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A novel approach to model enhanced coal bed methane recovery with discrete fracture characterizations in a geochemical simulator

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ABSTRACT

Coal bed methane (CBM) has received increasing attentions as a significant energy resource. Numerical modeling of the CBM recovery processes entails simulation of the complex coupled mechanisms, including desorption of methane from the coal matrix surface, diffusion of gas to coal cleats, and gas flow from coal cleats to the wellbore. Beyond these complex flowing mechanisms, it is crucially important to represent coal cleats, structural fractures, and/or hydraulic fractures realistically in CBM simulators as they provide flow channels and dominate CBM flow behaviors. Existing CBM simulators are typically extended from oil and gas reservoir simulators with either black-oil or compositional formulation, and sorption and desorption are usually modeled by the Langmuir isotherms. The concept of shape factor is commonly used to characterize the flow between matrix and cleats (or fractures). When the shape factor is treated as only a function of cleat spacing, the detailed characteristics of actual cleats (or fractures) are missing, including the spatial distribution of cleats and interconnectivity of cleats. In this study, we propose a new workflow to perform a 2-D coal bed methane recovery simulation with discrete fracture model (DFM) in consideration of both structural fractures (large-scale fractures) and cleats (small-scale fractures). There are two key steps in our approach. First, we use a detailed network of discrete fractures characterized from core samples to represent the actual distribution of identified cleats, and calculate the shape factor of the realistic cleated coal sample by running a flow simulation to pseudo-steady state. Second, we apply the shape factor to field-scale simulations in which large-scale fractures are modeled as DFM. For this purpose, we treat gas sorption and desorption as a "chemical reaction", and we developed an extension to an existing geochemical-reservoir simulator. We implemented both a "pseudo-compositional" and a "full-compositional" module to study the effect of mass exchange between gas and aqueous phases. We validated our new formulation and simulator development from a benchmark case in which our simulation results show close agreement with commercial simulators. We also demonstrated the significance of modeling mass exchange between fluid phases on CBM recovery in some cases, which is commonly missing in most commercial simulators. Finally, we presented our workflow in modeling an enhanced CO_2-ECBM recovery process to a complex fractured coal bed with both large-scale tectonic fractures and small-scale cleats.

1. Introduction

Coal bed methane (CBM) has received increasing attention as a vast energy resource. Different from conventional natural gas, which is freely stored in the pore space, the majority of coal bed methane is stored in the coal matrix by sorption. Because coals typically have large specific area, CBM reservoirs can accommodate a vast volume of methane. Former studies have shown that the amount of CBM resources in the United States ranges between 440 and 700 trillion cubic feet (TCF), of which approximately 150 TCF are considered recoverable (White et al., 2005). Over years, many technologies have emerged for enhancing the CBM recovery, among which the so-called enhanced coal bed methane (ECBM) process that entails injecting another gas component (e.g., CO_2) into the coal seams is proved to be highly efficient in laboratory experiments (Puri and Yee, 1990; Arri et al., 1992), and in field tests (Puri, 1996). Additionally, the CO_2-ECBM approach is naturally an appealing option for CO_2 sequestration.

Gas adsorption and desorption, and gas transport, are the keys to CBM production. Kinetics experiments and field practices have shown the gas is stored in coal by three mechanisms, including physically adsorbed compounds on the internal surfaces of the coal, compounds absorbed within the molecular lattice, and

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Nomenclature

C	concentration
D	diffusion coefficient
L	fracture spacing
M	symbols of species
S	saturation
V	bulk block volume
VL	Langmuir volume constant
X	species molar fraction
b	sorption constant
f	fugacity
p	phase pressure
q	component molar rate
u	Darcy velocity
ν	stoichiometric coefficients
r	reaction rate
ϕ	porosity
ρ	molar density
σ	shape factor
μ	viscosity
τ	sorption time
δ	proportional coefficient

Subscripts

c	species
e	element
f	fracture
g	gas
k	kinetic
l	liquid
m	matrix
p,j	phase
q	equilibrium
r	reaction
m	mobile
im	immobile

Metric conversion factors

°C	$1.8 \times$ °C $+32 =$ °F
km^2	$\times 247.1 =$ ac
kg/m^3	$\times 6.243E-2 = lb/ft^3$
m	$\times 3.28084 =$ ft
m^3/d	$\times 35.3147 =$ scf/d
kg	$\times 2.20462 =$ lb

capillary condensation within the micropore (Shi and Durucan, 2005). The concept of sorption is proposed to include the three mechanisms. Sorption isotherm can estimate the total content of adsorbed components, and one commonly used example in practice is the two-parameter Langmuir model characterized by the Langmuir volume and Langmuir sorption constants. In this approach, the gas phase partial pressure determines the thermodynamic equilibrium between the free gas in pore space and the adsorbed gas. In multi-component systems, an extended Langmuir model is commonly applied.

Characterizing gas transport from matrix to wellbore in coal seams entails simultaneously modeling of two mechanisms, the diffusion process driven by the gas concentration gradient, and the Darcy flow governed by permeability, viscosity, and pressure gradient (Law et al., 2002). Desorbed gas diffuses from the coal matrix surface to the cleats, which are composed of closely spaced small-scale fractures, and then transports towards the producer in larger-scale fractures (Fig. 1). The flow into and through the cleats (or fractures) are usually modeled with a dual-porosity model. In such approach, the flow transfer between adjacent mediums is scaled up to the entire block by introducing the shape factor (or transfer function) that is evaluated by the cleat spacing. Although efficient, the shape factor based on the standard dual porosity approach suffers from some significant limitations including that it is incapable of modeling complex fractures with sufficient details and it is difficult in accurately evaluating the transfer function between the matrix and the fractures (Karimi-Fard et al., 2006), though more advanced formulations exist (e.g., Lemonnier and Bourbiaux, 2010). In addition, in many CBM reservoirs, large-scale fractures (e.g., naturally occurred structural fractures, or hydraulic fractures) may dominate the gas flow, and thus require more detailed characterization. As an improvement to dual-porosity models, the discrete fracture model (DFM) enables modeling each fracture individually and explicitly, thus can better represent the fracture characterization. In this study, we propose a novel workflow to apply DFM to model coal bed methane recovery processes. Specifically, we first apply the DFM approach to calculate the shape factor for arbitrarily shaped matrix-cleat media by performing a core scale simulation. In the second step, we apply the shape factor or the lumped sorption time that calculated at core-scale to perform a field-scale simulation. The DFM approach is used again to model the large-scale structural factures.

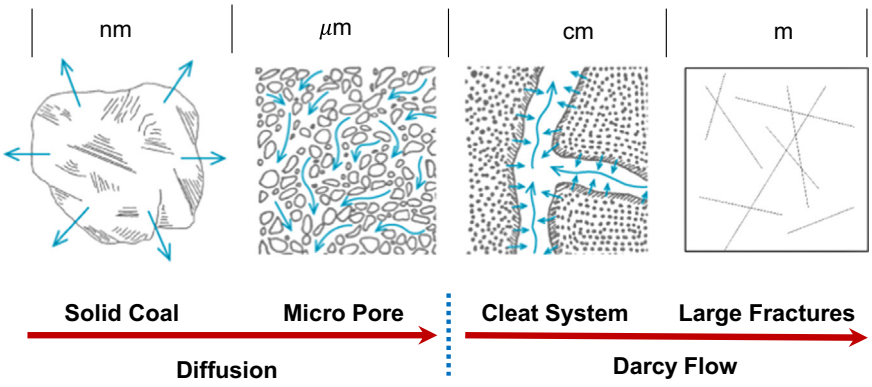

Fig. 1. Gas storage and transport in the coal medium (Remner et al., 1986).