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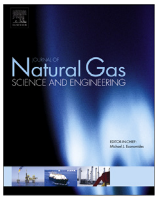

Modeling well performance for fractured horizontal gas wells

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ABSTRACT

In tight gas reservoirs, horizontal wells have been used to increase reservoir recovery and hydraulic fracturing has been applied to further extend the contact with the reservoir. In the past, many models, analytical or numerical, were developed to describe the flow behavior in horizontal wells with fractures. Source solution is one of analytical/semi-analytical approaches. The source method was advanced from point sources to volumetric source, and pressure change inside fractures was considered in the volumetric source method. We have developed a method that can predict horizontal well performance, and the model can also be applied to fractured horizontal wells. The method solves the problem by superposing a series of slab sources under transient or pseudo-steady state flow conditions. The principle of the method comprises the calculation of semi-analytical response of a rectilinear reservoir with closed outer boundaries. The slab source approach assigns sources a geometry dimension, similar to the volumetric source method; but has the solution similar to the point source method by neglecting the effect of the flow inside the source. When solving the source problem the pressure/flow effect inside source is considered sequentially by superposition principle over multiple sources.

The pressure response is integrated over time to provide continuous pressure behavior. Flow effect inside fractures can be studied by dividing the fracture into several segments, and each can be treated as a slab source. The method is validated by comparison with the results of analytical solutions and other commercial software of horizontal wells with uniform flux and infinite conductivity, and fractured wells with uniform flux, finite or infinite conductivity. For multiple fractures in a horizontal well, the method was also compared with some published field data. The method provides an effective tool for horizontal well design and well stimulation design for gas reservoirs.

In this paper, we present the details of model development. We use a case study to illustrate how the model can help to optimize wellbore and fracture design by comparing production performances of vertical well, slanted well, horizontal well, and fractured vertical and horizontal wells. The method in this paper is more accurate compared with conventional point-source solution, and can handle the transaction from transient flow to pseudo-steady state flow smoothly.

1. Introduction

Over the past decades, point source integrated over a line and/or a surface has been mostly used in solving single-phase flow problems in porous media when fluid movement is from a complex fractured well system. Horizontal well models with point source solution have been presented in many literatures. Gringarten and Ramey (1973) provided the tables of instantaneous Green's and source functions which can be used in combination with Newman's product method to generate solutions for different reservoir flow problems. Many studies of horizontal well problems used this approach (Clonts and Ramey, 1986; Daviau et al., 1988; Babu and Odeh, 1989). The analytical models are developed under assumptions about boundary conditions. Steady-state models assumed a constant pressure at the drainage boundary (Butler, 1994; Furui et al., 2003), pseudo-steady-state models assumed no flow crossing the boundary with either constant pressure gradient or constant flow rate (Babu and Odeh, 1988, 1989), and transient flow models uses an infinite acting drainage domain (Goode, 1987; Ozkan, 1988; Ozkan et al., 1995a,1995b; Goode and Kuchuk, 1991; Economides and Frick, 1994). For low permeability formation, transient flow period of a horizontal well may be significantly longer than for conventional formations. Valko and Amini (2007) developed a method with distributed volume sources to simulate fractured horizontal wells in a box-shaped reservoir. A source term was added to the diffusivity

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equation to calculate the pressure distribution. Then the production rate from a fracture is computed. Different from the other point source methods, the volume source approach is able to describe the pressure behavior inside sources and its influence to the flow field. Meyer and Bazan developed approximate analytical solution of complex linear flow for multiple finite-conductivity transverse fractures (Meyer et al., 2010). Fractured horizontal well performance is also studied by using reservoir simulation tools. Even though the numerical simulation is a more powerful tool to handle complex reservoirs, analytical/semi-analytical models by source approaches offer flexibility to count for the detail structure of wellbore, completion and fracture geometry; and thus, are invaluable tools in well performance prediction.

In this paper, we present a different approach to the problem of unsteady state flow of a compressible fluid in a rectilinear reservoir. The model is based the solution of slab sources. It can be used to calculate well performance for horizontal gas wells with or without fractures. Fractures can be longitudinal or transverse, single or multiple, and fractures can be infinite conductivity or uniform influx. Using the slab source approach, we assigned the sources (horizontal wells or fractures) a geometry dimension, and the effect of pressure behavior inside sources is considered by superposition principles. This method is relatively easy to apply because flow rate could be calculated directly from pressure difference between initial reservoir pressure and pressure in fracture, which is the same as wellbore flow pressure for an infinite conductivity fracture.

2. Semi-analytical slab source model

The slab source method solves the flow problem in a parallelepiped porous medium with a slab source, ***s***, placed in the domain, as shown in Fig. 1. The porous medium is assumed to be an anisotropic reservoir. Following the same approach as the conventional point source solution to apply Newman's principle, the three-dimensional pressure response of the system to an instantaneous source can be obtained as the production of the solutions of three one-dimensional problems from each principal direction.

The diffusivity equation in dimensionless format of a single-phase incompressible fluid is written as

$$\nabla^2 p_D = \frac{\partial p_D}{\partial t_D} \tag{1}$$

For an anisotropic medium, we can write the diffusivity in three directional as

$$\frac{\partial^2 p_D}{\partial x_D^2} + \frac{\partial^2 p}{\partial y_D^2} + \frac{\partial^2 p}{\partial z_D^2} = \frac{\partial p_D}{\partial t_D} \tag{2}$$

The dimensionless variables in the above equations are defined in Appendix A. Because the diffusivity equation is in the same format as the heat conduction problems, we can directly apply the sink/source technique to solve the flow in porous media. The solution from this technique applies to different state in the flow period, both transient flow and stabilized flow. The boundary condition of the reservoir can be constant pressure, no-flow or mixed boundary, which makes the model practical to a wide range of flow problems in petroleum engineering.

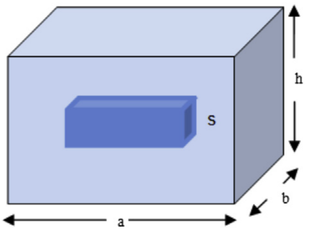

Fig. 1. Scheme of the slab source model.

The procedure of obtaining the solution is to obtain one-dimensional solution of the slab problem, applying Newman's product method based on instantaneous source function in an infinite reservoir to get three-dimensional solution, and then integrates the three-dimensional solution over time to get a continuous source function. Modifying the point source domain by placing a pair of parallel plates in the domain, as shown in Fig. 2, we began our model with one-dimensional instantaneous infinite slab source in an infinite slab reservoir. Green's functions (Carslaw and Jaeger, 1959) for different boundary conditions in infinite slab reservoirs with a system scheme in Fig. 2 are shown in Table 1.

To apply the instantaneous Green's function in the slab source model, Newman's method has been applied which states that at certain types of initial and boundary conditions, the solution of a three-dimensional problem is equal to the product of the solutions of three one-dimensional problems. We start with an instantaneous slab source in an infinite one-dimensional reservoir (Fig. 2), overlay three of such sources in x, y, and z direction to make a three-dimensional instantaneous slab source in a box-shaped reservoir. To obtain the solution of the new system, we multiply the three solutions of the original one-dimensional problem to an instantaneous solution for the three-dimensional system. Integrate over the well trajectory or the fracture length and height to get the instantaneous slab source solution for the performance of the well, and then integrate over the time to get the three-dimension continuous slab source solution to solve practical reservoir problems. The procedure is summarized in Fig. 3. The solution as instantaneous source depends on the locations of the slab source and the box shape reservoir. To apply this method for horizontal wells with or without fractures, we define the source term (the location and the dimensions of the source) and the main domain according to each individual physical system.

For instance, the pressure drop as a results of a constant production, q, at a position (x_0, y_0, z_0) in an anisotropic box-shaped reservoir measured at a position (x, y, z) is readily calculate by

$$\frac{\partial p_D}{\partial x_D \partial y_D \partial \mathrm{d}z_D \partial t_D} = s_x s_y s_z \tag{3}$$

where, S_x, S_y and S_z are the slab source functions in each direction, as shown in Table 1. For example, for the no-flow boundary, the s_x, s_y, and s_z is

$$s_x = \frac{x_f}{a}\left[1 + \frac{4a}{\pi x_f}\sum_{n=1}^{\infty}\frac{1}{n}\sin\frac{n\pi x_f}{2a}\cos\frac{n\pi x_o}{a}\cos\frac{n\pi x}{a}\exp\left(-\frac{n^2\pi^2 k_x \tau}{a^2}\right)\right]$$

$$s_y = \frac{y_f}{b}\left[1 + \frac{4b}{\pi y_f}\sum_{m=1}^{\infty}\frac{1}{m}\sin\frac{m\pi y_f}{2b}\cos\frac{m\pi y_o}{b}\cos\frac{m\pi y}{b} \times \exp\left(-\frac{m^2\pi^2 k_y \tau}{b^2}\right)\right]$$

$$s_z = \frac{z_f}{b}\left[1 + \frac{4h}{\pi z_f}\sum_{l=1}^{\infty}\frac{1}{l}\sin\frac{l\pi z_f}{2h}\cos\frac{l\pi z_o}{h}\cos\frac{l\pi z}{h}\exp\left(-\frac{l^2\pi^2 k_z \tau}{h^2}\right)\right]$$

After obtain the instantaneous slab source solution under defined boundary conditions, we integrate the instantaneous point source over a time interval to attain the continuous slab source solution. The pressure drop at point (x, y, z) as a result of the continuous production or injection at position (x_0, y_0, z_0) in an anisotropic box-shaped reservoir then is