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Multiscale imaging, modeling, and principal component analysis of gas transport in shale reservoirs

Cheng Chen

Virginia Tech, United States

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ABSTRACT

Characterization and upscaling of gas transport in shales is challenging because of the multiple spatial scales. Rock characterization using high-resolution imaging (e.g., X-ray computed tomography [CT] and scanning electron microscope [SEM]) captures fundamental geometrical and transport properties, but the obtained information is usually highly localized and contains significant uncertainties. An effective upscaling method is thus needed to propagate the pore-scale information across multiple spatial scales. A modified dual-porosity model was proposed to study multiscale gas transport in shales. The model consists of two domains, a kerogen domain, and an inorganic matrix. Within kerogen, gas transport is dominated by molecular diffusion and nonlinear adsorption and desorption. Within inorganic matrix, gas transport is dominated by viscous flow driven by a pressure gradient. A mass-exchange-rate coefficient is used to describe gas transport between kerogen and inorganic matrix. The modified dual-porosity model was used to perform history matching of a pressure-pulse-decay experiment in the laboratory. The long tail of the pressure decline curve was well-captured by the model, suggesting that it accounted for both fast and slow transport mechanisms. Sensitivity analysis was conducted to study the impact of input variation on model output. We found that the impact of the transport processes within the slower domain (kerogen) depends primarily on the transport rate within the faster domain (inorganic matrix). The principal component analysis (PCA) method was applied to study the continuous movement of the upstream pressure decline curve resulting from input parameter variation. This study is the first to apply the PCA method in analysis of pressure decline curve in reservoir engineering. We found that increased convective transport rate within inorganic matrix expedited upstream pressure decline; conversely, increased mass-exchange rate and desorption-rate coefficients slowed down upstream pressure decline in the short term, but expedited it in the long term, when convective transport within inorganic matrix was fast. We also conducted primary recovery simulations to study the impacts of adsorbed gas ratio and Klinkenberg effect on upstream pressure decline, recovery factor, and recovery rate. We found that a higher adsorbed gas ratio led to a longer recovery rate curve. This confirms that a higher adsorbed gas ratio increases the longevity of a gas-producing well. Furthermore, Klinkenberg effect significantly enhanced initial recovery rate while lowering recovery rate at later times. Therefore, it is critical to accurately evaluate adsorbed gas ratio because it determines the shape and longevity of production curves; when reservoir pressure is relatively low, Klinkenberg effect might affect both early- and later-time production and thus cannot be simply ignored.

1. Introduction

Global consumption of hydrocarbon energy has steadily increased during the past few decades. To meet increasing energy demands, recovery of unconventional hydrocarbons from shale reservoirs has attracted significant attention. Hydrocarbon recovery in tight reservoirs has proven difficult because of the relatively low porosity and extremely low permeability. Generally, the permeability of organic-rich shale reservoirs varies from nanodarcy (nD) to microdarcy (μD), and porosity is below 10%.

Production rate in shale gas reservoirs usually peaks within the first few months and then declines rapidly followed by a long tail [2]. This implies both fast and slow transport mechanisms exist within shale reservoirs during production; the fast transport processes occur within relatively large pores and fractures, leading to high production rates at early times, while the slow transport processes occur within relatively small pores and fractures,

E-mail address: chen08@vt.edu

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Nomenclature

b	Klinkenberg coefficient	M	molar mass
c	speed of sound	$\mathbf{M}$	covariance matrix
C	free gas molar density within inorganic matrix	m	mass-exchange-rate coefficient
C_k	free gas molar density within kerogen	p	pressure
C_μ	adsorbed gas molar density within kerogen	$\mathbf{p}$	pressure matrix
$C_{\mu s}$	maximum monolayer gas adsorption within kerogen	r	pore radius
C_g	gas compressibility	R	gas constant
D	free gas diffusivity within inorganic matrix	T	absolute temperature
D_p	pressure diffusivity	t	time
D_K	Knudsen diffusivity	t_c	characteristic time of pressure propagation
F	correction coefficient for slip boundary	x	distance
J	overall mass flux	z	compressibility factor
J_D	mass flux due to Darcy flow	α	tangential momentum accommodation coefficient
J_K	mass flux due to Knudsen diffusion	μ	dynamic viscosity
k	absolute permeability	ϕ	total porosity
k_a	apparent permeability	ρ	free gas mass density
Kn	Knudsen number	λ	free gas mean-free-path length
K	equilibrium partition coefficient	ε_{kp}	kerogen pore volume per unit total pore volume
k_{ads}	adsorption-rate coefficient	ε_{ks}	kerogen solid volume per unit total solid volume
K_{des}	desorption-rate coefficient	Γ	mass transfer rate between kerogen and inorganic matrix
L	core plug length		

contributing to low and persistent production rates at later times. It is widely accepted that the slow transport mechanisms are related to molecular diffusion and gas adsorption and desorption within kerogen, which should be characterized at the nanometer scale.

Recently, numerous researchers have employed scanning electron microscopes (SEMs) to visualize the internal structure of shale kerogen at the nanometer scale [4,8,15,17,21]. On the basis of image data, quantitative image analysis and pore-scale direct simulation using the lattice Boltzmann (LB) method were performed to obtain the geometrical and transport properties of kerogen, such as porosity, tortuosity, specific surface area, and absolute permeability [4]. Parallel computing on central processing units (CPUs) and graphics processing units (GPUs) was applied to optimize pore-scale LB simulation to handle larger computational domains [6].

The dual-porosity transport model has been widely used to describe transport processes within porous media consisting of two domains which have different porosities and permeabilities; a mass-exchange term is applied to account for mass transfer between the two domains [10,18]. Akkutlu and Fathi [1] used the dual-porosity mode to account for the fast and slow transport mechanisms in shale gas reservoirs. Sun et al. [20] showed that a dual-porosity dual-permeability model with Knudsen diffusion is in general adequate to model shale gas production.

This study presented a workflow for investigating gas transport in shale reservoirs, which includes multiscale imaging, mass flux modeling, upscaling, and sensitivity analysis. Principal component analysis (PCA) was used to quantitatively analyze the continuous movement of the pressure decline curve in response to input parameter variation. In addition, this study illustrated the role of pore-scale research in upscaling and multiscale research. The combination of pore-scale research, upscaling model, and PCA method leads to a methodology of multiscale investigation for gas transport within shale reservoirs.

2. Multiscale pore geometry imaging

Fig. 1 illustrates a two-dimensional (2D) raw image of a shale sample scanned using X-ray computed tomography (CT) with a resolution of 64 nm/pixel. The inorganic matrix, which appeared bright because of the higher density, contained relatively large pores which are referred to as inorganic pores. Conversely, the organic-rich clay, which appeared dark because of the lower density, contained nanometer-scale pores. These pores cannot be well-resolved using the current resolution, and thus require imaging approaches with a higher resolution, such as SEM [4,6]. This CT image demonstrates that shale rocks have heterogeneous pore size distributions and mineral compositions, which result in multiscale transport processes.

Fig. 2a presents a shale sample extracted from a Middle Eastern shale gas reservoir scanned using SEM with a resolution of 12 nm/

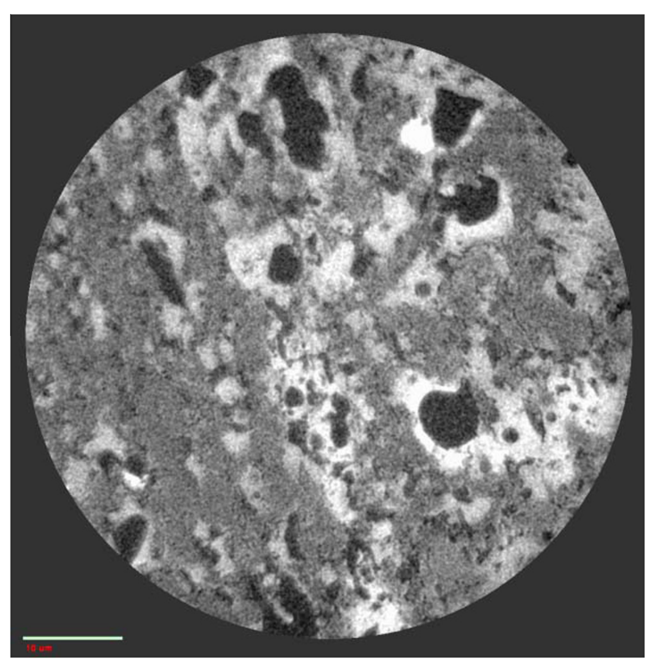

Fig. 1. A shale sample scanned using X-ray CT with a resolution of 64 nm/pixel. Bright regions correspond to inorganic matrix, which has relatively higher density, while gray regions correspond to organic-rich clay, which has relatively lower density. Relatively large pores are surrounded by inorganic matrix, while small pores are dispersed within organic-rich clay. The scale bar is 10-μm long.