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A unified method to evaluate shale gas flow behaviours in different flow regions

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ABSTRACT

As pore size of gas shale ranges widely, various flow types including viscous flow, slip flow and Knudsen flow could coexist during shale gas production. Currently, different models have to be applied to describe the gas transport behaviours in different flow regions and the selection of the models is highly dependent on the flow classification criteria. This also brings difficulty in selecting proper gas flow models near the flow region boundaries, which again depends on the flow classification criteria. To address this problem, this study proposes a unified method to describe the gas flow in the whole spectrum of flow regions by transforming all the gas transport equations for different flow types into a general form. The modelling results by the unified method are comparable with that by the previous models, but less input parameters are required for the unified method. Since the unified method provides a continuous permeability k_{ea} for all flow regions, it avoids discontinuity at the boundary of different flow regions caused by using piecewise flow models. The method is able to depict the gas permeability evolution with reservoir pressure change and is applied to interpret the literature permeability data and to predict the permeability variation among all the flow regions with different gas pressures and pore sizes. The results illustrate that the flow types may change within a specific pore (especially for small pores) during the pressure depletion in shale gas production and different gas transport mechanisms may coexist for some shales with typical bimodal pore size distribution under a specific gas pressure condition. This work provides a unified way to analyse gas flow behaviours and gas permeability variation in different regions and can be readily applied to the reservoir simulation models to predict the gas production behaviour especially the long term gas production behaviour.

1. Introduction

Shale gas has become an important source of unconventional hydrocarbon energy in the USA since 2000, and more interests have spread to China, Australia, Europe and many other countries for potential shale gas development (US EIA, 2011; McGlade et al., 2013). As maintaining long term economical shale gas production is still a challenging task at the moment (Hughes, 2013), understanding the gas transport mechanism and permeability in gas shale is a key scientific issue for extracting shale gas from underground.

Gas shale has complex pore structures (Wang et al., 2009; Passey et al., 2010; Andrade et al., 2011) including pores in inorganic and organic matters, natural and hydraulic fractures. The gas flow through the natural and hydraulic fractures is typically viscous flow, which is normally described by Darcy's law (Wang et al., 2009; Chen et al., 2012, 2015). Non-Darcy behaviour usually occurs in hydraulic fractures around the well (Holditch and Morse, 1976; Ye et al., 2014). The pore size in the shale matrix ranges from nanometres to micrometres, thus the gas flow through the shale matrix may experience several mechanisms at different pore scales, e.g. slip flow or Knudsen flow (Javadpour, 2009). Previous publications have been mainly focused on gas slippage behaviours in slip flow or transition flow region (Florence et al., 2007; Civan, 2010; Heid et al., 1950; Jones and Owens, 1979; Sampath and Keighin, 1982; Ertekin et al., 1986; Wu and Pruess, 1998; Karniadakis et al., 2002). Others have focused on modelling the flow transfer behaviour from shale matrix to fracture network (Ozkan et al., 2010; Ezulike and Dehghanpour, 2014). Hence, more efforts are expected to make to study the flow behaviours across different flow

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regions and especially at the flow region boundaries.

Various flow mechanisms, e.g. viscous flow, slip flow and Knudsen flow in porous media, are identified by Knudsen number Kn, which is defined as:

$$Kn = \lambda / l_c \quad (1)$$

where l_c is the characteristic length of the flow geometry which is taken as the radius of the typical pore size (Civan, 2010) and λ is the mean free path of gas molecules expressed as (Loeb, 1934):

$$\lambda = \frac{k_B T}{\sqrt{2}\pi d^2 p} \quad (2)$$

where k_B is the Boltzmann constant (1.38×10^{-23} J/K), T is temperature, d is the diameter of gas molecule (0.38 nm for methane), and p is gas pressure.

Knudsen number has been used to classify flow regions in shales or other tight reservoirs. Kast and Hohenthanner (2000) suggested the following classification criteria: continuum region ($Kn < 0.01$), transition (slip flow) region ($0.01 < Kn < 1$) and Knudsen region ($Kn > 1$). An additional flow region classification criteria has been suggested by other researchers (Florence et al., 2007; Freeman et al., 2011; Ziarani and Aguilera, 2012): continuum flow ($Kn < 0.01$), slip flow ($0.01 < Kn < 0.1$), transition flow ($0.1 < Kn < 10$) and Knudsen flow ($Kn > 10$). Some researchers suggested $Kn < 0.001$ as a cutting line for continuum flow (Roy et al., 2003). Thus, there has been no universal method for the flow region classification. This leads to difficulties in selecting the applicable model to describe flow, as Knudsen number has to be calculated and used: e.g. Darcy's law for continuum flow, Klinkenberg's correction for slip flow and Knudsen diffusion for Knudsen flow (Kast and Hohenthanner, 2000; Freeman et al., 2011; Ziarani and Aguilera, 2012). Since the cutting lines for different flow regions are controversial, as a result, the applicability of the flow equations could be questionable. In addition, it is difficult to choose an appropriate model near the boundary of different flow regions. Hence the validity or applicability of the existing models is highly dependent on the classification of flow regions.

As stated above, the ambiguity of boundary of flow regions causes difficulties in selecting flow models as well as the accuracy of the modelling in representing the flow at the boundaries near the cutting line. To address this problem, this study proposes a unified method to describe the gas flow in the whole spectrum of flow regions without classifying the flow regions in shale. Furthermore, this method makes the gas permeabilities in different flow regions comparable and consistent at the flow region boundaries. This method is then validated by comparing with previous models and applied to describe the flow mechanisms based on measured data.

2. Development of the unified method

In this section, we will firstly reform the flow equations of all three regions into the same form, then analyse the relationships among these equations and provide a unified flow model. As demonstrated above, three types of flow, e.g. viscous flow, slip flow and Knudsen flow are identified (see Fig. 1) but the existing models are not uniformed in units. We parameterise these three flow types by mass flow rate of N_d, N_s and N_{kn}, which denote to viscous flow, slip flow and Knudsen flow, respectively. These flow rate parameters are then transformed into the same form as a function of pressure gradient with the only difference in the permeability term, which are the absolute permeability, apparent permeability and equivalent Knudsen permeability, respectively.

The viscous gas flow in continuum region ($Kn < 0.01$) is governed by Darcy's law (Kast and Hohenthanner, 2000):

$$q_d = -\frac{k}{\mu}\nabla p \quad (3)$$

where q_d is the volumetric flow rate of Darcy flow, k is the intrinsic or absolute permeability, μ is the fluid dynamic viscosity and ∇p is pressure gradient. The mass flow rate for viscous flow is the product of gas density and volumetric Darcy flow rate:

$$N_d = \rho q_d = -\frac{k}{\mu}\rho\nabla p \quad (4)$$

where N_d is the mass flow rate of viscous flow or Darcy flow and ρ is the gas density.

In the Knudsen region, the gas transport occurs due to free-molecule flow (Knudsen, 1909). Knudsen diffusion based on concentration gradient is normally applied to describe Knudsen flow. This needs to be transformed to mass flow rate based on pressure gradient. For single component gas transport, the Knudsen diffusion can be transformed to the same form as mass flow rate of viscous flow, by introducing an equivalent Knudsen permeability to replace Knudsen diffusion coefficient:

$$N_{kn} = -D_{kn}M\nabla c = -\frac{k_{kn}}{\mu}\rho\nabla p \quad (5)$$

where N_{kn} is the mass flow rate of Knudsen flow, M is molecular weight, and D_{kn} is the effective diffusivity for Knudsen flow considering the porosity ϕ and tortuosity factor τ_{kn} assuming ideal gas (Kast and Hohenthanner, 2000):

$$D_{kn} = \frac{4}{3}L_p\frac{\phi}{\tau_{kn}}\sqrt{\frac{RT}{2\pi M}} \quad (6)$$

where L_p is the pore diameter, R is the gas constant (8.314 J/mol/K), and M is molar mass of gas. The equivalent Knudsen permeability, k_{kn}, is:

$$k_{kn} = \frac{\mu D_{kn}}{p} \quad (7)$$

For the transition flow region, the mass flow rate, N_s, can be described as the summation of Darcy flow N_d and Knudsen flow N_{kn} (also known as slip flow) (Kast and Hohenthanner, 2000):

$$N_s = N_d + N_{kn} = -(k + k_{kn})\frac{\rho}{\mu}\nabla p = -k_a\frac{\rho}{\mu}\nabla p \quad (8)$$

The apparent permeability, k_a, is the summation of the absolute permeability k of the viscous flow and the equivalent Knudsen permeability k_{kn} as expressed by:

$$k_a = k + k_{kn} = k(1 + k_{kn}/k) \quad (9)$$

Thus, Eqs. (4), (5) and (8) have the common form for flow permeability. An extended apparent permeability k_{ea} is introduced here to describe all three flow regions:

$$k_{ea} = \begin{cases} k & k \gg k_{kn} \quad \text{Continuum region} \\ k_a & \quad \text{Transition region} \\ k_{kn} & k_{kn} \gg k \quad \text{Knudsen region} \end{cases} \quad (10)$$

Accordingly the mass flow rate for all flow regions N is the function of k_{ea}