Fuel 106 (2013) 129–138

Contents lists available at SciVerse ScienceDirect

Fuel

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

A parametric study of coal mass and cap rock behaviour and carbon dioxide flow during and after carbon dioxide injection

M.S.A. Perera [a], P.G. Ranjith [a,*], S.K. Choi [b], A. Bouazza [a]

[a] Deep Earth Energy Lab, Department of Civil Engineering, Monash University, Building 60, Melbourne, VIC 3800, Australia
[b] Australian Commonwealth Scientific and Research Organization (CSIRO), Locked Bag 10, Clayton South, VIC 3169, Australia

HIGHLIGHTS

- Leakage of carbon dioxide is a major concern in carbon sequestration.
- COMSOL Multiphysics numerical simulator is used to model a deep coal seam.
- After some years of injection, CO_2 starts to move towards the cap rock layer.
- Cap rock may deform considerably due to CO_2 injection and CO_2 pressure built up along the cap rock.
- An existence of a fracture/s greatly increases the risk of CO_2 leakage into the atmosphere.

ARTICLE INFO

Article history:
Received 3 May 2011
Received in revised form 3 October 2012
Accepted 23 October 2012
Available online 15 November 2012

Keywords:
CO_2 sequestration
Cap rock deformation
Rock fracture
Back-migration

ABSTRACT

In recent years, scientists have focused on processes which can be used to reduce greenhouse gas emissions, and CO_2 sequestration in deep coal seams and saline aquifers has been identified as a potential method. However, there is a fundamental lack of understanding concerning the flow and mechanical phenomena that occur when CO_2 is injected into coal seams. The main objective of this parametric study is to model the effect of CO_2 injection pressure on cap rock deformation and investigate the possibility of leakage or back-migration of CO_2 to the atmosphere through the cap rock. The COMSOL Multiphysics numerical simulator was used to investigate the effect of CO_2 injection on coal and other adjacent rock strata. For the purpose of the model, a 200 m long and 5 m thick coal seam was assumed to be lying below a 200 m long and 3 m thick cap rock layer 1000 m below the surface. According to the model's results, the cap rock deforms considerably just after injection in an upward direction due to the CO_2 movement, and the amount of deformation greatly depends on the injecting gas pressure. When the injecting gas pressure is increased from 10.2 MPa to 30 MPa, the cap rock is raised from 0.2 mm to 15 mm during the injecting period. Moreover, CO_2 first spreads and is stored in the coal mass and then after about 3–4 years it starts to move towards the cap rock layer. In the second stage of the study, a small rock fracture was inserted between the cap rock and the coal layer and a sudden increase in leakage of CO_2 to the cap rock through the fracture was observed. The existence of a rock fracture is highly possible, and may happen naturally in coal seams. This model shows that this kind of fracture greatly increases the risk of back-migration of CO_2 into the atmosphere. The model can be used to study general coal mass and cap rock behaviour and the back-movement of CO_2 flow to the atmosphere.

1. Introduction

Carbon dioxide (CO_2) sequestration in coal seams has been identified as a potential solution for reducing global warming. This process can be used to reduce the large quantities of carbon dioxide in the atmosphere, and to produce an extensive amount of value-added product such as methane (CH_4) as an outcome. In this process, CO_2 released from industrial activities such as power plants and steel plants is collected and separated for pumping into the underground coal mass and is stored by a sorption process. According to Stevens et al. [1], the coal mass can store a substantial amount of gases due to its large surface area and highly porous structure. For instance, it has been estimated that the combined Bowen and Sydney basins in eastern Australia can store 11.2 Gt of CO_2 [2].

---

* Corresponding author. Address: iEnergy Initiative – Innovative Deep Earth Energy Research Centre, Building 60, Clayton Campus, Monash University, VIC 3800, Australia. Tel.: +61 3 99054982; fax: +61 3 99054944.

E-mail address: ranjith.pg@monash.edu (P.G. Ranjith).

URLs: http://eng.monash.edu.au/civil/about/people/profile/ranjithp, http://users.monash.edu.au/~ranjithp, http://www.monash.edu.au/research/profiles/profile.html?sid=5502&pid=3763 (P.G. Ranjith).

0016-2361/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2012.10.056

Nomenclature

c	CO_2 concentration of the fluid in the coal mass, kg m^{-3}
c_o	the initial water concentration means initial CO_2 concentration in the moisture in in situ coal mass (before injecting CO_2), kg m^{-3}
c_{CO_2}	injecting supercritical CO_2 concentration, kg m^{-3}
c_a	adsorbed CO_2 concentration into the coal mass, kg m^{-3}
C_m	cohesion, Pa
c_p	pore volume compressibility, Pa^{-1}
c_m	matrix shrinkage compressibility Pa^{-1}
D	vertical distance from the ground surface, m
D_L	hydrodynamic dispersion tensor, m^2 s^{-1} (function of tortuosity, diffusivity and dispersivity of the coal mass)
E_F	fracture Young's modulus, Pa
E	coal mass Young's modulus, Pa
F	vector that contains the fluid pressure gradient (includes the fluid flow and structure coupling term and other available body forces, Nm^{-3}
Fx	edge load in x direction, Nm^{-2}
Fy	edge load in y direction, Nm^{-2}
F_b	body forces in x and y direction, Nm^{-3}
g	gravitational acceleration, m s^{-2}
k	coal cleat permeability, m^2
k_o	coal cleat initial permeability, m^2
k_f	fracture permeability, m^2
n	directional vector component
p	pressure, Pa
p_F	pressure in the coal cleats, Pa
Δp	change of applied pressure in z direction, Pa
P_L	Langmuir pressure, Pa
ΔS	change of adsorbed CO_2 mass, mg kg^{-1}
S	storage coefficient, s^2 m kg^{-1}
t	time, s
u	total displacement, m
u_p	pore pressure, Pa
V	Darcy velocity, m s^{-1}
V_L	Langmuir volume, kg kg^{-1}
w	fracture width, m
y	depth, m
ν	Poisson's ratio
α	volumetric swelling coefficient
σ	stress, Pa
α_b	biot poro-elastic constant
ρ	fluid density in the coal mass, kg m^{-3}
ρ_o	initial coal moisture density (before mixing with the CO_2 flow, kg m^{-3}
ρ_{CO_2}	injecting supercritical CO_2 density, kg m^{-3}
ρ_r	rock density, kg m^{-3}
θ	porosity
θ_i	initial porosity
θ_s	fluid volume fraction in the coal mass pore space (equal to porosity in this study)
ϕ	anti-clockwise angle of any plane from the horizontal axis
ϕ_f	friction angle
η	viscosity of the fluid in the coal mass, Pa s
η_o	initial water viscosity (before mixing with the CO_2 flow) in the coal mass, Pa s
η_{CO_2}	injecting supercritical CO_2 viscosity, Pa s
τ_a	allowable shear strength, Pa
τ	shear stress, Pa
τ_{xy}	shear stress in x–y plane, Pa
σ_n	normal stress, Pa
σ_x	stress in x direction, Pa
σ_y	stress in y direction, Pa

Natural coal beds normally exist at deep locations (800–1000 m below the surface). Therefore the pressures in these locations are greater than the critical values of most of the gases in coal seams, such as CO_2 or CH_4, which therefore exist at their supercritical states [3–6]. For instance, the critical temperature for CO_2 gas is 304.8 K and the critical pressure is 7.38 MPa. In deep coal beds both factors exceed their critical values and CO_2 gas exists in its supercritical state. CO_2 density increases with pressure and at 313 K temperature and 20 MPa pressure, pure CO_2 density is closer to water density (around 900 kg/m^3). Akgerman and Giridhar [7] explain that supercritical fluids have liquid-like densities and solvent powers while having "gas-like" viscosities. Therefore, the supercritical CO_2 in deep coal seams preferably mixes with moisture in the coal pore structure, depending on the equation of state, such as pressure and temperature. The coal mass can be defined as a naturally-fractured reservoir for gas movement. The movement of gases through this highly complex coal mass structure depends on the permeability of the coal mass itself, which is governed by Darcian law and also the intrinsic permeability of the coal matrix, which is governed by Fickain diffusion.

However, CO_2 sequestration in deep coal seams process remains in the experimental stage as many aspects need to be studied before being put into practice. After a detailed review of the available studies related to CO_2 sequestration, White et al. [2] explained that "there is a fundamental lack of understanding concerning the physical, chemical and thermodynamic phenomena that occur when CO_2 is injected into a coal seam." The effects of CO_2 injection on the cap rock and the possibility of remigration of the injected CO_2 into the atmosphere through the cap rock are important aspects to be studied [8]. Moreover, rock faults or fractures may be present in the cap rock and coal seams and may cause injected CO_2 to leak to the atmosphere [9,10]. Numerical models play an important role in identifying the effect of the CO_2 sequestration process on the coal mass structure [11], and its effect on the cap rock and the back-migration of injected CO_2 into the atmosphere. In the present study the COMSOL Multiphysics numerical simulator was used to develop a numerical model to simulate the CO_2 sequestration process in a deep coal seam.

COMSOL Multiphysics is a partial differential equations (PDEs) and finite element analysis (FEM)-based numerical software, which can be used to model and solve a wide range of scientific and engineering problems. This simulator is available as a graphical user interface (GUI) or as a script programme in the MATLAB language. Of these, the former is easier and more user-friendly as models can be developed by giving several parameters, such as material properties, loads, constraints and sources. In this case, the user can easily select the equations necessary for the particular problem as the software itself contains a large number of PDEs. Moreover, in the COMSOL Multiphysics GUI, any type of equation can be introduced as a material parameter, boundary condition, load, constraint or source. However, since COMSOL Multiphysics is a basic type of numerical software which contains a large number of PDEs, the user must select the appropriate equations to solve their problem. COMSOL Multiphysics consists of several types of modules, including acoustics, chemical engineering, earth science, heat transfer and structure mechanics. The user can use one of these modules or several modules can be coupled using PDEs to develop the model. Of the modules, the heat transfer module has