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A new rate-transient analysis model for shale gas reservoirs coupled the effect of slip flow and surface diffusion

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ABSTRACT

Forecasting production in shale gas reservoirs accurately has been of growing interest in the industry. Horizontal wells with multiple fractures are commonly utilized to develop shale reservoirs, which indicates that the dominant flow regime observed will be linear flow for several years. Until now, it has been widely recognized that the rate-transient data analysis is the most efficient approach to estimate rate, where it appears as a straight line on the plot of normalized pressure vs. square root of time in linear flow. However, the traditional square-root-of-time plot may result in overestimation of reservoir properties and will not allow us to forecast production with confidence in shale gas reservoirs. In this paper, a new analytical methodology is put forward to analyze the rate-transient data from fractured wells in shale gas reservoirs producing at a constant flowing-pressure, which incorporates both slip flow/Knudsen diffusion of bulk gas and surface diffusion of adsorbed gas directly into the model. These flow mechanisms cannot be well described by traditional models. Depending on flow discrepancies from conventional reservoirs, the modified pseudo-pressure and pseudo-time equations to account for these critical transport mechanisms are constructed. In addition, a new procedure for rate-transient data analysis applying the proposed model is presented in details, which is reliable and easy to utilize. The novel approach is validated against numerically simulated cases and field observations. Comparisons between the new approach and traditional method are conducted by a number of test cases. The results demonstrate that the newly developed model dramatically eliminates the inaccuracy of production forecast and provides a more reliable estimated ultimate recovery (EUR). This work should provide an efficient guidance to assist analysts in evaluating hydrocarbon production accurately in shale gas reservoirs.

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1. Introduction

In the past two decades, the requirements of estimating production accurately in shale gas reservoirs has proliferated in the industry [1–9]. Horizontal wells with multiple fractures are commonly used to develop shale reservoirs, which demonstrates that the dominant flow regime will be linear flow for a couple of years. Until now, production data analysis models have been widely recognized as the most efficient and easiest approach to estimate gas production in shale [10–12].

Arps [13] presented empirical correlations for production analysis which are consisted of three forms: exponential, hyperbolic, and harmonic. Fetkovich [14] extended Arps decline relations in type curve format by employing novel dimensionless rate and time equations. Blasingame and Lee [15,16] introduced the concept of material balance time and material balance pseudo-time for oil and gas reservoirs to account for variable rate and pressure data. Additionally, depending on the linear flow regime, it has been mentioned that it appears as a straight line on the plot of normalized pressure vs. square root of time [17,18]. However, multiple research demonstrated that the square-root-of-time plot may result in overestimation of reservoir parameters in shale gas reservoirs [19–22]. In order to improve the accuracy of production analysis, Nobakht and Clarkson [22] proposed the corrected pseudo-time in which the gas viscosity and gas compressibility are evaluated at the average pressure in the region of influence. Unfortunately, this analytical method does not account for desorption and gas slippage effects. Later, Clarkson et al. [23] employed the pseudo-pressure and pseudo-time to include slippage effect

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into production data analysis. Also, Nobakht et al. [24] proposed the analytical approach of production data to incorporate desorption and slippage, which is suitable for fractured wells producing under a constant flowing-pressure constraint. Nevertheless, critical mechanisms of gas transport in nanopores of shale gas reservoirs cannot be well described in currently reported research, such as, slip flow/Knudsen diffusion of bulk gas and surface diffusion of adsorbed gas.

From the view of geology, organic pores in shale are generally smaller than 10 nm in diameter [25,26], which is similar to the order of gas-molecule free path. Compared with the collision between gas molecules, the collision between gas molecules and nanopore walls is also significant and must be considered [27,28–31]. Hence, the Knudsen diffusion of bulk gas phase is very prominent in shale gas reservoirs [32,33]. Many researches have been working on the bulk-gas-transfer models for shale nanopores. Currently, two possible types of models describing gas-transport mechanism in shale nanopores are playing a leading role. One is a hydrodynamic model by modifying a no-slip boundary condition in continuum models to account for a slip boundary condition [34–36]. The other is the combination of various transfer mechanisms by employing a certain weight coefficient [37–41].

In addition, the surface diffusion occurs under a concentration gradient and is also caused by desorption of adsorbed gas, which also plays an important part in gas transfer in nanopores [42–44]. For the organic matter with a large surface area, surface diffusion is a very significant transfer mechanism in nanopores of shale [25,45–47]. So far, several classical hopping models to characterize surface diffusion of adsorbed gas are introduced. Hwang and Kammermeyer [48] derived and verified an analytical model of surface diffusion from a hopping model, which is only suitable for a low-pressure condition. Guo et al. [49] fitted an empirical expression of a surface-diffusion coefficient in a methane/activated-carbon system, however, the influence of pressure was not considered and cannot be applied for surface-diffusion calculation of adsorbed gas for a high-pressure condition. Chen and Yang [50] derived a surface-diffusion model by incorporating the adsorbed-gas coverage based on a hopping model.

In this paper, a new methodology is proposed to accurately analyze the rate-transient data from fractured wells in shale gas reservoirs producing at a constant flowing-pressure in the presence of slip flow, Knudsen diffusion and surface diffusion. Depending on the flow discrepancies from conventional reservoirs, the advanced pseudo-pressure and pseudo-time equations to account for these transport mechanisms are put forward, which dramatically eliminates the inaccuracy of production prediction. It is a fully analytical approach rather than an empirical one, which can be widely applicable in regions where production is not relatively well established or a large number of data on historical production are scarce. In addition, based on the proposed approach, a new procedure for rate-transient data analysis is presented in details. Furthermore, this new model is validated using a number of numerically simulated cases, and comparisons between the new model and traditional model are conducted. It is found that the newly developed analytical method results in a more reliable estimate of shale gas production. Also, a good agreement between the field rates and calculated rates from the new model is obtained in Barnett Shale. The work in this paper should provide an efficient guidance to assist analysts in evaluating hydrocarbon production and EUR accurately in shale gas reservoirs.

2. Methodology

In general, the ratio of the mean free range of the gas molecules to the characteristic scale is called Knudsen number (K_n), which is

a critical criterion to distinguish gas transport mechanisms. The gas molecules slip on the wall when $10^{-3} < K_n < 10^{-1}$, where both the intermolecular and wall/molecule collisions play a significant role. The Knudsen diffusion dominates when $K_n \geqslant 1$, where the wall/molecule collisions cannot be ignored. In the actual shale-gas production, the Knudsen number ranges from 0.0002 to 6 [27], leading to the intermolecular collision and wall/molecule collision both becoming important. Overall, gas-transfer mechanisms in nanopores of shale gas reservoirs include slip flow/Knudsen diffusion of bulk gas phase and surface diffusion of adsorbed gas phase, as shown in Fig. 1.

Determining reasonable weighting coefficients of bulk-gas-transfer mechanisms in shale gas reservoirs is of great value. In this work, the calculation approach of weighting coefficients developed by Wu [27] is adopted. The ratios of molecule-collision frequency to total collision frequency and nanopore-wall/molecule-collision frequency to the total collision frequency are utilized to calculate the weighting coefficients of slip flow and Knudsen diffusion of the bulk gas phase in shale reservoirs, respectively. Then, the bulk-gas transfer flux in nanopores is as follows [27]:

$$J_b = \frac{\lambda_T}{\lambda} J_{VS} + \frac{\lambda_T}{2r} J_k \tag{1}$$

Here, J_b is the total bulk-gas flux, mol/(m^2 s); λ_T is the average free path of the overall gas molecules, m; λ is the gas-molecule free path, m; r is the nanopores radius, m; J_{vs} is the slop flow flux, mol/(m^2 s); J_k is the Knudsen diffusion flux, mol/(m^2 s).

The gas-slip flow considering a modification of the slip-boundary condition can be determined as [51]:

$$J_{vs} = -\xi_{mb} \frac{r^2 p}{8\eta RT} (1 + \alpha K_n) \left(1 + \frac{4K_n}{1 - bK_n}\right) \frac{dp}{dl} \tag{2}$$

The Knudsen equation can express the gas-diffusion flux in a circular tube with a radius of r in Eq. (3) [52]:

$$J_k = -\frac{2}{3} \xi_{mb} r \left(\frac{8}{\pi RTM}\right)^{0.5} \frac{dp}{dl} \tag{3}$$

After the unit conversion, the Knudsen-diffusion coefficient obtained from Eq. (3) yields:

$$D_k = \frac{2}{3} \xi_{mb} r \left(\frac{8RT}{\pi M}\right)^{0.5} \tag{4}$$

where D_k is the Knudsen-diffusion coefficient, m^2/s.

The effect of wall roughness on the Knudsen diffusion is significant, which decreases the Knudsen-diffusion efficiency owing to the long gas retention in the vicinity of pore wall. The Knudsen diffusion coefficient considering the wall roughness can be described as [44]:
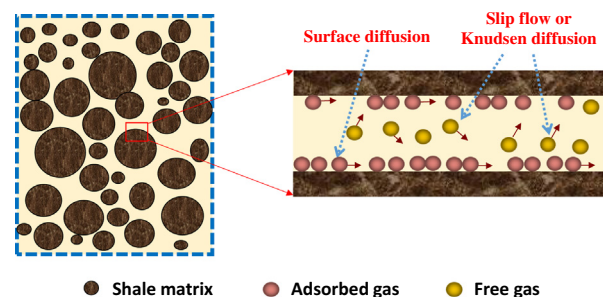
$$D_{eff-k} = \delta^{D_f - 2} D_k \tag{5}$$

Fig. 1. Schematic of gas transport mechanisms in shale gas reservoirs.