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General hydro-geological impact of cleats on underground coal gasification

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ABSTRACT

Potential aquifer contamination has been a huge environmental concern for the implementation of underground coal gasification (UCG) as coal seams are frequently overlaid by an aquifer. To explore the general impact of cleats on the mass transfer problems in UCG, particularly in the vertical direction, a dual-permeability (DP) cleat model was integrated into a 3-D numerical model which is dimensionally extensive to account for the hydrostatic effect of an aquifer. It was found that cleats favour UCG production, and the prime operational parameter, i.e., the injection pressure, plays a dominant role in governing vertical mass transport in UCG. Syngas production retains some constancy with variable geological settings unless a surge in the injection pressure occurs. Higher pressure injection generates higher peak rates but delayed production. At near-hydrostatic injection, gas species attain a weak presence in the overburden contrary to expectations based on key geological parameters. However, gas saturation in the cap rock increases appreciably under above-hydrostatic injection. The role of higher injection pressure becomes so overwhelming that variations or heterogeneity in geological parameters produce little difference in the transfer problems.

1. Introduction

Underground coal gasification (UCG), or in-situ coal gasification, is a process to convert coal in-situ into valuable combustible gases through the same chemical reactions that occur in surface gasifiers [1]. In practice enriched air or pure oxygen and/or steam are injected through an injection well to oxidize subsurface coal and initiate a series of chemical reactions to form synthesis gas (Syngas) constituting of primarily CH_4, CO, H_2, CO_2 and trace gases such as H_2S [2]. Syngas, which is brought to the surface through a producer, can be used to produce a wide range of products including transportation fuels and petrochemicals [3]. As a critical technology for recovering the energy of coal in-situ which is otherwise unmineable economically by conventional means, UCG has the merit of mitigating appreciably carbon pollution [4]. Therefore, it has a huge promise for compliance with the Paris Climate Agreement of mitigating markedly CO_2 intensity of fossil energy use.

Coals are organically rich resources with naturally fractured systems-called cleats-which cut across the bedding surfaces at approximately 90 degrees. Cleats correspond to joints in other sedimentary rocks [5,6], and usually occur in two sets of roughly mutual-perpendicular fractures. The dominant face cleats are parallel, through-going and extensive fractures that form first, whereas the other set of fractures-butt cleats-are less well-developed, often terminating at a face cleat [7,8]. These are parallel to the bedding strike while butt cleats are perpendicular to it. These mutually perpendicular fracture sets impart a blocky character to coal (Fig. 1a). A hierarchy of cleat sizes typify the population of cleats in a coal bed [7] (Fig. 1b).

Cleats are observed to nearly occur in all coal beds, provide most of the permeability of coal deposits, and thus can exert fundamental control on fluid flow behaviour in UCG. Darcy's flow of gas and water in cleats has been verified by numerous researchers using whole cores in the laboratory and in the field [9–11]. Attempts to flow water through non-cleated coal cores have been unsuccessful. In the mining industry, the significance of cleats in efficient design and safety of underground coal mines has continued to command attention [12–14]. In the development of coalbed methane, coal cleats are intensively characterized and utilized to enhance gas production [15]. The reality is that in the field of UCG cleats have gained little recognition despite their dominance in governing fluid flow and/or heat transfer. Actually the role a cleat system plays in mass transport in UCG can be more complex when heat is introduced. Therefore, the inclusion of a cleat network into coal models is necessary and imperative for the modelling of coal gasification in the subsurface. Buscheck et al. applied a dual-continuum model to study the effects of a water influx on UCG cavities by using Lawrence Livermore National Laboratory's proprietary Nonisothermal Unsaturated-saturated Flow and Transport (NUFT) code [16]. However, the underlying UCG model was oversimplified. For example, they included no chemical reactions and represented thermal influence of coal combustion with a specific heat-generation rate. A non-dynamic cavity

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Nomenclature

A	cross-sectional area in flow direction, m^2
C_i	molar concentration of component i, mol/m^3
C_{si}	molar concentration of solid component i, mol/m^3
C_p	isothermal compressibility, kPa^{-1}
C_T	isobaric expansion coefficient, K^{-1}
D_{ij}	molecular diffusivity of component i in phase j, m^2/s
E	activation energy, kJ/mol
g	acceleration due to gravity, m/s^2
H_j	enthalpy of phase j, kJ/kg
H_{rl}	enthalpy of reaction l, kJ/kg
k_0	initial permeability, md
k	absolute permeability, md
k_j	relative permeability to phase j, md
k_{mul}	pre-defined directional multiplier factor, integer
K	thermal conductivity, J/m-day-K
n_p	total number of phases
n_b	total number of gas species in gaseous phase
n_s	total number of solid components
n_r	total number of gases involved in reactions
s_{li}	stoichiometry coefficient of component i in the reactants of reaction l
s'_{li}	stoichiometry coefficient of component i in the products of reaction l
P	fluid phase pressure, kPa
P_r	reference pressure, kPa
P_j	pressure of phase j, kPa
q_{jk}	injection/production rate of phase j in layer k, m^3/day
$q_{aq_{wk}}$	water influx rate from surrounding, m^3/day
r	reaction rate constant, day^{-1}
r_l	chemical reaction rate of reaction l, day^{-1}
R	universal gas constant, J/mol-K
S_j	saturation of phase j, fraction
t	time, day
T	temperature, K
T_r	reference temperature, K
T_j	transmissibility of phase j, m^3/s-kPa
U_j	internal energy of phase j, kJ/kg
U_s	internal energy of phase j, kJ/kg
U_r	internal energy of rock, kJ/kg
v_j	fluid velocity of phase j, m/s
v_g	gaseous phase velocity, m/s
V	grid block volume, m^3
y_{ij}	more fraction of component i in phase j, fraction
Z	elevation, m
δ_{iw}	component i concentration in aqueous phase, fraction
ϕ	void porosity, fraction
ϕ_0	initial void porosity, fraction
ϕ_v	current void porosity, fraction
ϕ_f	fluid porosity, fraction
κ	reaction frequency factor, variable unit
σ_p	fracture-matrix transmissibility, fraction
σ_T	fracture-matrix thermal transmissibility, fraction
ρ_j	density of phase j, kg/m^3
ρ_g	gaseous phase density, kg/m^3
ρ_{si}	density of solid component i, kg/m^3
μ_j	viscosity of phase j, cp
Φ_j	fluid potential of phase j, kPa

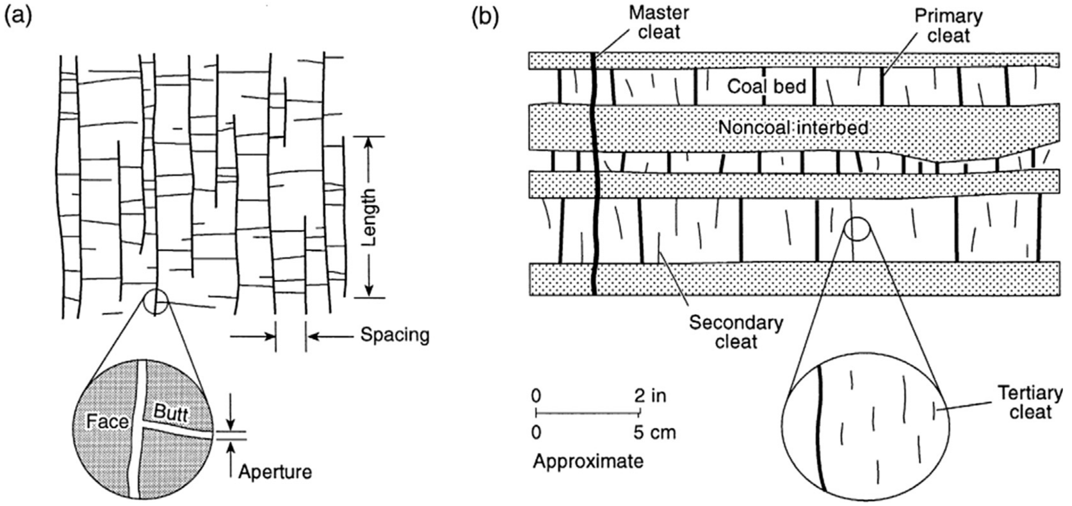

Fig. 1. Schematic illustration of coal cleat geometries. (a) Cleat-trace patterns in planar view. (b) Cleat hierarchies in cross-section view (after [7]).

was assumed to be a 0.2-m-diametr by 10-m-long zone. In this paper, a dual-permeability (DP) model was incorporated into a practical 3-D UCG model to simulate the general impact of cleats on the transfer problems in UCG using a reservoir simulator STARS from Computer Modelling Group Ltd., which is capable of modelling thermal and advanced processes with robust reaction kinetics and geomechanics capabilities [17]. Particular attention was given to mass transport in the vertical direction to investigate the likelihood of aquifer contamination by UCG.

2. Mathematical equations

Mathematical equations of conservation apply to both matrix and fracture domains in a fractured medium. The use of a DP model permits an inter-matrix exchange of mass and heat. Mass balance on component i in a multicomponent and multiphase system takes the following form on the dual continua, with subscripts m and f denoting matrix and fracture/cleat domains, respectively: