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A slip-flow model for oil transport in organic nanopores

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ABSTRACT

Shale oil reserves are becoming more important with the development of oil & gas industry. However, the transport mechanisms of oil in nanopores of kerogen remain a mystery. The understanding of the multiple transport mechanisms of oil in nanopores is crucial in the successful development of shale oil reservoirs. In this paper, a new model for flow enhancement of oil transport in nanopores of kerogen is proposed. Both boundary slip and physical adsorption are taken into consideration in the analytical model. Based on the previous experimental and theoretical studies, the model is validated.

Results show that: (a) Covering the Hagen–Poiseuille flow, specific oil flow and the water flow, the new model is more universal in practice; (b) When the radius of the nanotube is equal to 1 nm, the value of slip factor is between 24081 and 48161 (the corresponding correction factor is between 0.7 and 1.4); (c) the flow enhancement is negligible when the radius is larger than 10 nm under various values of correction factor conditions. Besides, the flow enhancement increases with the increasing of the correction factor; (d) when the correction factor is small, the section of the curve higher than zero is characterized with short and low; (e) when the correction factor is smaller than 0.007, the normalized velocity increases slowly with increasing of the correction factor. When the correction factor is higher than 0.07, the normalized velocity increases rapidly when the transport length in nanopores is increased from 10 nm to 200 nm.

1. Introduction

With the increasing demand for energy (Sun et al., 2017a, b, c; 2018a), unconventional resources are becoming more important to the human society (Afsharpoor and Javadpour, 2016; Yan et al., 2017; Sun et al., 2017d,e,f,g,h,i, 2018b,c,d,e,f,g,h,i,j,k,t,u,v). The unconventional resources mainly include heavy oil, low permeability reservoirs and shale reservoirs (Daniel et al., 2016; Mohamed F. El Amin et al., 2017; Sun et al., 2018l, m, n, o, p, q, r; Zhang et al., 2017a,b; 2018c). Among these unconventional resources, shale oil gradually becomes one of the replacement of new energy supplies (Feng et al., 2018a, b, c, d; Hu et al., 2018a, b, c; Zhang et al., 2018a; b). While shale oil resources are widely distributed throughout the world (Gürgey, 2015; Alfarge et al., 2017; Sayed et al., 2017; Daniel J. Soeder, 2018), the development of shale oil reservoirs are now facing great challenges due to the ultra-low permeability and disconnected nanopores in the shale formation (Aricò et al., 2005; Sparreboom et al., 2009; Warner et al., 2012; Siria et al., 2013; Keranen et al., 2014). At present, the knowledge about oil transport mechanisms through nanopores (e.g. slip flow at the fluid/wall boundary and the adsorption phenomenon) is quite limited (Lu et al., 2012; Falk et al., 2015; Zhu et al., 2016; Wu et al., 2017). Fortunately, practical investigations can be conducted due to the availability of new tools (Naguib et al., 2004; Sanhai et al., 2008; Shannon et al., 2008; Lasne et al., 2008; Mirsaidov et al., 2012; Ortiz-Young et al., 2013; Huang et al., 2013; Chiavazzo et al., 2014; Zhao et al., 2016, 2017; Li et al., 2017, 2018KP Wu et al., 2018a, b; C.W. Duan et al., 2018) and recent progress in nanofabrication (Holt et al., 2006; Karan et al., 2012; Surwade et al., 2015; M.Sheikholeslami, 2018a, c, d, e; Sheikholeslami et al., 2018b; Fu and Liu, 2017; Fu et al., 2018; Wen et al., 2018a, b, c; Xiong and Wu, 2018), which can be used to validate a

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new theory of oil flow at the nanoscale.

At present, there is very limited literature published to discuss the mobility of adsorbed components of oil on the surface wall. However, it is a hot spot in the research of water adsorption in nanotubes with various materials. It has been reported that, for the majority of water–wall systems, the adsorbed water cannot move on the wall (Wu et al., 2017). However, by adopting the molecular simulation method, Ho et al. (2011) concluded that water can move directly on a hydrophilic wall of nanotube if preferential adsorption sites located on the wall are close enough.

Given the fact that the components in crude oil is much more complex than water, and the microstructure of kerogen is even can be regarded as a puzzle compared with that of pure material nanotubes, the authors cannot concluded whether the adsorbed oil will flow or not. Under certain conditions, we may conclude that the adsorbed oil is hard to move directly on a wall of nanopore of kerogen. But we cannot conclude that the adsorbed oil cannot move directly on a wall of nanopore of kerogen.

At present, very limited studies were conducted on the oil flow mechanisms in kerogen. The knowledge about the pore characteristics of kerogen is quite limited and it is experimentally difficult to obtain a complete kerogen particle from the shale specimen (Ibrahimov and Bissada, 2010; Suleimenova et al., 2014). As a result, the molecular dynamics simulation (MDS) method was widely adopted in early research (Raviv et al., 2001; Craig et al., 2001; Werder et al., 2003; Liu et al., 2005; Thomas and McGaughey, 2008; Chen et al., 2008; Huang et al., 2008; Sendner et al., 2009; Hilder et al., 2009; Ye et al., 2011; Zhang et al., 2011; Hoang and Galliero, 2012; Cottin-Bizonne et al., 2003; Kelly et al., 2015; Neek-Amal et al., 2016). In their studies, the kerogen was always reduced to graphene for the sake of simplicity (Ambrose et al., 2012; Mosher et al., 2013; Harrison et al., 2014; Wang et al., 2015, 2016a,b). Based on the MDS method, Wang et al. (2015, 2016a,b) studied the transport characteristics of oil in kerogen under reservoir condition with consideration of multi-layer adsorption. It is found out that the velocity profile of oil in kerogen is piston-like, which is quite different from that of fluid flow in conventional macropores. Besides, the mass transport rate of oil in nanopores is 1-3 orders of magnitude higher than that of the non-slip Hagen–Poiseuille flow. This is because there exists slip flow in the nanopores, and the conventional description of fluid viscosity should be replaced with the new physical quantity of apparent viscosity (Majumder et al., 2005; Chen et al., 2008). While the MDS method is useful in simulating fluid flow in nanopores under some certain conditions, it is difficult to capture those physical parameters as mixed wettability, tube-wall roughness, heterogeneity and tortuosity (Schmatko et al., 2005; Bahrami et al., 2006; Joseph and Aluru, 2008; Falk et al., 2010; Yang et al., 2015a; Gu et al., 2016; Guo et al., 2016; Joly et al., 2016). However, ignoring these factors can lead to calculation deviations from the real kerogen body to a certain degree. Besides, the MDS method cannot be used to quantitatively describe the interfacial phenomenon (Secchi et al., 2016), and it is also time-consuming for the modeling process. While empirical formulas can be obtained through the MDS method, it is beyond the capacity in revealing the internal flow mechanisms of oil transport in nanopores. Besides, the velocity profile in the kerogen nanopores should be quantitatively described. Moreover, physical quantities of slip length and the apparent viscosity should be further modeled to meet the real characteristics of nanopores in kerogen. In fact, the viscosity of bulk oil in kerogen nanopores is almost equal to that at the macroscale. Applying the apparent viscosity model cannot capture the key physics in nanopores represented by the velocity profile (Myers, 2011).

In the study of water flow in carbon nanotubes, it has been pointed out that the flow enhancement induced by boundary slip is the main factor contributing to the deviations of water flow at nanoscale from the non-slip Hagen–Poiseuille flow (Neto et al., 2005; Thomas and McGaughey, 2009; Li et al., 2010; Ho et al., 2011; Botan et al., 2011; Lee et al., 2012). In fact, the dominant factors controlling the key behaviors of fluid flow at nanoscale are the hydrophobicity of the fluid and the wettability of the nanotube (Majumder et al., 2011; Gruener et al., 2016). This phenomenon is the one of the main distinguished characteristic that separates the fluid flow at the nanoscale from that at the micro or macroscale.

Mattia and Calabro (2012) developed a model for predicting the slip-flow velocity of water in a carbon nanotube and the flow enhancement was studied. In their model, the effect of nanotube on the transport behaviors of fluid (e.g. surface diffusion, adhesion work as well as the geometric parameters) was taken into consideration (Park and Aluru, 2007; Park and Aluru, 2010; Wei et al., 2011). Compared with the MDS method, theoretical method is able to take the tube-wall roughness as well as the mixed wettability into consideration (Mattia et al., 2015). However, their model did not show good agreement with experimental data due to the complexity of the tube-wall roughness or the hydrogen bonding networks (Zhang et al., 2002; Mashl et al., 2003; Joseph and Aluru, 2008; Wei et al., 2011; Kou et al., 2014, 2015). Then, with the MDS method, Ritos et al. (2014) extended Mattia's model to a wider range of tube material.

Mattia et al. (2015) presented a simplified model for predicting the permeability of carbon nanotubes as a function of the molecular interactions between the fluid and nanotube wall. However, all of these works were focused on the flow behaviors of water in carbon nanotubes (Joseph and Aluru, 2008; Thomas and McGaughey, 2008, 2009, Thomas et al., 2010; Kannam et al., 2013; Muscatello et al., 2016). At present, the validation is in need to test whether their model can be extended to describe the flow behaviors of oil in kerogen. Besides, Mattia's model neglected the adsorption phenomenon of some components from the fluid on the nanotube wall. Given the fact that crude oil is a complex mixture comprised of various components, neglecting the adsorption phenomenon can lead to deviations from the real conditions. It has been reported that the polar components absorbed on the wall surface can be regarded as rock matrix. Because the adsorption process can be regarded as irreversibility (Schwark et al., 1997; Qin et al., 2000; Pan et al., 2005).

It has also been documented that the adsorption induced by Van der Waals is the dominant factor (McGonigal et al., 1990). In the conventional study of water flow in carbon nanotubes, the physical adsorption was always neglected due to strong slip flow at the tube wall (Kondratyuk and Yates, 2007). This assumption can cause deviations from the real distribution of fluid density in the nanotube. The adsorption region can be defined as the area where fluid density is higher or lower than that of bulk fluid (Do and Do, 2005; Severson and Snurr, 2007; Sha et al., 2008; Wu et al., 2017). Riewchotisakul and Akkutlu (2016) developed a model for gas transport through organic nanotubes considering the adsorption phenomenon. It is found out that the adsorbed monolayer has a significant influence on the bulk gas flow in the nanotubes, which proved correctness of previous researchers involved in the area (Akkutlu and Fathi, 2012; Deng et al., 2014; Yang et al., 2015b). However, it has been documented that the physical adsorption was negligible compared with the boundary slip when it comes to oil transport in nanopores (Cui et al., 2017). This may be because the density of bulk oil is obviously higher than that of bulk gas.

Based on the study of water transport in carbon nanotubes, Cui et al. (2017) proposed an analytical model for oil transport in kerogen. It is found out that the boundary slip is the dominant factor contributing to the enhanced flow of oil in kerogen. However, they did not verify well the applicability of water-model to oil flow in nanopores. In fact, the slip flow model should be modified before it can be adopted to describe oil flow (Sun et al., 2018s).

In this paper, an improved analytical model is proposed for evaluating oil transport performance in organic nanopores. This paper has three major contributions to the existing body of knowledge in this field: (a). An improved analytical equation is developed for describing the slip flow of oil in organic nanopores of kerogen. (b). A new model is proposed to quantitatively estimate the flow enhancement. In addition,