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Analytical dual-porosity gas model for reserve evaluation of naturally fractured gas reservoirs using a density-based approach

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ABSTRACT

The development of naturally fractured gas reservoirs often requires the deployment of rigorous techniques for production data analysis incorporating dual-porosity gas behavior. It has been a prominent problem to linearize and analytically solve the governing equations for dual-porosity gas systems. This study applies a pseudo-pressure-based interporosity flow equation to derive a density-based rate-transient analysis method to accurately predict the gas production rate and estimate the amount of original gas in place (G_i) for the systems. The methodology also predicts the gas production rate by transforming the response of its liquid counterpart via a decoupling of the pressure-dependent effects using dimensionless depletion-driven parameters.

For the first time, the density-based flowing material balance method is derived for the dual-porosity gas reservoir. More than that, an innovative fracture productivity equation that was missing for the dual-porosity system is derived as well. This study provided detailed derivations for the model and relationship used in past density-based dual-porosity rate-transient analysis. The dual-porosity productivity equation and the relationship between average matrix pseudopressure and average fracture pseudopressure are rigorously derived. The re-scaling relationship between the dual-porosity liquid solution and the dual-porosity gas solution is also demonstrated in detail. An appropriate interporosity flow equation for gas is used. Based on that, the results show that the density-based approach is able to successfully capture the dual-porosity behavior of gas for constant bottomhole pressure condition.

1. Introduction

Naturally fractured reservoirs are heterogeneous in nature. Many of them comprise discrete volumes of matrix rock separated by fractures. The fractures disrupt the matrix blocks and form continuous networks. Fractures are highly permeable and occupy a small percentage of total reservoir volume. The matrices, on the other hand, are of low permeability and have a large storage capacity. Because of high fracture permeability, most of the fluid flow within a reservoir occurs in the fracture network, while the majority of the fluid is stored in the reservoir's matrix.

Studies of naturally fractured reservoirs have been conducted for decades. This research has proven increasingly important because of the ballooning production from unconventional reservoirs. Barenblatt et al. (1960) proposed a dual-porosity model for liquid, using an interporosity flow equation and a diffusivity equation for the fracture system. The fracture system is treated as a continuous porous medium, while the matrix system is treated as a source of hydrocarbon that provides fluids to the fracture system. The dual-porosity model has been described using partial-differential equations. Warren and Root (1963) used Barenblatt et al. (1960) method for analyzing well test data of oil reservoirs. They assumed a systematic array of identical, rectangular parallelepiped representing matrix blocks throughout an anisotropic reservoir. Warren and Root (1963) analytically solved their governing equations for constant-rate production, examined pressure-buildup performance, and obtained asymptotic solutions. Techniques for analyzing drawdown and build-up data were then proposed by them. They pointed out that storativity ratio and interporosity flow coefficient are controlling parameters in dual-porosity behavior. Of the two controlling parameters, the storativity ratio, ω, is a measure of fluid capacitance of the fracture system, and the interporosity flow coefficient, ξ, represents degree of heterogeneity in the dual-porosity system. The equations for describing the dual-porosity reservoir for homogeneous and isotropic reservoirs following Warren and Root's model in dimensionless form could be written as follows:

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$$\frac{\partial^2 p_{fD}}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial p_{fD}}{\partial r_D} = (1-\omega)\frac{\partial p_{mD}}{\partial t_D} + \omega\frac{\partial p_{fD}}{\partial t_D} \quad (1)$$

$$(1-\omega)\frac{\partial p_{mD}}{\partial t_D} = \xi(p_{fD} - p_{mD}) \quad (2)$$

where $\omega = \frac{\phi_f c_f}{\phi_f c_f + \phi_m c_m}$; $\xi = \alpha\frac{k_m}{k_f}r_w^2$; $p_{Df} = \frac{k_f h\left(p_i - p_f\right)}{qB_o\mu}$, dimensionless fracture pressure; $p_{Dm} = \frac{k_f h(p_i - p_m)}{qB_o\mu}$, dimensionless matrix pressure; $r_D = \frac{r}{r_w}$, dimensionless radius; $t_D = \frac{k_f t}{\left(\phi_f c_f + \phi_m c_m\right)\mu r_w^2}$, dimensionless time; c_f is fracture compressibility plus liquid compressibility; c_m is matrix compressibility plus liquid compressibility; k_f is fracture permeability; k_m is matrix permeability; α is shape factor; ϕ_m is matrix porosity; and ϕ_f is fracture porosity. Note that ξ is used instead of λ to avoid confusion with λ in λ and β rescaling approach. Equation (2) is the pseudo-steady state interporosity flow equation in dimensionless form, as used in the Warren and Root model proposed for liquid. Zimmerman et al. (1993) showed derivation of dimensional form of Equation (2) assuming quasi-steady state flow. Crawford et al. (1976) analyzed pressure buildup data from known naturally fractured reservoirs and found that the Warren and Root model can successfully describe behaviors of these reservoirs. Da Prat et al. (1981) derived a constant bottom-hole-pressure solution in a closed, circular dual-porosity system using the Warren and Root model. Moench (1984) proposed a transient interporosity flow model incorporating skin effect at the interface between matrix and fracture. The skin may result from underground water circulating in groundwater and geothermal reservoirs. Moench found that the pseudo-steady state interporosity flow applies even in early stages when the skin effect was strong enough. Wang et al. (2018) extend the dual-porosity to model cases with fractal property distribution. Yuan et al. (2017) developed a workflow for analyzing production data of naturally fractured shale formations.

On the gas side, efforts have been made to linearize these governing equations using concepts of pseudo-pressure and pseudo-time. However, for gas dual-porosity systems, fluids in the two overlapping continua may be found at different pressures at any given location, leading to markedly different gas properties. Resulting flow equations thus become difficult to linearize and solve analytically. As a result, traditional production decline analysis using pseudo-functions has yet to be proven fully successful.

Spivey and Semmelbeck (1995) used pseudo-time and pseudo-pressure to forecast long-term gas production in shale gas and dewatered coal seams. Pseudo-time accounts for desorption effects by using modified compressibility. This may predict the long-term gas production for a wide range of parameters. However, it is not applicable when there is a small ξr_{eD}^2 or drawdown. Moreover, the applicability of this approach to naturally fractured reservoirs has not been rigorously proven.

Gerami et al. (2007) used pseudo-functions to study dual-porosity systems. Pseudo-time has been defined so as to incorporate the water saturation and compressibilities (Gerami et al., 2007). They presented an innovative interporosity flow equation for gas without derivation. The equation they presented is similar to the equation for liquid but with a changing storativity ratio, ϖ , given as a function of pressure, which implies both nonlinearity and an unsolvable nature. To tackle this problem, Gerami et al. (2007) first solved the equations assuming a constant ϖ. The authors assumed that the same analytical result may be used for gas if ϖ is updated at each time step. The error in using this method increases with the CMG-IMEX results as production continues.

Ye and Ayala (2012, 2013) and Ayala and Ye (2012, 2013) proposed a λ and β density-based approach to analyzing unsteady state flow under constant bottom-hole pressure. Zhang and Ayala (Ayala and Zhang, 2013; Zhang and Ayala, 2014a, 2014b) rigorously derived λ and β and extended them to the variable pressure drawdown/variable rate systems in later work. This density-based approach mostly circumvents the concepts of pseudo-functions and enables straightforward G_i prediction and gas well performance forecasting. Zhang and Ayala (2016) applied the density-based approach to naturally fractured gas reservoirs and observed that the density-based method provides accurate estimations.

In this study, we presented a theoretical basis for using the density-based method in naturally fractured reservoirs and show that behavior of constant-bottomhole-pressure dual-porosity systems is able to be captured by this extended approach at the late stages. This work provides a theoretical background for Zhang and Ayala (2017), which applies the developed dual-porosity gas model for more complex variable drawdown/variable-rate cases and extends the theory to the liquid case. The relationship between matrix gas pseudo-pressure and fracture gas pseudo-pressure used in that work is rigorously developed in this study. This work also presents the rigorous development of the dual-porosity productivity equation used in the previous work. The rescaling relationship between the dual-porosity liquid solution and the dual-porosity gas solution is derived as well, explaining the rescaling relationship discovered in Zhang and Ayala (2016).

1.1. Interporosity flow Equation

The interporosity flow equation employed in Barenblatt et al. (1960) and Warren and Root (1963) has been proposed for a pseudo-steady state liquid flow from the matrix blocks to the fracture system. Starting from physical principles, Zimmerman et al. (1993) derived this interporosity flow equation for liquid using spherical matrix blocks. The development procedure has assumed the “quasi-steady state” approximation, which treats fracture pressure on the outer boundary, p_f, as a constant throughout the derivation.

Owing to pressure-dependent nature of compressibility and viscosity for gas, gas flow from the matrix gridlock behaves differently than the liquid flow. Thus, it is inadequate to use the interporosity flow equation for gas. Instead, The use of an appropriate gas interporosity flow equation is necessary to provide a better description of the gas flow between the matrix blocks and the fracture system. Following Zimmerman's et al. (1993) approach and incorporating the compressibility-viscosity effects over time, we are able to symbolically derive an interporosity flow equation for gas from physical principles as follows:

$$\phi_m\frac{d\rho_m}{dt} = \frac{\alpha k_m}{2\theta}\left(m(p_f) - m(p_m)\right) \quad (3)$$

where ρ_m is matrix fluid density, $\theta = RT/MW$, and $m(p_f)$ and $m(p_m)$ are fracture pseudo-pressure and matrix pseudo-pressure, respectively. Appendix A shows the development of Equation (3) in detail. In the development process, an incompressible matrix is assumed for simplicity. A general form of interporosity flow equation considering formation compressibility and connate water is also presented in Appendix A. We consider no desorption or slippage effects and focus instead on the dual-porosity behavior of gas flow. Equation (3) is in the similar form to the interporosity flow equation written by Gerami et al. (2007) without derivation[1]. Equation (3) takes into account the compressibility-viscosity effects for gas flow out of the matrix blocks. By substituting the definition of pseudo-pressure, we can rewrite Equation (3) as:

$$\phi_m\frac{d\rho_m}{dt} = \alpha k_m\left(\int_0^{p_f}\frac{1}{\mu_{gf}c_{gf}}d\rho_f - \int_0^{p_m}\frac{1}{\mu_{gm}c_{gm}}d\rho_m\right) \quad (4)$$

In the case of liquid, Equation (4) collapses to

[1] Per personal communication with Dr. Pooladi-Darvish where he indicated that and they wrote it using an analogy with the liquid formulation.