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A semi-analytical mathematical model for transient pressure behavior of multiple fractured vertical well in coal reservoirs incorporating with diffusion, adsorption, and stress-sensitivity

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ABSTRACT

Vertically fractured wells have been widely used in coal gas reservoirs. Investigating transient pressure behaviors (TPB) of these wells is a considerably significant task for fracturing evaluation as well as productivity prediction. Although some studies have been done in this area, most of them focus on two-wing fractured wells. Both micro-seismic fracture imaging and samples testing strongly showed that multiple fractures can develop during hydraulic fracturing in naturally fractured reservoirs like coal seam. However, little work has been done to study the TPB of multiple fractured vertical wells (MFVW) in coal reservoirs.

In this paper, to study this problem thoroughly, a well testing model of MFVW at a constant production rate was established with consideration of multiple mechanisms including diffusion, adsorption, and stress-sensitivity effect. Applying line source function, superposition principle, Pedrosa's substation, Gauss elimination, and Stehfest numerical inversion, the transient pressure solution of the mathematical model was solved. Based on this solution, model validation was conducted by selecting a case in literature. In addition, the influences of some critical parameters on TPB were studied, containing fracture length, fracture conductivity, fracture number, fracture length asymmetry, fracture conductivity asymmetry, and fracture angle asymmetry.

This work provides important references for some reservoir engineers in performance forecast and completion design of MFVW in coal gas reservoirs.

1. Introduction

As a perfectly alternative energy for conventional hydrogen gas, coal gas is being studied globally. To raise its production, massive hydraulic fracturing measures have been applied in coal gas wells. Undoubtedly, transient pressure analysis in these wells is one of the most effective and significant tasks for fracturing evaluation.

Many researchers (Prats, 1961; Gringarten et al., 1975; Choo and Wu, 1987; Tiab, 2005; Tiab et al., 2010; Lei et al., 2014) proposed analytical or numerical methods to study the TPB of wells with two fracture wings in conventional reservoirs. For instance, Gringarten et al. (1975) analyzed the TPB of fractured wells. In his work, both vertically and horizontally two-wing fractures are studied. However, the main weakness is that the fractures are assumed as to be infinite-conductivity, which can surely cause errors when investigating the TPB.

To reduce the deviations caused by infinite conductivity, semi-analytical transient pressure solutions for finite-conductivity fractured wells are presented (Cinco et al., 1978; Cinco-Ley and Samaniego, 1981). Based on these studies, further analyses for transient pressure and production data are conducted (Tiab, 1995; Agarwal et al., 1998; Pratikno et al., 2003; Tiab, 2005; Lei et al., 2007; Hagoort, 2009). Unfortunately, due to complex mechanisms like diffusion, adsorption, and stress-sensitivity effect in coal gas reservoirs (Han and Dusseault, 2003; Wang et al., 2013), the theoretical system of studying TPB for conventional reservoirs cannot be suitable for coal bed methane (CBM). Therefore, special work needs to be done to investigate TPB of fractured coal gas wells.

Anbarci and Ertekin (1990, 1992) discussed the TPB of infinite-conductivity fractured wells in coal gas reservoirs by proposing a mathematical well testing model. In this work, many situations are

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considered including unsteady flow, pseudo-steady state flow, and boundary conditions. However, the fractures in their model are still considered to be infinite-conductivity, and the stress-sensitivity effect is also ignored.

To overcome this weakness, Clarkson et al. (2009) made production data analyses of finite-conductivity fractured wells in coal gas reservoirs. Wang et al. (2013) proposed a semi-analytical solution for TPB of finite-conductivity fractured wells. However, the stress-sensitivity effect is still neglected.

In addition, most of these researches focused on two-wing fractured wells. However, micro-seismic fracture imaging strongly shows that fracture networks can be created by hydraulic fracturing, especially for natural fracture reservoirs like coal seam (Fisher et al., 2004, 2005; Mayerhofer et al., 2006; Luo and Tang, 2014; Chen et al., 2014). It is also found by direct observations on fractured samples that multiple fractures can develop along the wellbore (Germanovich et al., 1997; Molenaar et al., 2012; Sierra et al., 2008), as shown in Fig. 1. Unfortunately, little work has been done to focus the TPB of MFVW in coal gas reservoirs.

Choo and Wu (1987) established a numerical model to study the TPB of wells containing multiple fractures in gas reservoirs. But, the numerical methods are complex and time consuming. Further, due to the limitation of grid number, the modeled fractures are either gourd-shaped in polar coordinates or equivalent-conductivity in Cartesian coordinates, which are not in accord with practices (Chen et al., 2014). Thus, numerical methods could lead to mistakes when investigating TPB. In addition, the objective in this paper is conventional gas reservoir which is significantly different from coal seam.

Further, Craig and Blasingame (2006) and Luo and Tang (2014) also investigated the TPB of MFVW in conventional oil reservoirs. In their works, both infinite-conductivity and finite-conductivity fractured wells have been studied. But, the works cannot be used for coal gas wells because complex mechanisms including stress-sensitivity effect, diffusion, and adsorption are not considered.

In this paper, a well testing model of MFVW at a constant production rate was developed. To make it more in line with the actual reservoir situation, the mechanisms of diffusion, adsorption, and stress-sensitivity are incorporated. Model validations were conducted by selecting the data in literature, and the influences of some critical parameters on TPB are also studied.

2. Physical model

Fig. 2 shows that a vertically fractured well is located in the center of a coal reservoir. The reservoir is assumed to be infinite-lateral, and multiple fractures are connected to the fractured wellbore. Other assumptions of the physical model are as following:

- Coal gas reservoir has an uniform initial pressure p_i, constant temperature T, and thickness h. The absolute permeability K and porosity ϕ of natural fracture system are homogenous.

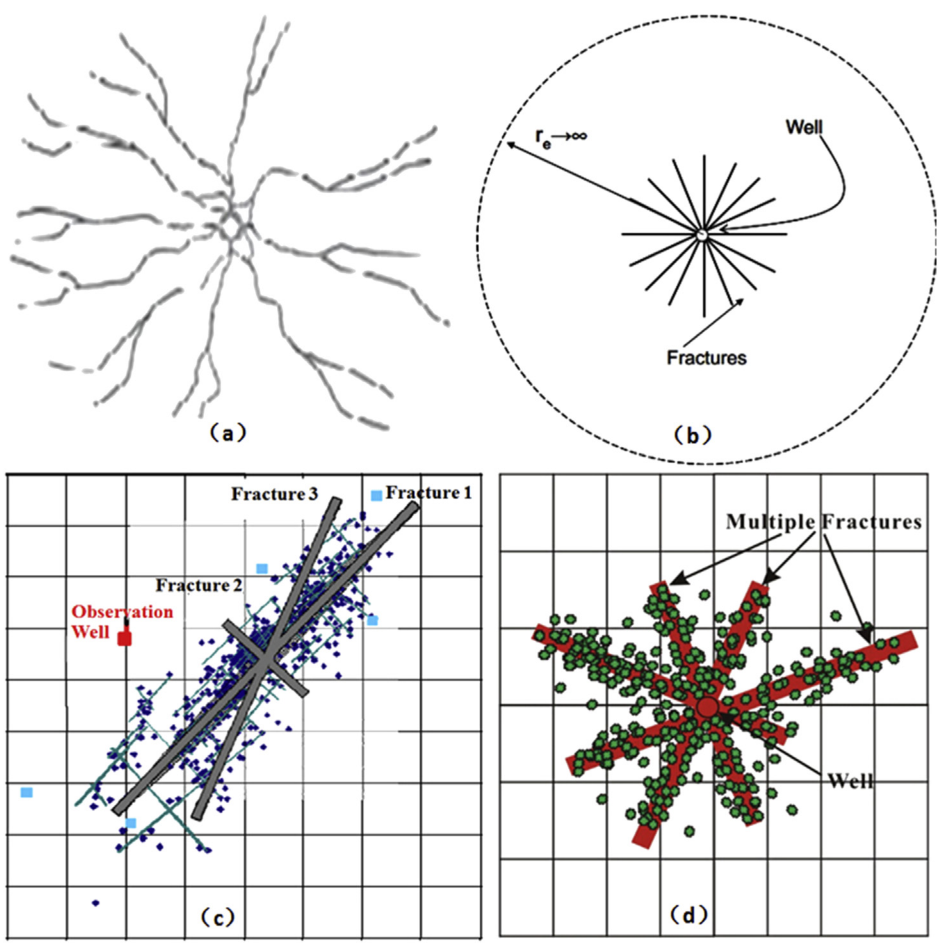

Fig. 1. Multiple radial fractures connected to the wellbore: (a) Germanovich et al., 1997; Fisher et al., 2004, Fisher et al., 2005; (b) Restrepo and Tiab, 2009; (c) Craig and Blasingame, 2006; (d) Chen et al., 2014.