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Application of porous medium approach to simulate UCG process

Mojtaba Seifi, Jalal Abedi *, Zhangxin Chen

Department of Chemical & Petroleum Engineering, University of Calgary, Calgary, Canada

HIGHLIGHTS

- Describing main assumptions in order to adapt the porous medium approach for UCG simulation.
- Developing relationships between basic analyses on coal and required parameters for porous medium simulators.
- Developing a numerical simulation model for pyrolysis process using porous medium approach.
- Simulating self-gasification process in cylindrical coal using hydrocarbon simulators.

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ABSTRACT

Underground coal gasification (UCG) is a promising technique where coal is converted into valuable syngas in underground reactors developed in coal seams. This method is of paramount interest due to its lower cost, the ability to access coal at greater depths, and the utilization of oil and gas technologies and previously drilled wells to reach the coal seams. In this study, the main assumptions of a porous medium approach for the simulation of the UCG process are explained in detail. Moreover, the formula and procedure to obtain the required parameters through hydrocarbon reservoir simulators are presented. The proposed method is evaluated with three case studies. Computer Modelling Group's STARS software is used in this study.

1. Introduction

Underground coal gasification (UCG) is a technique for the utilization of coal reserves, particularly at great depths where mining is not economical. UCG is an in situ process that converts solid fuel to synthetic gas (syngas) in the presence of steam and oxygen. This process has only a modest environmental impact and produces an easily transportable product. The intended uses of this syngas include the production of electrical power and chemicals [1,2].

UCG involves the gasification of coal in the seam by injecting oxidants through an injection well and extracting the syngas through a production well. The configuration of these wells implies different technologies, such as linked vertical wells, steeply dipping seams, linear controlled retracting injection point (CRIP), and parallel CRIP.

Due to the low permeability nature of the coal seams, the injection and production wells are linked by a channel, which can be developed with several proven techniques, such as reverse combustion, hydraulic fracturing, and directional drilling. Coal is then ignited around the injection point, producing a cavity as coal is combusted and gasified. In the area between the internal cavity surface and the original coal, several phenomena take place that control the heat and mass fluxes within the solid porous coal around the cavity. These phenomena include a gas film on the internal surface of the cavity, an ash layer on the cavity surface, pyrolysis, self-gasification, vaporization of the moisture content, and possible water inflow.

As shown in Fig. 1, the cavity itself can be divided into two parts: first, rubble material at the bottom of the cavity around the injection point, which may include ash, dry char and coal spalling and collapsing from the top of the cavity, and overburden materials; and second, void space on the top of the rubble materials, containing a gas mixture. In this void space, the temperature and concentration of the gas mixture may vary over time. As a result, there is a double-diffusive, turbulent-free convection flow that controls the transportation of the gaseous reactants from the bulk of the gas to the surface of the cavity [2–4].

UCG is a complex process; its modeling is crucial in order to understand the details of the process and the effect of different operating parameters on the objective parameters, such as the quality, rate and composition of the produced syngas, and the growth rate and shape of the developed cavity. For decades,

* Corresponding author. Address: 2500 University Dr., NW, Calgary, Alberta T2N 1N4, Canada. Tel.: +1 403 220 5594; fax: +1 403 282 4852.
E-mail address: jabedi@ucalgary.ca (J. Abedi).

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Nomenclature

A_0	frequency factor, variable unit
A_{0i}	frequency factor of evolution of *i*th species, 1/s
C_S^o	initial coal concentration (daf basis), mol/m^3 pore volume
E_a	activation energy, kJ/mol
E_{ai}	activation energy of evolution of *i*th species
k_g	thermal conductivity of gas mixture, J/m-day-K
k_r	thermal conductivity of rock (ash), J/m-day-K
k_s	thermal conductivity of solid fuel (char and coal), J/m-day-K
k_w	thermal conductivity of water, J/m-day-K
m_i	cumulative amount of *i*th volatile matter released by time *t*, g
m_i^*	initial amount of *i*th volatile matter can be released during pyrolysis, g
MW_c	carbon (char) molecular weight, kg/mol
MW_{daf_coal}	dry-ash-free (daf) coal molecular weight, g/mol
MW_i	molecular weight of species *i*, g/mol
R	gas constant, 8.314 J/mol-K
T	temperature, K
x_{ash}	mass percentage of coal ash content
x_{H2O}	mass percentage of coal moisture content

Greek letters

β	heating rate, °C/min
ρ_a^o	initial ash solid density, kg/m^3
ρ_{wat}^o	water density at coal seam initial condition, kg/m^3
ρ_{wc}^o	initial wet coal bulk density, kg/m^3
$\emptyset_f$	fluid porosity
$\emptyset_f^o$	initial fluid porosity
$\emptyset_v$	void porosity of the system
$\emptyset_v^o$	initial void porosity

researchers have been developing models to investigate specific aspects of this process. These models include the channel model, the packed bed model, the coal block model, and the process model.

Channel models assume a cylindrical coal seam with a channel in the middle with either a circular or rectangular cross section. The diameter of the internal channel can be fixed or variable. These models can be used to investigate the composition of the produced gas and the cavity growth rate through heterogeneous reactions. Packed bed models consider coal as a highly permeable dry or wet porous medium. These models are useful in the prediction of the composition of the product gas. In coal block models, wet or dry coal is assumed to have very low permeability in a one-dimensional (1D) semi-infinite domain. One side of this block is exposed to a mixture of gas mimicking the bulk gas mixture within the cavity and is ignited. This allows for the prediction of the rate of pyrolysis, the fire front advancement, and the temperature profile inside the coal ahead of the fire front. Process models are very simplified models used to investigate the effects of specific phenomena, such as water influx, spalling, and flow properties inside the cavity [3-10].

All the current models in the literature are, however, small scale models and need to satisfy certain assumptions on the shape of the cavity, such as cylindrical or rectangular. In these models, the effects of different well configurations, coal seam geology and layering cannot be investigated, and large-scale simulation cannot be performed. Therefore, the application of hydrocarbon reservoir simulators for modeling of the UCG process has been proposed previously by the authors [11].

Since oil and gas reservoirs have a different nature than that of coal seams, the major assumptions for the utilization of these porous medium based simulators for the UCG process are explained in this paper. A procedure and formulas are proposed to obtain the required information for the model from basic elemental and proximate analyses of coal and ash. The assumptions and procedure are evaluated with three case studies. The first case is the qualitative evaluation of the model according to a heavy oil in situ combustion tube test. Case two matches the results of an analytical method for modeling of the pyrolysis process using this proposed method. Finally, case three is the simulation of the self-gasification experiment. The agreement between the results of the proposed simulation model and the analytical and experimental results confirms the validity of this method.

2. Simulation domain structure

The existence of a rock structure in hydrocarbon reservoirs is the major difference between coal seams and hydrocarbon reservoirs, particularly those of heavy oil. In coal seams, there is a large volume of very low porous coal that is composed of moisture,

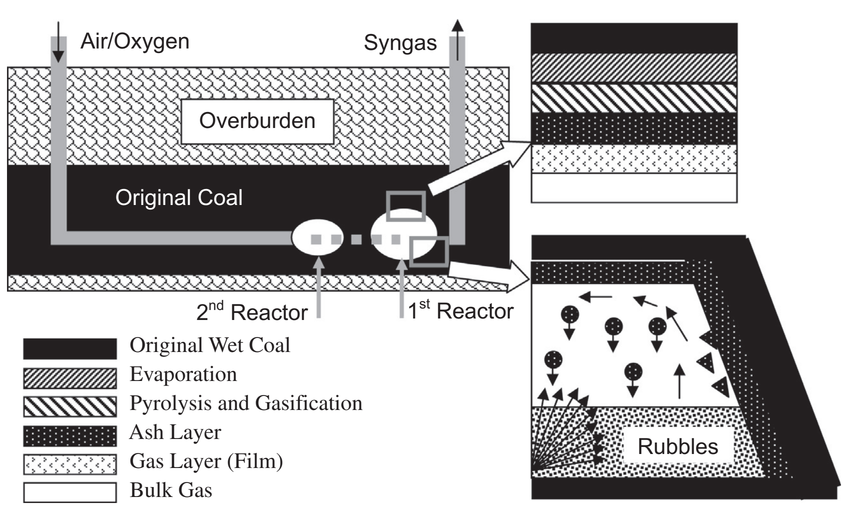

Fig. 1. Schematic of linear CRIP and underground cavities with relevant phenomena.