International Journal of Coal Geology 121 (2014) 98–109

Contents lists available at ScienceDirect

International Journal of Coal Geology

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

Modeling gas-adsorption-induced swelling and permeability changes in coals

Pongtorn Chareonsuppanimit, Sayeed A. Mohammad, Robert L. Robinson Jr., Khaled A.M. Gasem *

School of Chemical Engineering, Oklahoma State University, Stillwater, OK 74078, United States

ARTICLE INFO

Article history:
Received 8 May 2013
Received in revised form 19 November 2013
Accepted 22 November 2013
Available online 28 November 2013

Keywords:
Coal swelling
Gas adsorption isotherm
Local-density model
Generalization
Surface potential
CO_2 sequestration

ABSTRACT

The swelling of a coal matrix as the result of gas adsorption can have important implications in operations related to the production of coalbed gases and the sequestration of greenhouse gases in coalbeds. In view of this, we undertook a modeling study to describe the relationships among gas adsorption on coals, coal swelling and permeability changes. Specifically, we incorporated the simplified-local-density (SLD) adsorption model within the theory-based swelling model by Pan and Connell (PC). The resultant, internally-consistent SLD-PC model was used to investigate the swelling behavior caused by adsorption of methane, nitrogen and CO_2 on several coals, using data from the literature. The SLD-PC model was found capable of representing both the gas adsorption and the adsorption-induced swelling data on these coals.

The PC swelling model relates the linear strain or adsorption-induced swelling in coals to the surface potential of the coal, which herein is calculated by the SLD adsorption model. Two model parameterization scenarios were considered for describing the quantitative relationship between swelling and adsorption surface potential. Results indicate that the SLD-PC approach provides lower errors in representing swelling behavior than the original PC model utilizing the Langmuir adsorption model. This improvement in representing swelling behavior with the SLD-PC model, which was especially true for CO_2, is attributed to a combination of two factors: (1) a more accurate description of surface potential and (2) the non-linear relation between the surface potential and strain that is accounted for in the SLD-PC approach.

In cases where swelling data were reported without the corresponding gas adsorption data, we utilized our previously-developed generalized model to predict gas adsorption on coals. The predicted adsorption data were then used successfully in the SLD-PC model for systems lacking experimental adsorption data. The efficacy of this approach was verified using an additional test system from the literature. Further, we also tested the hypothesis by Pan and Connell that coal swelling is more dependent on the molar amount of gas adsorbed than on the particular gas being adsorbed. Current results confirm that the linear strains induced in coals are similar when compared at equal levels of adsorption of different gases.

Lastly, we utilized adsorption-induced strain information obtained from the SLD-PC approach to model normalized permeability changes in coal. Our results suggest that the SLD-PC approach combined with the Pan and Connell permeability model may be capable of providing useful description of the adsorption-induced normalized permeability changes in coal. The development of completely predictive models for coal swelling and permeability changes, however, will require additional experimental data and further testing.

1. Introduction

The significant increase in greenhouse gas emissions has stimulated research efforts on CO_2 capture and subsequent storage of CO_2 in underground reservoirs such as depleted oil and gas fields, unmineable coalbeds and saline aquifers. The geological storage or sequestration of CO_2 into deep, unmineable coal seams offers a particularly attractive method since the sequestration often provides another benefit — additional recovery of coalbed methane or natural gas. However, modeling these processes requires detailed knowledge regarding gas adsorption and transport within the reservoir, among other factors. Although significant efforts have been made to investigate gas adsorption in coals, the adsorption-induced swelling of coals has received limited theoretical attention thus far. CO_2 sequestration capability can be affected significantly by the adsorption-induced expansion of coal — more commonly referred to as coal swelling. This phenomenon can reduce the cleat permeability by constricting the porous cleat networks, as illustrated in Fig. 1(a), thereby causing decreased injectivity of CO_2 into the reservoir. Therefore, gas adsorption-induced swelling of coals is an important factor for the optimal design of CO_2 sequestration processes in coalbed reservoirs.

The relationship between gas adsorption and coal swelling has been studied by several authors. Reucroft and Patel (1986) measured

* Corresponding author. Tel.: +1 405 744 5280; fax: +1 405 744 6338.
E-mail address: gasem@okstate.edu (K.A.M. Gasem).

0166-5162/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coal.2013.11.009

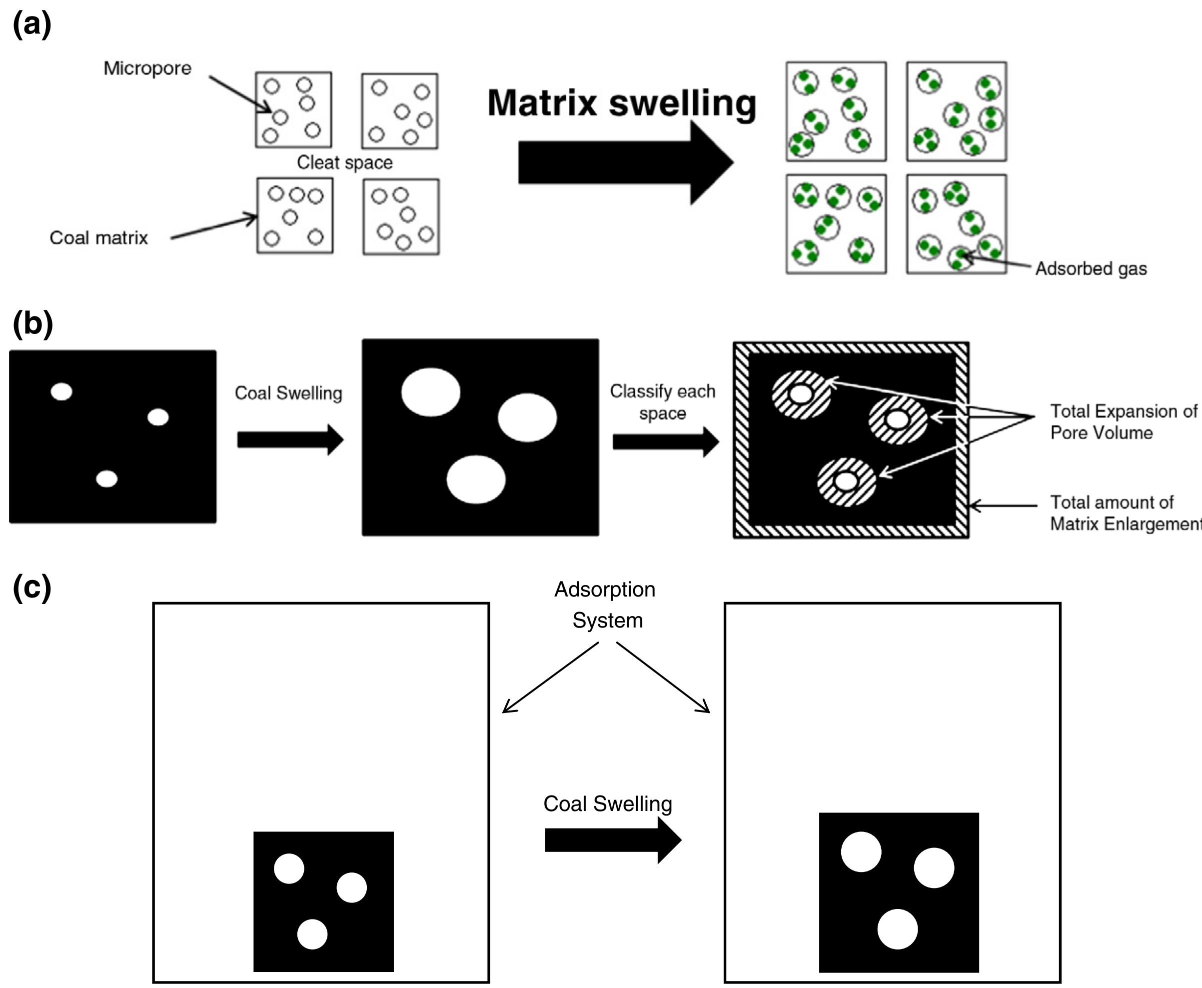

Fig. 1. (a). Adsorption and swelling of coal matrix. (b) Equality of Total expansion of pore volume and total amount of matrix enlargement. (c) Constant empty space in an adsorption system: white area represents void space and black area represents coal solid in adsorption system.

CO_2-induced coal swelling by recording the change in length of coal samples. They found that CO_2 could swell coals ranging from about 0.36% to 1.31% volumetrically, whereas a non-adsorbed gas such as helium produced negligible dimension changes to the coal samples. Levine (1996) measured the swelling of coals by methane and CO_2 and showed that CO_2 caused about three-fold larger swelling than methane at the same bulk pressure. Similarly, Pini et al. (2009) measured the swelling of coal due to adsorption of nitrogen and CO_2. The authors observed that the swelling of coal due to CO_2 was significantly larger than swelling from nitrogen adsorption. CO_2 is the most strongly adsorbed gas and nitrogen is least adsorbed, while methane adsorption is intermediate to these gases. Pan and Connell (2011) also measured coal swelling caused by methane, nitrogen and CO_2 adsorption. The authors observed that the coal swelling caused by different gases was very similar when compared at the same molar adsorption amounts (viz. at different pressures). In other words, they observed that the coal swelling is dependent on adsorption amounts, and equal adsorbed amounts of different gases produced similar levels of swelling in coals. This observation is tested in Section 4.3.

The reversibility of gas adsorption-induced swelling of coals on release of gas pressure was also studied by several authors (Day et al., 2008; Levine, 1996; Ottiger et al., 2008; Pini et al., 2009). These authors found that the dimensional changes in coals were negligible after evacuation of the adsorbates from their experimental apparatus and, thus, swelling appeared to be largely reversible under laboratory conditions.

Several attempts have been made to quantify the relationship between gas adsorption and the swelling of coals. Levine (1996) observed that swelling vs. pressure profiles measured in terms of the linear strain were Langmuir-like. The author used an empirical expression similar to the well-known Langmuir adsorption equation to model coal swelling. Cui et al. (2007) observed a linear relation between the volumetric strain and the adsorbed amount in the pressure range of 0–6 MPa. Recently, Pan and Connell (2011) and Day et al. (2008) showed that the relation between adsorbed amount and coal swelling was not necessarily linear, especially at the higher pressures.

Coal swelling and its effect on data reduction from adsorption experiments has also been studied. Several authors have included empirical corrections for coal swelling in adsorption isotherm data reduction calculations. For example, corrections for swelling that have been introduced include the Langmuir model (Ozdemir et al., 2003) and Dubinin–Radushkevich model (Sakurovs et al., 2007). Although these empirical corrections can describe adsorption data on specific systems, they do not possess predictive capabilities due to their inherently empirical nature. In contrast, theoretically rigorous models would offer a distinct advantage in modeling of gas adsorption as well as coal swelling.

Pan and Connell (2007) developed a theoretical model for describing coal swelling by considering the changes in surface potential energy due to gas adsorption. In their work, they utilized an energy balance approach that assumes equality between the surface potential and the elastic energy change of a solid adsorbent or coal. The surface