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Effect of microscale compressibility on apparent porosity and permeability in shale gas reservoirs

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ABSTRACT

The pore network in shale reservoirs comprise of nanoporous organic matter (OM) and micron-size pores in inorganic material (iOM). Accurate gas transport models in shale must include gas slippage, Knudsen diffusion, surface diffusion, and sorption. The change in pore size due to the applied stress could consequently affect gas transport processes. In this study we a compression coefficient to characterize the influence of stress sensitivity on key parameters for gas transport. We consider separate stress response in nanoporous organic matter and iOM because of their different mechanical properties. The effects of compressibility on apparent permeability of OM and iOM are analyzed at different pore sizes, pore pressures and for different gas compositions. Our results show that compressibility has a greater influence on the apparent permeability of iOM than on OM when pore sizes are smaller than 10 nm, whereas compression has similar impact on apparent permeability of both media when pore sizes are larger than 10 nm. With the same effective stress, lower pore pressure results in greater impair in permeability. We conducted a reservoir simulation study using conventional dual-continua model with our developed pressure dependent porosity and permeability to showcase field implication of this study. This work is an important and timely investigation of the development of shale-reservoir-flow simulators.

1. Introduction

Shale gas reservoirs are composed mainly of OM and iOM. Research shows that pore sizes in shale gas reservoirs range from 1 to 200 nm [26,28,56,58,59] and that organic pores are usually smaller than 10 nm in diameter [3,41,45,46]. The mechanisms of gas migration in microscale pores, which differ from those in conventional reservoirs (Fig. 1), include viscous flow with slippage, Knudsen diffusion, surface diffusion, and gas adsorption and desorption [1,13,16,20,29,33,49,57,64]. Unlike conventional reservoirs, migration of shale gas in microscale media is strongly influenced by factors such as absorbed gas, pore pressure, pore size, and properties of porous media. Therefore, the conventional Darcy equation and intrinsic-property parameters of a reservoir (such as permeability and porosity) are no longer applicable for describing complex gas- transport mechanisms in shale reservoirs.

In recent years, researchers have introduced "apparent permeability" for shale gas reservoirs to describe gas transport in microscale pores. Javadpour [20] first introduced an apparent-permeability model that couples viscous flow and Knudsen diffusion in nanopores by comparing formulation for gas flow with the Darcy equation. On the basis of the Javadpour model, many scholars have developed numerous shale models that can couple complex gas-transport mechanisms by apparent permeability. Present-day apparent-permeability models for shale gas reservoirs can be divided into the following three types:

- Javadpour models based on the pore radius of porous media [1,2,20,33–34,36,47,62]
- Civan models based on Knudsen number [11,12,19,38,40,44,49,54]
- The Dusty-Gas Model (DGM) based on diffusion coefficient [17,22,25,27,52,61]

Javadpour models characterize intrinsic permeability, Knudsen diffusion coefficient, and slip factor using pore size and propose coupled-flow equations considering viscous flow, slippage effect, Knudsen diffusion, and surface diffusion. Civan models apply the Beskok model [5] to describe gas migration in porous media and use the Knudsen number in models to couple viscous flow and Knudsen diffusion. The DGM couples viscous flow, Knudsen diffusion, and molecular diffusion in porous media. In the DGM,

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Nomenclature

C_g	gas compressibility, MPa^{-1}
C_k	OM total compressibility, MPa^{-1}
C_m	iOM total compressibility, MPa^{-1}
$c_{\mu s}$	Langmuir volume on the OM surface, mol/m^3
c_k	amount of free gas in unit OM, mol/m^3
c_μ	amount of adsorbed gas in unit OM, mol/m^3
c_m	amount of free gas in unit iOM, mol/m^3
D_{k_kn}	Knudsen diffusion coefficient of OM, m^2/s
D_{km}	Knudsen diffusion coefficient of iOM, m^2/s
D_s	surface diffusion coefficient of OM, m^2/s
$D_{s,0}$	surface diffusion coefficient of OM at zero loading, m^2/s
f	tangential momentum accommodation coefficient (TMAC)
k_{kv}	intrinsic permeability of OM, m^2
M	molecular weight, kg/mol
N_{k_kn}	flux for Knudsen diffusion of free gas, $mol/(m^2 \cdot s)$
N_{k_vs}	flux for slippage viscous flow of free gas, $mol/(m^2 \cdot s)$
N_{k_su}	flux for surface diffusion of adsorbed gas, $mol/(m^2 \cdot s)$
p_{ini}	initial pressure in reservoir, MPa
p_k	pressure in OM, MPa
p_m	pressure in iOM, MPa
p_L	Langmuir's pressure, MPa
r_k	effective radius of pores in OM, m
r_{k_ini}	initial effective radius of pores in OM, m
r_{m_ini}	initial radius of pores in iOM, m
R	universal gas constant, 8.314 J/(K·mol)
T	formation temperature, K
Z	compression factor
ϕ_k	effective intrinsic porosity of OM
ϕ_{k_ini}	effective initial intrinsic porosity of porous keregen
ϕ_m	intrinsic porosity of iOM
τ_k	tortuosity correction factor of OM
τ_m	tortuosity correction factor of iOM
μ_g	gas viscosity, mPa·s
ε_{ks}	proportion of solid OM volume in total interconnected matrix pore volume
θ_k	the surface coverage of the adsorption layer on the porewall

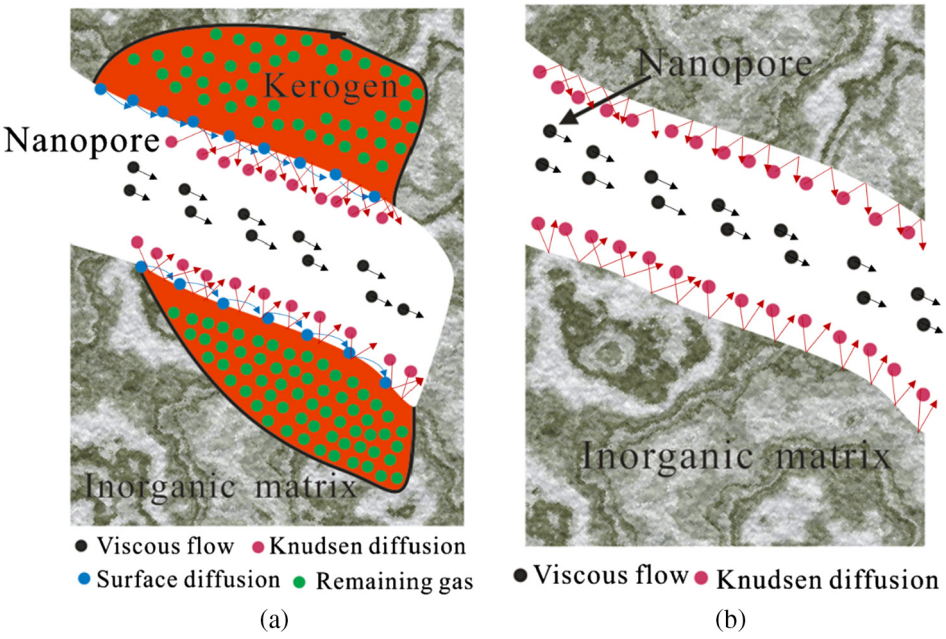

Fig. 1. Mechanisms of shale gas migration in (a) OM, and (b) iOM.

apparent permeability is presented in the form of the Klinkenberg effect for one-component gas in shale gas reservoirs with viscous flow and Knudsen diffusion.

Extensive research has shown that apparent permeability of shale gas reservoirs is affected by many factors, including pore pressure, reservoir temperature, surface roughness, and phase change [8,14,37,43,60].

Stress sensitivity is the effect of pore-throat shrinkage on permeability. During depressurization development, effective stress increases, resulting in the rearrangement and crushing of matrix particles. Stress sensitivity of rock occurs with specific petrophysical phenomena, including decreases in pore size, intrinsic porosity, and intrinsic permeability [50]. Compared with sandstone, shale matrix strength is weaker with more deformation, and the effect on stress sensitivity is stronger [15,48]. Related experiments showed that permeability and porosity decrease significantly with the increase of effective stress in shale reservoirs [2,10,15,30]. When Dong et al. [15] measured stress-dependent permeability and porosity, results showed that permeability of shale was more sensitive to effective confining pressure than was permeability of sandstone, while sandstone and shale showed a similar sensitivity of porosity to effective pressure. Dong et al. [15] results also indicated that power law can be used to characterize regularity permeability and porosity with stress dependence.

Mokhtari et al. [30] characterized natural or induced fractures in several shale reservoirs using computed tomography (CT) scans in various resolutions and evaluated the effect of stress on permeability. Results showed that effective permeability to gas declined