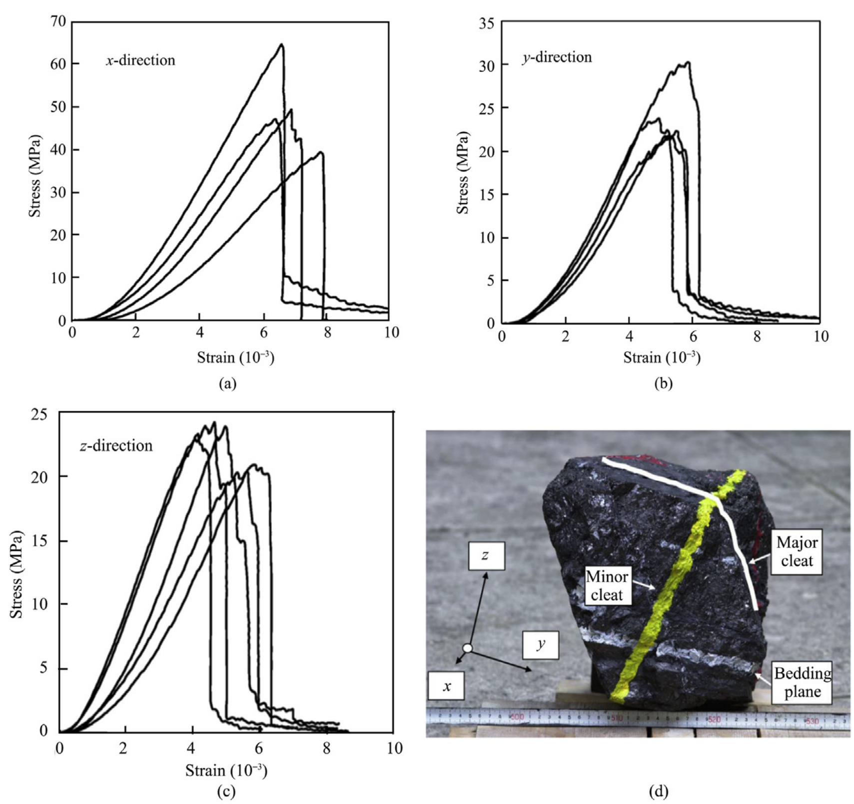

Fig. 4. The stress–strain curves for uniaxial compression of coal samples at orientations relative to bedding plane, major and minor cleats. *x* is perpendicular to major cleats and *z* is perpendicular to the bedding plane (adopted from Okubo et al., 2006).

increases as a result of fracture/cleat density although there are very limited data on this relationship. This effect has been observed in other types of rocks as well (Gercek, 2007). Also the relationship between coal rank/carbon content and its Poisson's ratio was not found in the literature and as stated by Peng et al. (2006) it needs experimental investigations.

On the other hand, as mentioned earlier, coal is an anisotropic material and similar to other parameters, increasing anisotropy can be observed in Poisson's ratio as the carbon content increases. Fig. 6 shows the anisotropy in vitrinite (a coal maceral) which implies that the observed anisotropy in coal is not only because of the existence of the fractures but also due to the polymeric structure of coal. It can be seen that coals with carbon content of larger than 90% can be considerably anisotropic.

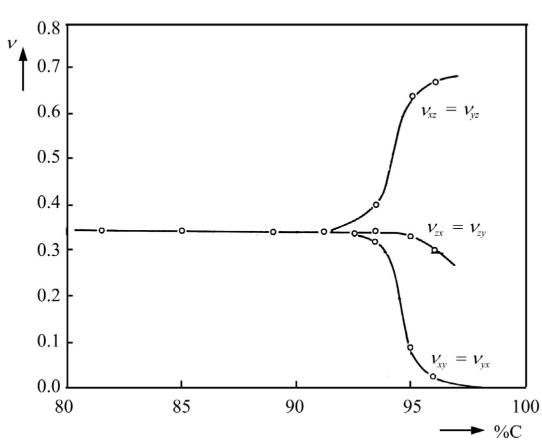

Fig. 6. Poisson's ratio anisotropy of vitrinite vs. 90% carbon content (van Krevelen, 1993).

5.3. Analytical modelling of stress and strain distribution within coalbeds

As discussed earlier, different geomechanical processes occur within a coalbed reservoir when injecting CO_2. In order to successfully model the geomechanical response of coalbeds to CO_2 injection, these processes should be considered. However, the geomechanical modelling needs to be coupled with the reservoir and adsorption behaviour of coalbeds. Usually, the coupling is conducted using the definition of the effective stress which defines the effect of pressure on mechanical load applied to the solid matrix of porous media. To find the changes in stress and strain within a reservoir, the deformation equations must be solved along with strain compatibility equation and equation of equilibrium. These equations, however, depend on the assumption and boundary conditions of the problem. Due to complexity of poro-mechanical governing equations, it is generally difficult to find closed-form solutions and hence the solutions can be usually obtained using numerical techniques. However, to author's knowledge, no studies have considered the plastic deformations in coalbeds, while plastic deformations can have an important impact on stress distribution, especially around wellbores. On the other hand, studies have provided some analytical solutions being used for poro-elastic modelling of coalbed geosequestration (e.g. Connell and Detournay, 2009; Masoudian et al., 2013b). Discussion on numerical modelling techniques is beyond the scope of this paper and only the most widely used analytical approaches used for geomechanical modelling of coalbeds are discussed here. Note that the main advantages of analytical geomechanical models are the ease of implementation and the very fast computations for permeability models nested in reservoir models.

5.3.1. Uniaxial deformation model

For an isotropic linear elastic medium in a Cartesian system of coordinates (x, y and z directions are the directions of major, intermediate, and minor principal stresses, respectively), Eq. (20) can be rewritten as follows:

$$\left.\begin{aligned}
\sigma_{xx}-\alpha P &= \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_{xx}^{m}+\nu\left(\varepsilon_{yy}^{m}+\varepsilon_{zz}^{m}\right)\right]+\frac{E}{1-2\nu}\varepsilon_{xx}^{s}\\
\sigma_{yy}-\alpha P &= \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_{yy}^{m}+\nu\left(\varepsilon_{xx}^{m}+\varepsilon_{zz}^{m}\right)\right]+\frac{E}{1-2\nu}\varepsilon_{yy}^{s}\\
\sigma_{zz}-\alpha P &= \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_{zz}^{m}+\nu\left(\varepsilon_{xx}^{m}+\varepsilon_{yy}^{m}\right)\right]+\frac{E}{1-2\nu}\varepsilon_{zz}^{s}
\end{aligned}\right\} \tag{24}$$

The assumption of uniaxial vertical deformation has been widely used in reservoir geomechanics studies as a helpful simplification for reservoir and geomechanical coupling (e.g. Shi and Durucan, 2005; Connell and Detournay, 2009). Under uniaxial vertical strain condition, i.e. $\varepsilon_{xx}=\varepsilon_{yy}=0$, and assuming isotropic sorption strain and horizontal symmetry of the problem, the stress and strain within the reservoir can be estimated using the following equation:

$$\left.\begin{aligned}
\sigma_{xx} &= \sigma_{yy} = \frac{\nu}{1-\nu}\sigma_{zz}+\frac{1-2\nu}{1-\nu}\alpha P+\frac{E}{3(1-\nu)}\varepsilon_{v}^{s}\\
\varepsilon_{zz} &= \frac{1}{E}\left[-\nu(\sigma_{rr}+\sigma_{\theta\theta})-(1-2\nu)\alpha P\right]
\end{aligned}\right\} \tag{25}$$

5.3.2. Plane-strain model

Coal seams are often horizontal and are surrounded by stronger and thicker formations above and beneath them (Cui et al., 2007). The strong formations above and beneath coal seams prevent them from undergoing large vertical deformations. Therefore, when studying stress and/or strain around a wellbore drilled in a coal seam, a plane-strain model can be a useful tool. Masoudian (2013) found the stress and strain distribution within a disk-shaped isotropic elastic reservoir under a plane-strain condition. In order to achieve this, the following equations of equilibrium and strain compatibility can be considered in polar coordinates:

$$\frac{\partial\sigma'_{rr}}{\partial r}=\frac{\sigma'_{\theta\theta}-\sigma'_{rr}}{r} \tag{26}$$

$$\frac{\partial\varepsilon_{\theta\theta}}{\partial r}=\frac{\varepsilon_{rr}-\varepsilon_{\theta\theta}}{r} \tag{27}$$

while the elastic strain–stress equations can be written:

$$\left.\begin{aligned}
\varepsilon_{rr}^{m} &= \frac{1}{E}\left[\sigma_{rr}-\nu(\sigma_{\theta\theta}+\sigma_{zz})-(1-2\nu)\alpha P\right]+\frac{\varepsilon^{s}}{3}\\
\varepsilon_{\theta\theta}^{m} &= \frac{1}{E}\left[\sigma_{\theta\theta}-\nu(\sigma_{zz}+\sigma_{rr})-(1-2\nu)\alpha P\right]+\frac{\varepsilon^{s}}{3}\\
\varepsilon_{zz}^{m} &= \frac{1}{E}\left[\sigma_{zz}-\nu(\sigma_{rr}+\sigma_{\theta\theta})-(1-2\nu)\alpha P\right]+\frac{\varepsilon^{s}}{3}
\end{aligned}\right\} \tag{28}$$

Combining these three equations (Eqs. (26)–(28)), the stress distribution within a coal seam in which CO_2 is being injected is obtained as

$$\left.\begin{aligned}\sigma_{rr} &= \frac{1}{r^2}\frac{1-2\nu}{1-\nu}\int_{r_w}^{r}\alpha P r\mathrm{d}r + \frac{1}{3r^2(1-\nu)}\int_{r_w}^{r}E\varepsilon^{s} r\mathrm{d}r + C_2\left(1-\frac{r_w^2}{r^2}\right)+\frac{C_1}{r^2}\\ \sigma_{\theta\theta} &= -\frac{1}{r^2}\frac{1-2\nu}{1-\nu}\int_{r_w}^{r}\alpha P r\mathrm{d}r - \frac{1}{3r^2(1-\nu)}\int_{r_w}^{r}E\varepsilon^{s} r\mathrm{d}r + C_2\left(1+\frac{r_w^2}{r^2}\right)-\frac{C_1}{r^2}+\frac{1-2\nu}{1-\nu}\alpha P+\frac{E}{3(1-\nu)}\varepsilon^{s}\\ \sigma_{zz} &= \nu(\sigma_{rr}+\sigma_{\theta\theta})+\frac{E}{3}\varepsilon^{s}+(1-2\nu)\alpha P\end{aligned}\right\} \tag{29}$$

where r_w is the wellbore radius, and C_1 and C_2 are the constants that can be determined when the boundary conditions are applied to the equations. Assuming that the stresses at the wellbore and the outer boundary of the coal seam are constant, the integration constants are

$$\left.\begin{aligned}C_1 &= P_w r_w^2\\ C_2 &= \frac{1}{r_o^2-r_w^2}\left[\sigma_o r_o^2 - P_w r_w^2 - \frac{1-2\nu}{1-\nu}\int_{r_w}^{r_o}\alpha P r\mathrm{d}r - \frac{1}{3(1-\nu)}\int_{r_w}^{r_o}E\varepsilon^{s} r\mathrm{d}r\right]\end{aligned}\right\} \tag{30}$$

where r_o is the outer boundary radius; P_w and σ_o are the injection pressure at the wellbore and the stress on the outer boundary of the coal seam, respectively. Note that these relationships for stresses and strains can be expressed in the rate form which makes it easier to deal with a variety of problems with complex boundary conditions as explained by Masoudian (2013). Additional formulations for different boundary conditions and stress–strain regimes can be found in Cui et al. (2007).

6. Changes in properties of coalbeds due to CO_2 injection

6.1. Changes in permeability

The permeability of coalbeds changes during geosequestration and ECBM recovery due to two mechanisms: alteration of the stress field distribution, and swelling/shrinkage of the coal matrix. The former mechanism happens because of depletion (in CBM) or injection (ECBM and/or CO_2 geosequestration) and the latter may take place due to the sorption of gas onto coal microporous surface. Many studies have tried to model the changes in the permeability of coalbeds as a result of adsorption-induced swelling and changes in effective stress.

Generally, two approaches have been employed to model the permeability of coal, i.e. relating the permeability to either porosity or stress. The basic equation to relate the change in permeability to the change in porosity can be written below:

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3 \tag{31}$$

where the subscript "0" denotes the initial values. Using this relationship, Palmer and Mansoori (1996) developed a porosity-based model which can be presented below:

$$\frac{k}{k_0} = \left[1+\frac{P-P_0}{M\varphi_0}+\frac{\varepsilon^{s}_{\max}}{\phi_0}\left(\frac{K}{M}-1\right)\left(\frac{P_0}{P_\varepsilon+P_0}-\frac{P}{P_\varepsilon+P}\right)\right]^3 \tag{32}$$

where the swelling strain is estimated using swelling models (e.g. Eq. (16)), while K and M are the bulk modulus and the constrained axial modulus, respectively, as defined below:

$$\left.\begin{aligned}K &= \frac{E}{3(1-2\nu)}\\ M &= \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\end{aligned}\right\} \tag{33}$$

On the other hand, the most widely used equation for stress-based permeability models relates the permeability to the change in the horizontal effective stress which can be written as

$$\frac{k}{k_0} = \exp\left[-3c_f({\sigma'}_h-{\sigma'}_{h0})\right] \tag{34}$$

where the subscript "h" denotes the horizontal direction and c_f is the fracture compressibility defined when discussing flow equations. Shi and Durucan (2005) developed the most widely used stress-based permeability model in which the change in horizontal

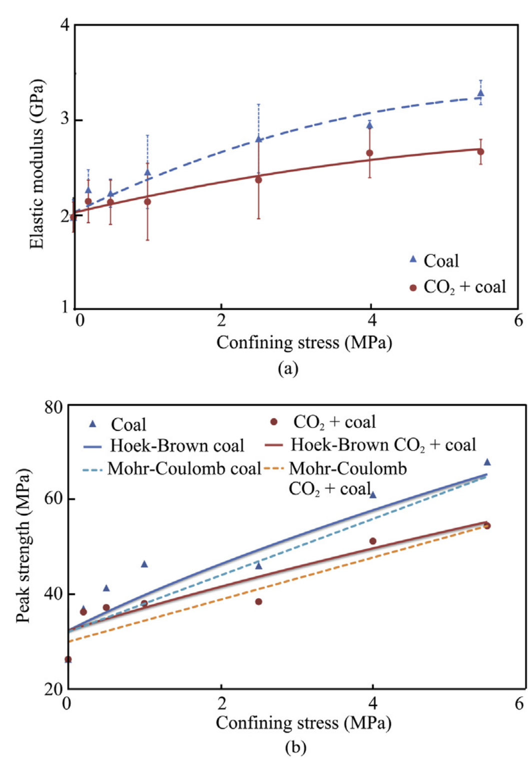

Fig. 7. The effect of CO_2 on elastic modulus (a) and strength (b) of coal (Masoudian et al., 2014).

effective stress is obtained for uniaxial deformation condition. In other words, they substituted Eqs. (16) and (25) into Eq. (34) and assumed that the vertical stress is constant, the permeability model then can be written as

$$\frac{k}{k_0}=\exp\left\{-3c_{\mathrm{f}}\left[-\frac{\nu}{1-\nu}\alpha(P-P_0)+\frac{E}{3(1-\nu)}\left(\frac{P_0}{P_\varepsilon+P_0}-\frac{P}{P_\varepsilon+P}\right)\right]\right\} \tag{35}$$

In addition to this model, one can find different permeability models by substituting other horizontal stress expressions. For example, one can use the mean horizontal effective stress estimated by a plane-strain model (i.e. Eq. (29)) to estimate the permeability within a coal seam (e.g. Cui et al., 2007). The numerical models can also be used to determine the change in horizontal stress and then the permeability can be estimated. Predicting the permeability of coal seam is one of the most important studies in reservoir engineering and there exist a few papers providing comprehensive reviews of permeability models for coalbeds (e.g. Pan and Connell, 2012). Thus, permeability models will not be discussed further in this paper, although the effect of geomechanical parameters on permeability prediction will be discussed later.

6.2. Changes in elastic modulus and strength

It has been shown that vapour and gas sorption can affect the mechanical properties of solid bodies (Czapliński and Hołda, 1982). Only limited data are available regarding the effect of gas sorption on mechanical properties of coal. Recent experiments on brown (Viete and Ranjith, 2006) and bituminous coal (Viete and Ranjith, 2006; Masoudian et al., 2013a, 2014; Wang et al., 2013a; Vishal et al., 2015) have shown changes in stiffness and strength. Fig. 7 shows the experimental results that display how the adsorption of CO_2 results in reductions in elastic modulus and strength of coal. Note that the fitted Mohr–Coulomb and Hoek–Brown failure criteria are also shown for CO_2 saturated coal. Fig. 8 illustrates the stress–strain curves of two black coal samples saturated with water and CO_2 and it can be seen that the strength of CO_2 saturated sample is significantly lower than that of water saturated sample.

The microstructures of unplasticised and plasticised polymers have been studied for decades and many investigations have confirmed a significant change in polymer surface appearance as a result of plasticisation. Fig. 9 shows typical SEM images (Gezovich and Geil, 1971) of the effect of adding a plasticiser on the microstructure of polyvinylchloride (PVC). It can be seen that adding plasticiser (dioctylphthalate) decreases the surface roughness and

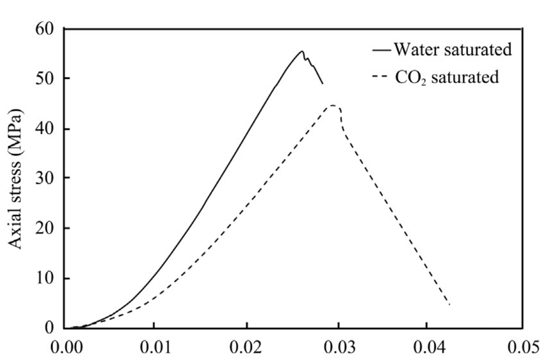

Fig. 8. Stress–strain curves for CO_2 and water saturated coal (injection pressure and confining stress of 1.0 MPa) (Masoudian et al., 2013b).

crystalline texture. Fig. 10 shows typical SEM images of water saturated and CO_2 saturated coal. It can be seen that there has been a significant change in the appearance of the coal, and the well-defined structure of the water saturated specimen is not as clearly visible in the CO_2 saturated specimen. Similar to the changes observed in SEM images of plasticised polymers, the surface of CO_2 saturated coal is smooth and it can be attributed to the plasticising effect of CO_2, i.e. shortening the polymer chains and reducting entanglements between the shortened chains.

It should be noted that the plasticising effect of CO_2 has not observed in all microscopic studies (e.g. Hol et al., 2012b). In order to prove the plasticisation effect of CO_2 on coal, further microscopic studies of the coal macerals and their response to CO_2 adsorption would be helpful. In addition, as Kutchko et al. (2013) explained, all of the current studies have investigated the microstructure of coal before and after exposure to CO_2 rather than under in-situ conditions. Thus, improvements in the methodology of microscopic studies would be also helpful to shed a light on the effect of CO_2 on microstructure of coal.

7. The role of geomechanical properties in reservoir and geomechanical aspects of CO_2 sequestration

7.1. The role of elastic modulus

Elastic modulus is an important factor in permeability predictions in coal seams as the swelling-induced stress is proportionally related to elastic modulus (see Eqs. (32) and (35)). Levine (1996) and Balan and Gumrah (2009) analysed the influence of elastic modulus during methane production from a coal seam and found that a lower elastic modulus resulted in a higher value of permeability (see Fig. 11), and estimates of the amount of producible methane will be different (Fig. 12). This is due to the fact that the lower elastic modulus results in a greater shrinkage of the coal matrix and therefore the increase in permeability is larger during CBM operation. Also, during CO_2-ECBM, the swelling will be higher with lower elastic modulus and therefore the permeability reduction is larger which results in a lower production of methane. They also stated that elastic modulus is the second most important parameter in permeability prediction and reservoir simulation after initial cleat porosity.

The mechanical response of a coal seam to CO_2 injection is very important in the assessment of fault/fracture reactivation, cap rock integrity, ground surface movement, and wellbore stability analysis. There are a few hydro-mechanical models that have been used to study the mechanical response of coalbeds to CO_2 injection (e.g. Li et al., 2006; Connell and Detournay, 2009; Liu and Smirnov, 2009; Chen et al., 2010), but these models have not been used to study the possible fault reactivation, surface subsidence/uplift or the mechanical integrity of wellbore and their consequent leakage risks. In order to highlight these aspects, the results of a sensitivity analysis conducted by Chen (2011) were presented in which the effect of the mechanical properties of a hydrocarbon reservoir on the ground surface movements in response to fluid injection was studied. It should be noted that these results may be not directly applicable to coal seams but they provide a qualitative sense of the importance of the mechanical parameters. For example, Fig. 13 shows that higher values of the elastic modulus of the reservoir can increase the ground surface displacement. Although the values of uplift predicted in this example are not significant, they will depend on the production rate and structural geology of the field, and the potential for the subsidence/uplift could be much larger. For example, the deformation in the surrounding rock masses may result in fracture/fault reactivations and consequently gas leakage to the surface and additional ground movement and subsidence/

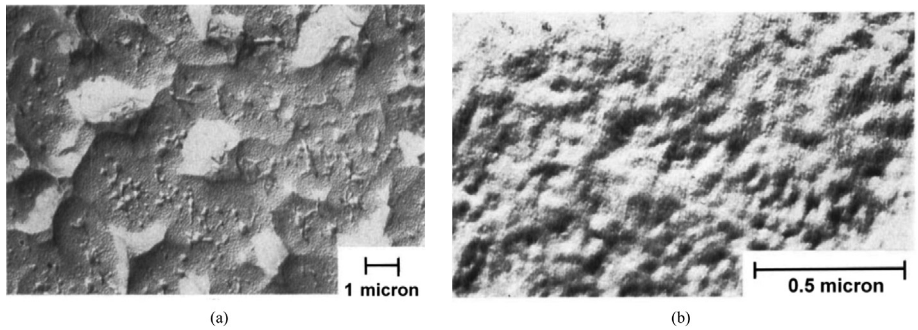

Fig. 9. SEM images of (a) unplasticised and (b) dioctylphthalate plasticised PVC (Gezovich and Geil, 1971).

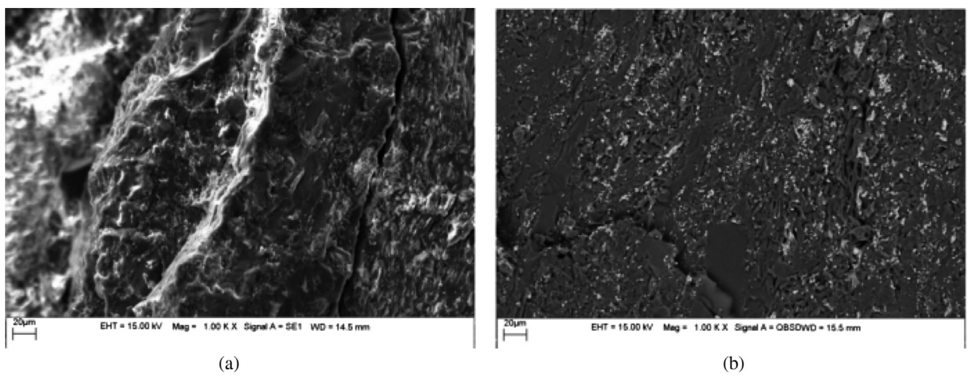

Fig. 10. SEM images of (a) water saturated coal and (b) CO_2 saturated coal (Masoudian et al., 2013b).

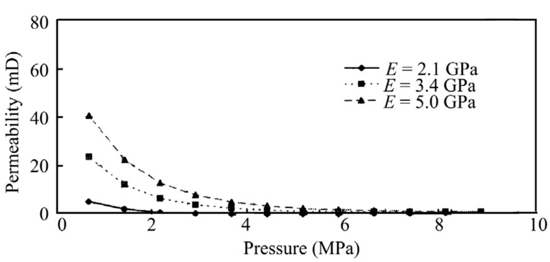

Fig. 11. Effect of elastic modulus of coal on permeability prediction (Levine, 1996).

uplift (Streit and Hillis, 2004; Chan and Zoback, 2007). Robertson et al. (2012) reviewed the published information on hydrocarbon production-induced subsidence and stated that annual subsidence rates of several centimetres per year are common and total subsidence of up to nearly 10 m has been reported. In addition to the damage to the injection/production facilities (well casing, wellhead equipment, etc.), the damage to the existing surface structures due to ground movements can be significant, and on rare occasions disastrous. As an example, the failure of the Baldwin Hills Dam is believed to be due to fault reactivation as a result of water injection into the nearby oilfield conducted as a production enhancing measure (Hamilton and Meehan, 1971).

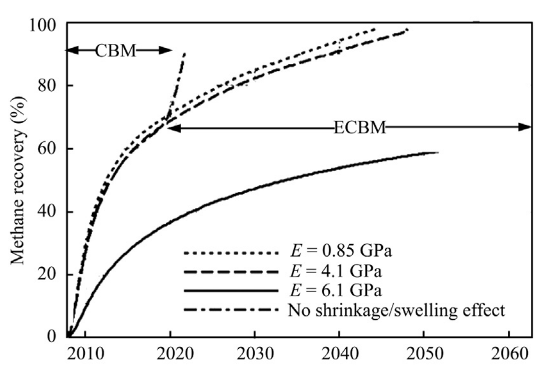

Fig. 12. Influence of elastic modulus on the amount of recoverable methane from a coalbed (adopted from Balan and Gumrah, 2009).

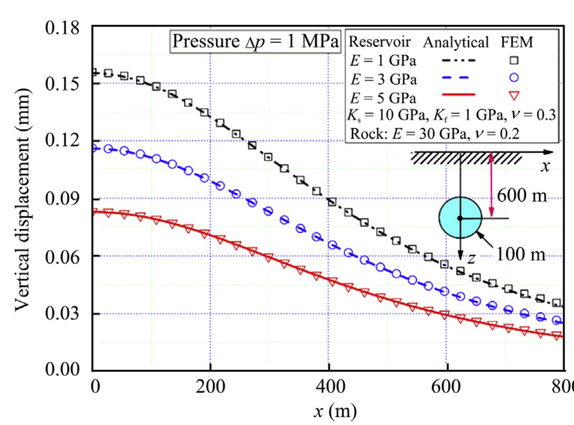

Fig. 13. Sensitivity of the ground surface subsidence to elastic modulus value (Chen, 2011).

7.2. The role of strength

The mechanical strength of coal can be crucial in CO_2 sequestration operations in both reservoir performance and safety aspects since it affects the post-failure permeability of coal (Viete and Ranjith, 2006; Wang et al., 2013b). Experiments conducted by Wang and Park (2002) on mudstones and sandstones showed that permeability decreases in the early stages of triaxial compression and then starts to increase in the non-elastic pre-failure deformation stage. Permeability keeps increasing to a peak in the post-failure stage when the newly produced fractures provide the maximum permeability, and then it drops during the residual stage (see Fig. 14a–c). A similar effect has been observed in Australian brown coals by Viete and Ranjith (2006), although brown coal has shown a ductile failure (see Fig. 14d). These observations imply that coal deformation and failure may affect the reservoir performance of a coal seam.

7.3. The role of Poisson's ratio

Since the value of Poisson's ratio influences the calculated reservoir effective stress due to reservoir compaction/expansion (see Eqs. (32) and (35)), it can also affect the permeability prediction and therefore an accurate assessment of Poisson's ratio is required. Fig. 15 shows the results of a sensitivity analysis performed by Levine (1996) where the change in the value of Poisson's ratio has influenced the predicted permeability changes in a coalbed, with a more significant influence when Poisson's ratio is higher. The effect of Poisson's ratio on methane recovery from a coalbed has been investigated in a more recent study by Balan and Gumrah (2009). As shown in Fig. 16, the methane recovery is significantly higher with a larger Poisson's ratio during ECBM operation although the effect is not significant during CBM operation. This is expected because during ECBM, the effect of adsorption-induced swelling somewhat cancels the effect of desorption-induced shrinkage on permeability which helps the reservoir compaction/expansion to be the main controlling factor in permeability calculation, while in case of CBM, the effects of shrinkage and compaction are of the same order.

On the other hand, Poisson's ratio is important in structural analysis of the coal reservoir. Many studies have investigated the effect of Poisson's ratio of other reservoirs on the movement of rock masses above the reservoir (e.g. Chen, 2011; Segura et al., 2011;

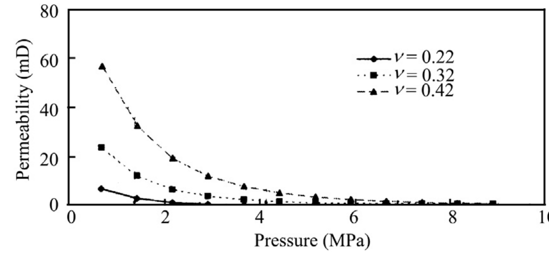

Fig. 15. Influence of Poisson's ratio on the predicted permeability during methane production from a coalbed (Levine, 1996).

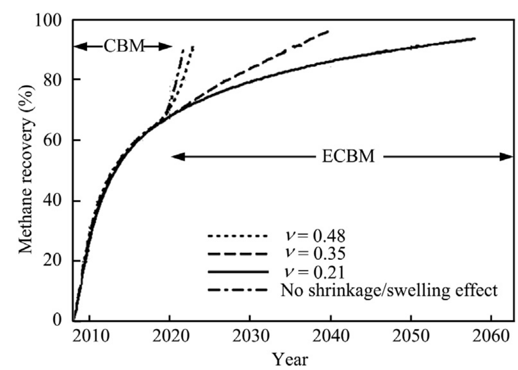

Fig. 16. The influence of Poisson's ratio on the amount of recoverable methane from coalbed (adopted from Balan and Gumrah, 2009).

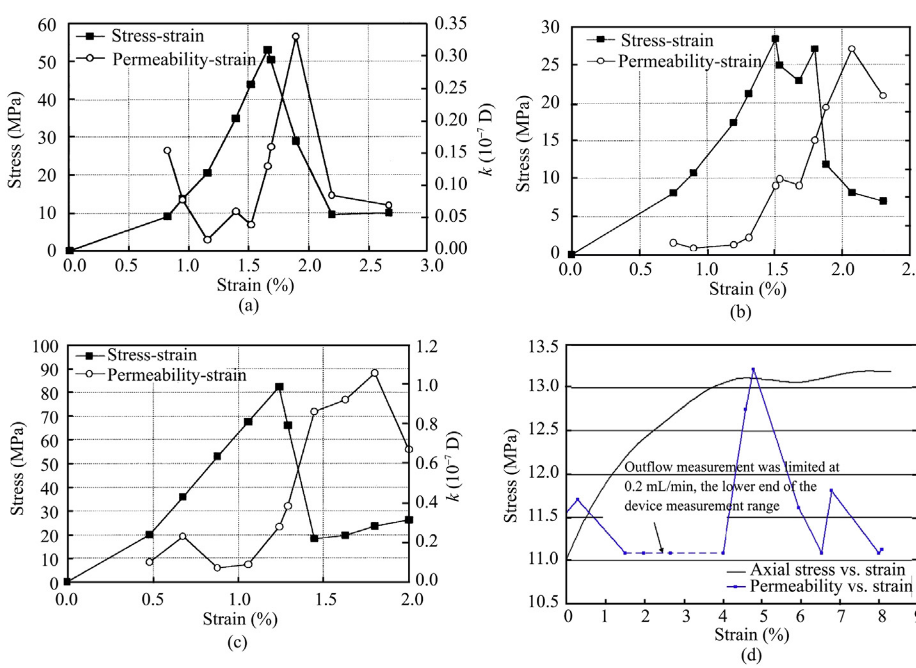

Fig. 14. Permeability during triaxial compression on (a) mudstone (Wang and Park, 2002), (b) sandy shale (Wang and Park, 2002), (c) fine sandstone (Wang and Park, 2002), and (d) coal (Viete and Ranjith, 2006).

Soltanzadeh et al., 2007). Chen (2011) reported that the value of Poisson's ratio can have a significant effect on the surface uplift of a hydrocarbon reservoir (Fig. 17). Lower Poisson's ratio results in a larger movement of ground surface so that in this example, the predicted uplift with $\nu = 0.2$ is almost twice that with $\nu = 0.4$.

8. Recommendations for future research

8.1. Knowledge gaps in adsorption and reservoir behaviour of coalbeds

A wide range of experimental and theoretical studies has been performed to investigate the mass transport mechanisms occurring in CO_2-ECBM and geosequestration. However, the available data cannot be simply applied to in-situ conditions at elevated temperature and pressure. Thus, more experimental studies need to be conducted to enable analysing the subsurface material transport under in-situ conditions. The review has indicated a number of shortcomings in our understanding of the chemical and hydraulic responses of coalbeds during sequestration of CO_2 that are summarised below.

(1) Molecular and porous structure of coal. A comprehensive knowledge about the structure of both macro- and microporosity (or even mesoporosity) of coal is required to understand the flow and transport mechanism of CO_2 in coal. However, it has been a long-term issue, and different and even contradictory theories have been presented. New advanced technologies that allow direct observation of coal structure, such as X-ray tomography, can improve the current knowledge of gas transport in coal. In particular, knowledge of the alteration of the molecular and porous structure of coal in the presence of CO_2 should be possible as direct observation techniques advance. This could significantly change and improve the current models for adsorption, diffusion and swelling of coal.

(2) Adsorption mechanisms. The assumed adsorption model has a significant effect on the estimated gas storage. There remain uncertainties about competitive sorption and the effects of temperature, pressure and phase, and how these vary with coal rank, porosity and stress level.

(3) Gas permeability. Gas storage and production estimates depend on the permeability and its change as CO_2 is adsorbed. Uncertainties remain about the coupling of swelling and mechanical changes that affect the permeability estimations, and there are limited experimental and numerical studies that describe the permeability of water/gas mixtures in coal.

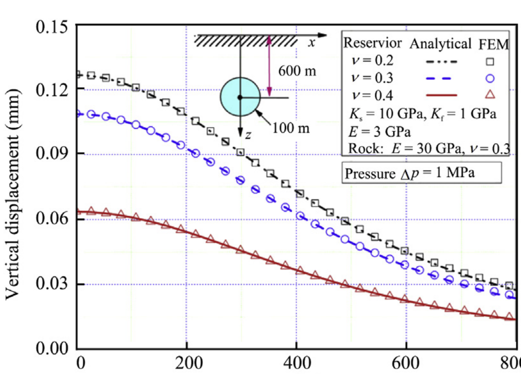

Fig. 17. Influence of Poisson's ratio on the vertical displacement of the ground surface due to a change in pore pressure (Chen, 2011).

(4) Gas diffusion. The database on diffusion of CO_2 into coal is limited and the influence of coal rank and porosity is not well understood. Further experiments on solid coal specimens are required to extend the database and understand the effects of gas mixture, pressure, temperature and effective stress. In addition, innovative experimental investigations and modelling efforts are required to overcome the shortcomings in the area of adsorption. One of these innovative approaches can be the integrated estimation of transport properties of CO_2 in coal.

(5) Reservoir simulation. The main problem with current reservoir simulators is the inaccuracy of the quasi-steady state matrix-fracture transfer function. On the other hand, the use of more recent matrix-fracture transfer functions may not numerically feasible. For example, the transient function presented in this paper is numerically expensive. Hence new models or algorithms are required to enhance the applicability of the transient matrix-fracture transfer function by simultaneously decreasing the computational needs and increasing the accuracy.

8.2. Knowledge gaps in geomechanical behaviour of coalbeds

It is believed that the geomechanical aspects of coalbed geosequestration are important in assessing the storage capacity and gas flow mechanisms. On the other hand, geomechanical aspects of CO_2 sequestration sites are the key factors in safety assessment of a specific sequestration project. As can be seen from the review above, the geomechanical aspects of CO_2 sequestration in coal seams are not well studied and understood. The main shortcomings identified related to the geomechanical response of coal seams are summarised below:

(1) Swelling. It is well established that volume changes occur when coal is saturated with CO_2. However, the magnitude and sign of the volume change and how these are related to properties of the coal need further investigation. In addition, the effect of effective stress on the adsorption-induced swelling of coal has been neglected in most studies.

(2) Geomechanical characterisation of coalbeds. The relationship between coal composition (e.g. carbon content) and its mechanical parameters has not been well investigated, especially the anisotropy of coal needs to be studied extensively. It can be helpful to study the mechanical properties of bulk coal and coal matrix separately. Moreover, the effect of temperature can be of importance when characterising the mechanics of coal seams since it can help to understand the mechanical and hydraulic behaviours of coal under in-situ conditions.

(3) The effect of CO_2/methane saturation on geomechanical behaviour of coal. Only limited data are available concerning the change in mechanical properties of coal but an extension to those studies could be conducting experiments at high (in-situ) pressure/temperature and also the effect of gas desaturation. In addition, the influence of altered elastic modulus on permeability and reservoir performance is of importance.

(4) The deformation regime in coalbeds. Almost all of the existing studies have assumed that all deformations within coalbeds are in elastic regime. Experimental and numerical studies are required to enhance the understanding of the effect of failure and plastic deformations on reservoir and mechanical behaviours of coalbeds.

(5) Modelling of stress and strain within coalbeds. The analytical solutions can provide useful tools to increase the computational efficiency of coupled hydro-mechanical coalbed simulators. Only few studies have provided analytical solution for stress and strain distributions within coal seam. Thus, new

analytical tools are required to improve the modelling of more complex reservoir geometries which consequently leads to better permeability models and reservoir simulation techniques.

(6) Geomechanical response of rock mass above coal seam. Studying the ground movement in response of CO_2 injection is vital to the viability of a coalbed sequestration project and elastic modulus is one of the most important parameters in its geomechanical aspects. Further study is required to enable predicting the hydraulic and mechanical integrity of cap rock and subsidence/uplift of the ground surface during CO_2 sequestration in coal seams.

(7) Induced tectonic/seismic activities. In order to assess the integrity and safety of storage sites, experimental and numerical studies are required to investigate the effect of tectonic activities of the Earth, fault reactivation, and the injection-induced micro-seismicity.

9. Conclusions

The processes associated with coalbed geosequestration of CO_2 can be classified into three categories of adsorption, reservoir and geomechanical behaviours. In addition, these three behaviours have complex interactions. The adsorption and reservoir behaviours have received a considerable attention while the geomechanical behaviour of coalbeds has received little studies. This paper provided a summary of these three aspects of CO_2 sequestration with a special reference to the geomechanical behaviour of coalbeds. This paper illustrated the importance of geomechanical parameters in geosequestration operations and their impacts on reservoir and geomechanical behaviours of coalbeds. A range of analytical tools useful for modelling of the CO_2 sequestration was introduced and the mathematical complexity of different behaviours and their interactions was depicted. This paper identified a range of knowledge gaps which open new gateways to geoscientists and geo-engineers to contribute in extending the current understanding on the safety and storage integrity of the coalbeds and the risks associated with CO_2 geosequestration and ECBM operations.

Conflict of interest

The author wishes to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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