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Coupled reservoir and geomechanical simulation for a deep underground coal gasification project

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ABSTRACT

Underground Coal Gasification (UCG) is an in-situ technology for extraction of energy from otherwise un-mineable coal seams. As coal is gasified, high temperature is generated and cavities are formed. Hence, the UCG imposes significant geomechanical changes to strata. The province of Alberta, Canada recently operated a deep UCG demonstration project, at a depth of 1400 m. The demonstration project successfully produced methane, hydrogen, and other gases. The current study aimed at conducting a sequentially coupled coal gasification and geomechanical simulation to study effects of the Alberta UCG on the coal seam and bounding seal system. A mechanical earth model was built for the test site utilizing geological layers reported for the site and under anisotropic in-situ stress magnitudes and orientations, particular to the Western Canadian Sedimentary basin. Ten chemical reactions along with their kinetics were implemented in a reservoir simulator. The Controlled Retraction Injection Point (CRIP) method was studied, in which four gasification chambers were simulated. The product gas compositions, over a period of 60 days, were in good agreement with the syngas composition measured at the demonstration project. By utilizing the coupling workflow, complex three-dimensional (3D) geometry of the UCG cavities as well as temperature and pore pressure, were passed along from the gasification module to a geomechanical simulator. This allowed simultaneous observation of geomechanical response of the strata as the gasification process advanced, syngas produced, and cavities developed.

1. Introduction

Coal is currently the world's second largest source of primary energy (after oil) and accounts for about 40% of global electricity production (World Energy Council, 2013). In the province of Alberta, Canada, coal supplied 52% of the province's electricity in both 2012 and 2013 (Government of Alberta, 2014). The Alberta's coal reserves and resources were estimated at 33.2 and 2000 billion tonnes, respectively (Alberta Energy Regulator, AER, 2014). It is predicted that energy generated by the Alberta' coal resources can be more than three times of its oil sands; however; much of these coal resources are currently un-mineable (Richardson and Singh, 2012).

The major concern about coal-fired power plants is greenhouse gas (GHG) emission. The 2035 outlook of Canada's energy future highlights that any coal facilities built after July 1st, 2015 should be equipped with carbon capture and storage (CCS) technology in order to be permitted to operate (National Energy Board, 2013). An alternative method for extracting coal energy from Alberta coal seams, with less GHG emissions could be Underground Coal Gasification (UCG). Recently, a UCG demonstration facility was constructed and successfully tested in a deep coal seam (depth of 1400 m) near Swan Hills, Alberta (Swan Hills Synfuels, 2012).

The produced gas in a UCG plant mainly contains H_2, CH_4, CO, CO_2, and small amount of some contaminants. The syngas can be combusted for power generation; liquefied to fuels, separated into methane and hydrogen for petrochemical use (Couch, 2009). A UCG operation generally includes a system of injector and producer wells. There are several operational techniques for the UCG explained elsewhere (e.g., Burton et al., 2006; Couch, 2009). The Controlled Retraction Injection Point (CRIP) method, in particular, is suitable for deep coal seams. In this method, after igniting the coal at a point near a vertical producer well, an oxygen-based mixture is provided downhole via a horizontal in-seam injector well to maintain the gasification process. The injection point is retracted in the upstream direction after some coal has been gasified. During a UCG operation, temperature may increase over 1000 °C, coal turns

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into ash, cavities are developed while cavity walls and rock layers may spall into the void areas. Also, groundwater might be contaminated (Burton et al., 2006; Couch, 2009; Sury et al., 2004a, 2004b). Porosity and permeability of coal and rock formations in the disturbed zone are compromised. The later will, in turn, influence the chemical process of coal gasification. In conclusion, the UCG represents a coupled hydro-thermo-chemical-mechanical process. Conducting coupled modeling can help investigate effect of different UCG operational scenarios while minimizing the geomechanical and environmental risks.

Extensive coal gasification simulations of UCG were conducted to study syngas flow rate and composition, temperature, porosity, permeability, and syngas heating value, etc. In these studies, a series of chemical reactions were implemented in either a Computational Fluid Dynamics (CFD) based software (e.g., Sarraf Shirazi et al., 2013; Zogala and Janoszek, 2015) or a reservoir engineering simulator (e.g., Nourozieh et al., 2010; Seifi et al., 2011). Khan et al. (2015) recently reviewed underground coal gasification modeling works. Several geomechanical modeling of UCG process were also published (e.g., Advani et al., 1976; 1977; Akbarzadeh and Chalaturnyk, 2013; Laouafa et al., 2016; Morris et al., 2009; Tan et al., 2008; Vorobiev et al., 2008). In these works, simplified geometries were usually assumed for the UCG cavities; with or without syngas pressure and temperature. The Lawrence Livermore National Laboratory (LLNL) developed a couplde UCG simulator (Camp et al., 2012; Nitao et al., 2011); however, this package is not commercially available. Akbarzadeh and Chalaturnyk (2016) accomplished a numerical modeling workflow for UCG to couple two commercial software; a gasification simulator to a geomechanical modeller. To date, there has not been any published coupled gasification-geomechanical simulation of the Alberta deep UCG test.

2. Scope and objectives

The objective of this study was to investigate potential geomechanical impacts of the Alberta deep UCG by means of performing 3D coupled gasification-geomechanical simulation utilizing publically available information regarding geology of the site, in-situ stresses, and material properties. This paper is structured in the following way. Initially, geology of the UCG site and the inferred corresponding in-situ stresses are presented. Description of the gasification model, chemical reactions, and governing equations solved in the reservoir simulator are provided next. The geomechanical model and governing equations solved in the geomechanical simulator is discussed. An overview of the coupling workflow is followed by presentation of the model results.

3. Model descriptions

3.1. Geology

The site under study is located in the Western Canadian Sedimentary Basin, WCSB (Fig. 1), near the town of Swan Hills, Alberta, Canada. A simplified 3D geological model was built for the site based on information reported by Swan Hills Synfuels (2012), a vertical section of which is shown in Fig. 2 a. Swan Hills Synfuels (2012) stated that during drilling the horizontal injector well, no faults were observed; hence, current study did not consider any faults in geomechanical simulations. The geological strata, from the ground surface downwards include: 795.5 m of sandstones, siltstones, and shales from the Paskapoo, Scollard, and Wapiti groups; 500 m of the Lea Park and Colorado shales; immediate overburden which is 101.5 m thick; Medicine River coal seam; and underburden rock. The Lea Park and Colorado shales are supposed to be the major caprock which plays reservoir containment role (Swan Hills Synfuels, 2012). The immediate overburden includes 13 m thick Viking sandstone, 8.5 m Joli Fou shale, and 80 m Mannville interbedded layers. The underburden rock belongs to the Mannville interbedded layers which includes sandstones, siltstones, and mudstones. The Medicine River coal seam belongs to the Upper Mannville formation. It exists at a depth of about 1400 m. It is moderately to poorly cleated and is 7.2–7.9 m thick. The coal seam contains two claystone partings. The partings share 8–19% in total thickness of the coal seam (Swan Hills Synfuels, 2012). The current study assumed a 6 m thick single layer of coal.

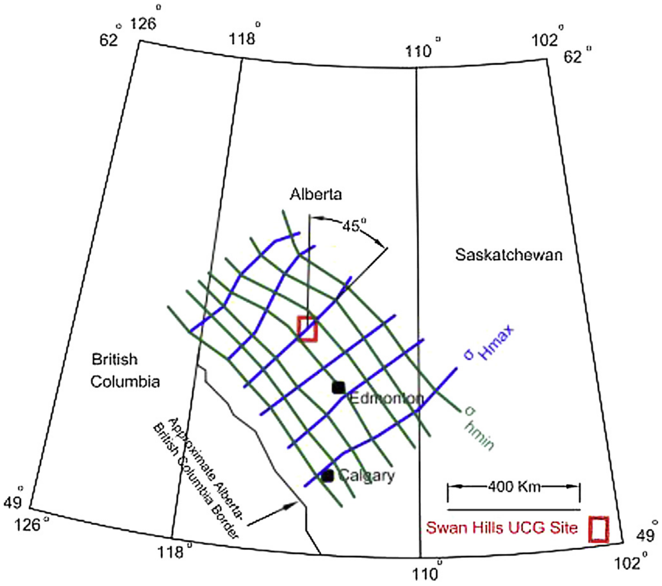

Fig. 1. In-situ horizontal stress trajectories of the WCSB (modified from Bell and Grasby, 2012) and placement of the Swan Hills UCG site.
*Note: The red symbol which represents the site is not set to the scale of the map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. In-situ stresses

Fig. 1 also shows placement of the Swan Hills UCG site in regards to σ_{hmin} and σ_{Hmax} stress trajectories of the WCSB. The site is located is the S-N direction with the producer well sitting in the northern part. The injector well is positioned in the southern side and turns to horizontal within the coal seam and extends all the way up to the north, very close to the producer well. If one assumes X-axis in the S-N direction, σ_{Hmax} would be compressional stress acting in the NE-SW direction. Using the same justification, σ_{hmin} would be compressional stress acting in the NW-SE. The other principal stress is overburden stress (σ_v) which is vertical.

To define a complete in-situ stress state, principal stresses magnitudes were calculated using a study by Hawkes et al. (2005). As shown in Fig. 3 a, the UCG site under study is positioned in region 3 (close to border with the region 8) of the Albert Basin zoning map for lower bound of σ_{hmin} reported by Hawkes et al. (2005). For the region 3, vertical stress gradient was 23.8 kPa/m. Gradient of σ_{hmin} was interpreted 17.0 kPa/m for depths from 250 to some 750 m and 12.9 kPa/m thereafter to a depth of 3000 m (Fig. 3b). Hawkes et al. (2005) interpreted the gradient of 12.9 kPa/m from depleted reservoirs; hence, the actual initial gradient in those regions might be greater than this value. Despite this limitation and because this is the only data available to this research program, it was used in current work. Since there is a normal stress regime in