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Apparent permeability for liquid transport in nanopores of shale reservoirs: Coupling flow enhancement and near wall flow

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ABSTRACT

Multiple mechanisms of oil transport in inorganic and organic nanopores of shale oil reservoirs are still unclear and possibly more complex than those of gas transport in nanoporous media, due to differences of molecules free path and fluid-solid molecular interactions. The accurate apparent permeability model considering oil transport mechanisms and different pore types is important for macroscale modeling in shale oil reservoirs development. Based on studies of molecular dynamics simulations (MDS), liquid flow through carbon nanotubes (CNTs) and theoretical analysis, a unified apparent permeability model of liquid hydrocarbon flow in the shale is derived coupling different transport mechanisms in inorganic and organic nanopores. The model of oil-wet organic nanopores considers liquid-solid adsorption, while the model of water-wet inorganic nanopores incorporates near wall flow and velocity slip. We then introduce complicated structural parameters including the tortuosity, porosity and total organic carbon (TOC) to develop models from nanotubes into porous media. After that, the proposed model is validated by MDS and experimental results, and the total apparent liquid permeability (ALP) as well as contributions of different mechanisms are studied. The results indicate that, flow enhancement should be considered in the characterization of oil transport in nanopores, and the velocity of oil in inorganic nanopores much faster than that in organic nanopores in this work. For pore radii under 10 nm, the total ALP is much larger than intrinsic permeability, and adsorption effect as well as velocity slip in organic matter (OM) and inorganic matter (IM) influence the total ALP slightly when the pore radius is larger than 100 nm. In addition, the greater slip length in IM results in greater contributions of oil transport in IM to the total ALP if slip length is less than 10 nm. Moreover, the ratio of the total ALP to intrinsic permeability decreases as TOC increases when TOC is larger than 20%. This work focuses on enriching the theoretical research of oil transport in nanopores and provides a unified ALP model for macroscale modeling study in the shale reservoirs development.

1. Introduction

Shortage of conventional resources has accelerated the development of unconventional resources, such as shale gas and oil reservoirs. Shale oil with rich reserves, great potential and especially the efficient development in North America and China, has gained an increasing amount of worldwide attention [1]. However, the distinguishing characteristics of shale oil from other unconventional resources are mainly caused by the hydrocarbon accumulation mechanism and reserving space types. Similar to shale gas reservoirs, oil is stored in both organic and inorganic pores with nanoporosity and extreme low permeability, which makes oil transport mechanisms in shale difficult to clearly understand [2,3]. Meanwhile, Darcy's law cannot be used to describe liquid transport in shale. Currently, limited studies focusing on oil transport in the nanotube are almost based on MDS [4,5]. Therefore, a further understanding of oil transport mechanisms in different nanopore types is urgently needed, and a mathematical model of ALP coupling multiple mechanisms is essential for macroscale numerical simulation, production forecast and optimization [6,7].

Experimental studies, such as Atomic force microscopy (AFM) and scanning electron microscopy (SEM) used to characterize shale pore structures, suggest that nanopores ranging in size from 1 to 200 nm are abundant presence, and most frequent pore radii are generally smaller than 5 nm [8]. Through X-ray diffraction (XRD) mineralogy analysis, typical components of shales can be divided into OM (oil-wet kerogen) and IM (water-wet quartz, clays et al.)

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Nomenclature

CNT (s)	carbon nanotube (s)
MDS	molecular dynamics simulation (s)
AFM	atomic force microscopy
SEM	scanning electron microscopy
XRD	X-ray diffraction
OM	organic matter
IM	inorganic matter
LBM	lattice Boltzmann method
HP	Hagen-Poiseuille
ALP	apparent liquid permeability
TOC	total organic carbon
C	slip velocity coefficient in inorganic pores (dimensionless)
C_{or}	slip velocity coefficient in organic pores (dimensionless)
c_1	unknown related to slip velocity (m/s)
c_2	unknown related to slip velocity (m/s)
D_s	surface diffusion coefficient (m^2/s)
J_{or}	total mass flux in OM (kg/(m^2 s))
J_{in}	total mass flux in IM (kg/(m^2 s))
J	total mass flux in the porous medium (kg/(m^2 s))
J_v	mass flux in the porous medium with no-slip (kg/(m^2 s))
k_{ins}	intrinsic permeability of the porous medium (m^2)
k_{or}	apparent permeability of organic pores (m^2)
k_{or_b}	apparent permeability of bulk oil on in organic pores (m^2)
k_{or_ads}	apparent permeability of adsorbed oil in organic pores (m^2)
k_{app}	total ALP of shale reservoirs (m^2)
k_{in}	apparent permeability of inorganic pores (m^2)
k_{in_b}	apparent permeability of bulk oil in inorganic pores (m^2)
k_{in_w}	apparent permeability of near wall oil in inorganic pores (m^2)
L	pore length (m)
n_L	number of molecules per unit adsorbed volume (dimensionless)
Δp	differential pressure (MPa)
Q_b	volume flux of bulk oil (m/s)
Q_w	volume flux of near wall oil (m/s)
q_{in}	mass flux in inorganic pores (kg/s)
q_b	mass flux of bulk oil (kg/s)
q_w	mass flux of near wall oil (kg/s)
q_{or}	mass flux in organic pores (kg/s)
R	average pore radius (m)
r	radial distance from the pore center (m)
T	Temperature (K)
v	velocity profile at r (m/s)
v_b	bulk oil velocity at r (m)
v_w	near wall oil velocity at r (m/s)
W_A	adhesion work (J/m^2)
α	total organic carbon (dimensionless)
δ	near wall oil thickness (m)
δ'	adsorbed oil thickness (m)
κ_B	Boltzmann's constant (J/K)
λ	slip length (m)
λ_b	bulk factor (dimensionless)
λ_c	slip factor (dimensionless)
μ	oil viscosity (mPa·s)
μ_{ads}	adsorbed oil viscosity (mPa·s)
μ_{bulk}	bulk oil viscosity (mPa·s)
μ_o	average oil viscosity in porous medium (mPa·s)
μ_w	average oil viscosity in near wall region (mPa·s)
ξ_{ads}'	correction factor for adsorbed oil (dimensionless)
ξ_b	correction factor for bulk oil in IM (dimensionless)
ξ_b'	correction factor for bulk oil in OM (dimensionless)
ξ_w	correction factor for near wall oil (dimensionless)
ρ_w	average density of near wall oil (kg/m^3)
ρ_b	average density of bulk oil (kg/m^3)
ρ_o	average oil density in the porous medium (kg/m^3)
ρ_{ads}	average adsorbed oil density (kg/m^3)
τ	tortuosity of the porous medium (dimensionless)
ϕ	porosity of the porous medium (dimensionless)
ϕ_{ads}'	effective porosity for adsorbed oil (dimensionless)
ϕ_b	effective porosity for bulk oil in IM (dimensionless)
ϕ_b'	effective porosity for bulk oil in OM (dimensionless)
ϕ_w	effective porosity for near wall oil (dimensionless)

as shown in Fig. 1 [9], in which black spots in the dark gray area represent nanopores within OM, while the light dark area is IM composed of quartz, clays et al. Up to now, the gaseous methane transport behavior through porous shale media has been mentioned by researchers using experimental [10] and numerical methods, like MDS [11] and the lattice Boltzmann method (LBM) [12]. Several types of apparent gas permeability models based on Knudsen number and microscale pores have been presented for the macroscale flow simulation [2,13–16]. Different from the gaseous methane, mean free path of liquid molecule is greatly smaller than that of gas molecule, in addition to stronger liquid-solid molecular interactions [17], which might lead to more complex transport behaviors. However, the studies of oil transport mechanisms in nanopores are still limited, especially oil transport behavior in OM [4,18].

Like gas slippage, liquid slippage has also been confirmed to exist between liquid molecules and pore inner wall by experimental methods and MDS [19]. Studies about liquid flow in nanotubes suggest that the slip boundary condition is related to wettability and significantly different from the no-slip boundary condition [4,19–27]. Whitby and Quirke [20] reviewed some experimental results with an emphasis on fluid flow through CNTs, and investigated that water flow rates through CNTs were 560–8400 times higher than those predicted from the macroscale no-slip Hagen-Poiseuille (HP) equation. Hence, the enhancement factor is defined as the ratio of flow rate in a CNT to no-slip HP flow [21]. Majumder et al. [22] observed that the enhancement flow rates of water, hexane, ethanol and alkanes through the multiwalled carbon nanotubes (MWNT) composite membranes were 4–5 orders of magnitude greater than those calculated by HP equation. Their results also show that slip length from 3 to 70 μm is much longer than the tube diameter (7 nm), and decreases as the liquids become more hydrophobic. Holt et al. [23] measured water transport velocity through microfabricated membranes composited of CNTs with <2 nm diameter, and the enhancement factor was calculated to be 3 orders of magnitude. Recently, experimental results have involved in a wide range of CNT diameter from 0.8 to 44 nm, CNT length from 2 to 280 μm, and pressure condition from 0.1–100 MPa [18,22–25]. However, owing to the difficulties of experiments, engineers and scientists focus on the application of MDS to study hydrodynamic properties of fluid transport in nanopores and the near wall region. Barrat and Bocquet [26] used extensive MDS to study hydrodynamic properties of fluid in microscale pores with slip and no-slip boundary conditions, and found slip length exceeding 30 molecular diameters in mercury on glass system. Falk et al. [27] applied MDS to calculate the friction