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A new method to calculate the early performance of solution-gas-drive reservoirs

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ABSTRACT

The performance of gas-solution-drive reservoirs is difficult to figure out since the treatment of highly nonlinear partial differential equations. In previous works, studies about gas-solution-drive reservoirs are restricted to production data analysis and the calculation of performance is almost lacking. The objective of this paper is to propose a novel application of Boltzmann transformation along with an adaptive-size fourth-order Runge-Kutta to figure out the performance of gas-solution-drive reservoirs in early time from the perspective of a well test analysis. Mathematical models about two-phase flow of one-dimensional linear flow and planar radial flow are established respectively. Through solving the governing equations of constant pressure production, the distribution of pressure and saturation at any time can be obtained easily, and curves of pressure and saturation versus time at a specific position can be also achieved. In addition, profiles of gas and oil flow rate at wellbore in terms of time can be acquired. The effect of bottom-hole pressure (BHP) on pressure, saturation and flow rate in early time is investigated. The results obtained from the newly proposed method are compared with numerical simulation results, and comparison results illustrate that the performance of solution-gas-drive reservoirs can be obtained fast and accurately through the new method.

1. Introduction

Solution-gas-drive reservoirs with low permeability require that the well should produce under the condition of large pressure drop. Commonly, large pressure drop results in the flowing pressure quickly dropping below the bubble point pressure of fluid, then two-phase flow occurs. However, the nonlinearities of the governing equations of two-phase flow make the mathematic model of solution-gas-drive reservoirs a challenging task. This is because fluid density, viscosity, formation compressibility and permeability are all functions of pressure.

Scholars have studied solution-gas-drive reservoirs mainly from two aspects. On the one hand, almost all the available analytical techniques published for solution-gas-drive reservoirs have been intended mainly for production data analysis techniques. Martin (1959) developed simplified equations for the multiphase flow in gas-drive reservoirs, which is analogous to single-phase flow. However, his method has some approximations, for example, he assumed that the terms containing pressure and saturation gradients can be neglected and only when in the analysis of certain phenomena occurring over relatively short time period, the coefficient in the governing equation can be approximated by a constant. Raghavan (1976) used pseudopressure function to analyze the pressure data when two-phase of oil and gas flows in the solution-gas-drive reservoirs. This method can obtain absolute formation permeability not the effective permeability. In his well test method, the relationship between saturation and pressure is essential for obtaining the pseudopressure function, so he got the relationship from the production gas-oil ratio equation. Raghavan (1977) also used similar method to analyze transient pressure data of a vertically fractured well in a solution-gas-drive reservoir. The absolute permeability of the reservoir and length of the fracture can be computed accurately. Pseudopressure and time transformation were used to study the buildup response in solution-gas-drive reservoirs (Camacho-V and Raghavan, 1991). His method involves many approximations and the calculation procedure is very tedious. In addition, pseudopressure function combining with conventional semilog analysis method (Serra et al., 1990a,b) was used to obtain the estimate effective permeabilities and the skin factor of solution-gas-drive reservoirs. Perrine (1956) assumed that the effective total mobility and production rate are, respectively,

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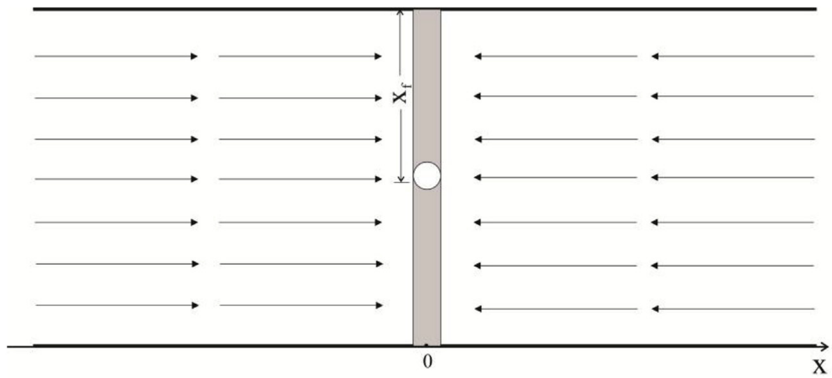

Fig. 1. The scheme of 1D linear flow.

the sums of mobility and production rates. He used conventional well test method to calculate some parameters and suggested a reliable procedure for successful buildup analysis. Raghavan (1989a,b) summarized the methods of well test analysis for multiphase flow and recognized the advantage of Perrine-Martin hypothesis that their method can extend conventional well-test-analysis techniques of single-phase flow to multiphase flow.

On the other hand, only a few scholars have tried to solve the governing equations of two-phase flow in petroleum or groundwater reservoirs. Boltzmann (1894) firstly brought in a convenient solving process for the concentration diffusion problem, transforming the complicated PDEs into ODEs. It proves to be true that applying similarity method to solve strongly nonlinear equations without linearization is a useful method. Afterwards, Levine and Prats (1961) applied finite-difference method to the initial governing equations of the two-phase flow in solution-gas-drive reservoirs. His method must use a high-speed computer. Actually, his finite-difference method aims to solve the initial partial differential equations, which is certain to consume more computation time. The strongly nonlinear equations of multi-phase flow in a geothermal well were solved (O'Sullivan and Pruess, 1980; O'Sullivan, 1981) by applying similarity method. Burnell et al. (1989; 1991) and Kissling et al. (1992) used Boltzmann transformation along with some analytic approximations to solve the governing equations of a well in a geothermal reservoir with steam and water, and successfully obtained the pressure and saturation profiles. Recently, Qanbari and Clarkson (2013) applied similarity-based methodology to an ideal linear flow equation in a linear slab gas reservoir with a hydraulically-fractured well and introduced a measure of nonlinearity. Chen and Raghavan (2013) also applied similarity transformation to infinite-acting gas linear flow analysis for constant bottom-hole pressure production and achieved the solution of dimensionless productivity.

Despite the efforts presented in the literature, there have still been some limitations in previous works about solution-gas-drive reservoirs or multiphase flow. Firstly, almost all the works about solution-gas-drive reservoirs are restricted to production data analysis. In order to extend pressure data analysis techniques of single-phase flow to multiphase flow, they must use pseudopressure function and simplified equations to change the governing equations of two-phase flow. Reservoir permeability and skin factor can be calculated using the typical well test curves. The calculation of pseudopressure depends on the relationship between saturation and pressure. In previous works using material balance method or the equation of production gas-oil-ratio, the relationship can be obtained in advance. Secondly, previous studies about handling two-phase flow problems need to neglect some nonlinearity presented in the governing equations and introduce some simplification. Thirdly, in standard commercial reservoir numerical simulators (e.g. Eclipse), the highly nonlinear fluid governing equations are solved simultaneously by using finite-difference discretization, which consumes much time to calculate the PDEs.

Accordingly, this study mainly has three innovations. Firstly, so far there has almost been no calculation about the performance of gas-solution-drive reservoirs and this paper aims to propose a new method to fill this gap, that is, Boltzmann transformation method. This new method is only suitable for infinite-acting boundary condition because initial condition and outer boundary condition for pressure must be integrated into one condition. Besides, pressure and saturation can be solved simultaneously and independently without knowing the relationship of them in advance. Secondly, using Boltzmann transformation method is a much less expensive alternative to solve the original system of PDEs compared to traditional finite-difference numerical simulators, because it just needs to solve the derived system of ODEs. Thirdly, the new method does not need to neglect any nonlinearity in the governing equations, so the results are relatively accurate.

2. 1D linear flow

2.1. Physical model

As shown in Fig. 1, in this paper we consider the problems of two-phase flow in early time in a solution-gas-drive reservoir. The top and bottom boundaries are impermeable. There is an infinite-conductivity vertical fracture fully penetrating the reservoir. The half-length of the fracture is x_f. Thickness of the reservoir is h, porosity is φ and permeability is k. The initial reservoir pressure is equal to the bubble point pressure at 322.22 K, 22×10^6Pa. The PVT properties and relative permeability relationship of the oil and gas for conditions investigated in this study are presented in Fig. 2 and Fig. 3. Other basic assumptions of the model are as follows:

(1) The reservoir is homogeneous and the fluid is of a slightly compressible liquid. Isothermal fluid flow is assumed and the fluid flow obeys Darcy's law.
(2) No oil is dissolved in the gas phase. Water saturation is assumed to be immobile and is considered to be a part of the rock volume. The reservoir is considered to be completely saturated with oil at the beginning.
(3) The influence of both gravity and capillary force are ignored.

2.2. Solution

2.2.1. Mathematical model

The equations describing 1D flow of oil and gas in Cartesian coordinates can be written as:

$$\frac{\partial}{\partial x}\left(\frac{k_{ro}}{\mu_o B_o}\frac{\partial p}{\partial x}\right) = \frac{\varphi}{\alpha_t k}\frac{\partial}{\partial t}\left(\frac{S_o}{B_o}\right) \tag{1}$$