Journal of Natural Gas Science and Engineering 21 (2014) 608–624

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

A general productivity model for optimization of multiple fractures with heterogeneous properties

Junlei Wang*, Ailin Jia

Research Institute of Petroleum Exploration and Development, PetroChina, Beijing, China

A R T I C L E I N F O

Article history:
Received 17 June 2014
Received in revised form
16 September 2014
Accepted 17 September 2014
Available online

Keywords:
Multiple fractured horizontal well (MFHW)
Productivity index
Multi direct boundary element method
Proppant number
Fracture heterogeneity
Optimization

A B S T R A C T

The principle focus of this work is on developing a general productivity model to fill the gap in simultaneously optimizing multiple hydraulic fractures with different properties in heterogeneous spaced fracture configuration. Based on the instantaneous point source solutions, a rigorous mathematical model is established by coupling reservoir flow model with fracture flow model in a box-shaped reservoir, which takes into account fracture interaction, fracture conductivity, contacted reservoir area with fractures, and heterogeneity of fracture properties. A corresponding semi-analytical solution is further proposed to solve the model by using a new discretization algorithm called multi direct boundary element methodology (MDBEM). Based on the general model, the maximum productivity index (PI) is obtained by optimizing properties of fractures under the limitation of given proppant volume, which puts a constraint on number of fractures, fracture conductivity and fracture length. The heterogeneity effect of fracture properties on optimization is discussed in detail, and results indicate that it is more advantageous and practical to create more fractures with identical properties in homogeneous fractured configuration.

1. Introduction

Tight gas and shale gas have become alternative commercial hydrocarbon production targets. These unconventional gas reservoirs will play an increasingly important role because of its potential to offset declining in conventional gas production. In the development of unconventional gas reservoirs with extremely low permeability, hydraulic fracturing and horizontal drilling are the two essential technologies that have made unconventional gas reservoir economical. Currently, fracturing horizontal well has been widely accepted as a viable complementary option to maximize connected area by creating a very large artificial fracture system. Gas production from these low permeability reservoirs is entirely challenging due to complicated flow behavior and the various fracture configurations along horizontal wellbore (Javadpour, 2009; Cipolla, 2009; Soliman and Kabir, 2012; Yu et al., 2014). Therefore, it is very significant to optimize multiple fractures based on productivity index model to obtain a higher production rate.

In the practical view of evaluating the production ability of a specific well, productivity index is a critical criterion in production prediction and management. It is widely accepted that pseudo steady productivity study is consistent with transient pressure analysis in the purpose of determining productivity index. By now there is a wide variety of papers on transient pressure analysis of well intersected by infinite conductivity and finite conductivity fractures (Chen and Raghavan, 1997; Soliman et al., 1999; Al-Kobaisi et al., 2006; Valkó and Amini, 2007; Yao et al., 2013). In the aspect of pseudo steady productivity index, long-time performance behavior of a well, Prats (1961) was the first researcher to introduce Optimum Fracture Design (OFD) for maximizing PI of well intersected by single vertical fracture, with which to assess the performance of fractured well and account for the stimulation effects. The work on geometry and conductivity of single fracture in infinite-acting reservoir had been excellently accomplished by Cinco-Ley and Samaniego (1981) and Cinco-Ley and Meng (1988). Thereafter, Valkó and Economides (1998) presented the physical optimization method of hydraulic fracture to maximize PI in regularly shaped (circular or square) reservoir drainage. Their technique known as Unified Fracture Design (UFD) provided the correlation of optimum fracture conductivity and maximum PI under the constraint of proppant number, which was a normalizing and descriptive parameter. Subsequently, Demarchos et al. (2006) calculated the

* Corresponding author. Tel.: +86 10 835 95238.
E-mail addresses: williamwang_2@126.com (J. Wang), jal@petrochina.com.cn (A. Jia).

http://dx.doi.org/10.1016/j.jngse.2014.09.024
1875-5100/

pseudo steady PI in irregularly shaped reservoir, and provided the correlated factor to account for the department from the optimum results in square reservoir. Using reservoir/fracture domain resistivity concept, Meyer et al. (2010) provided a comprehensive method incorporating trilinear flow solution (Lee and Brockenbrough, 1986) and the pseudo steady state resistivity model (Meyer and Jacot, 2005) for predicting the productivity and optimizing finite conductivity fracture.

For multiple fracture model, it is assumed that whole drainage can be isolated evenly into a series of same zones occupied by individual fractures, Bhattacharya et al. (2012) utilized single fracture model to determine and optimize multiple fractures based on the results of Daal and Economides (2006), and developed an empirical equation for optimum fracture conductivity as a function of reservoir aspect ratio and proppant number. Rbeawi and Tiab (2013) presented an analytical productivity model of horizontal well with multiple partially penetrated fractures based on the assumption of equally spaced fractures and uniform flux distribution along fracture. Yu et al. (2014) performed a sensitivity study of gas production with different geometries of multiple transverse hydraulic fractures by using numerical simulation. However, few works put focus on simultaneously optimizing multiple heterogeneous spaced fractures with different properties in the condition of considering fracture interference. In our work, an exact semi-analytical productivity model of MFHW is developed to account for fracture interaction and interference, fracture conductivity, contacted reservoir area with fractures, and heterogeneity of fracture properties.

2. Pseudo steady state productivity model

Productivity of well determines the ability of exploiting liquid from reservoirs, which is defined as the ratio of production rate and pressure drawdown. In the terms of pressure drawdown, the productivity can be mainly divided into two categories including transient productivity (Wan and Aziz, 2002; Medeiros et al., 2010) and pseudo steady productivity (Meyer and Jacot, 2005; Meyer et al., 2010; Lu and Tiab, 2008). For transient productivity, the pressure drawdown is defined as the difference between initial pressure and bottom hole pressure (BHP), which varies as time varies. For pseudo steady productivity, pressure drawdown is the difference between reservoir average pressure and BHP. During the pseudo steady state (PSS), the declining rate of average pressure is identical to that of BHP, so the pressure drawdown keeps constant. Therefore, the pseudo steady productivity index of gas well can be written as the following dimensionless form

$$\mathrm{PI} = \frac{N_{\mathrm{fD}}}{m_{\mathrm{D}}\left(p_{\mathrm{wD}} - m_{\mathrm{D}}\left(p_{\mathrm{avgD}}\right)\right)} \tag{1}$$

In fact, the dimensionless PI is the reciprocal of flow resistivity (Ramey and Cobb, 1971; Gringarten et al., 1974), which can be rewritten in another form

$$\mathrm{PI} = \left(\frac{1}{2}\ln\frac{4A}{e^{\gamma}C_{\mathrm{A}}r_{\mathrm{eff}}^{2}}\right)^{-1} \tag{2}$$

where A is the drainage area, γ is the Eular constant (=0.5772), r_{eff} is the effective wellbore radius, and C_{A} is the shape factor depending on the geometry of drainage area and location of well. For horizontal well with multiple fractures, Raghavan et al. (1997) presented an effective wellbore radius model, which was a function of fracture conductivity and number of fractures. In essence, the purpose of our work is just to obtain maximum effective wellbore radius by optimizing multiple fractures under the limitation of given proppant volume.

2.1. Coupled reservoir-fracture flow model

In this section, a mathematical model for multiple fractured horizontal well is established. As seen Fig. 1, the following assumptions are made:

1) An isotropic, horizontal, slap gas reservoir is bounded by overlying and underlying impermeable strata.
2) The reservoir possesses uniform thickness, permeability, and porosity.
3) The production process is assumed to be isothermal. Flow in reservoir matrix and hydraulic fracture all obeys Darcy's law, and matrix and fracture are considered incompressible compared to gas compression.
4) The flow from the reservoir to horizontal wellbore section between fractures is negligible. The reservoir is produced only through a set of fully penetrating, finite-conductivity hydraulic fractures. Fractures have constant half-length, width, permeability, and porosity. Fracture wings are symmetrically spaced with regard to horizontal wellbore.
5) The well is produced at constant production rate. Wellbore storage effect and fracture face damage skin are not considered in our model.

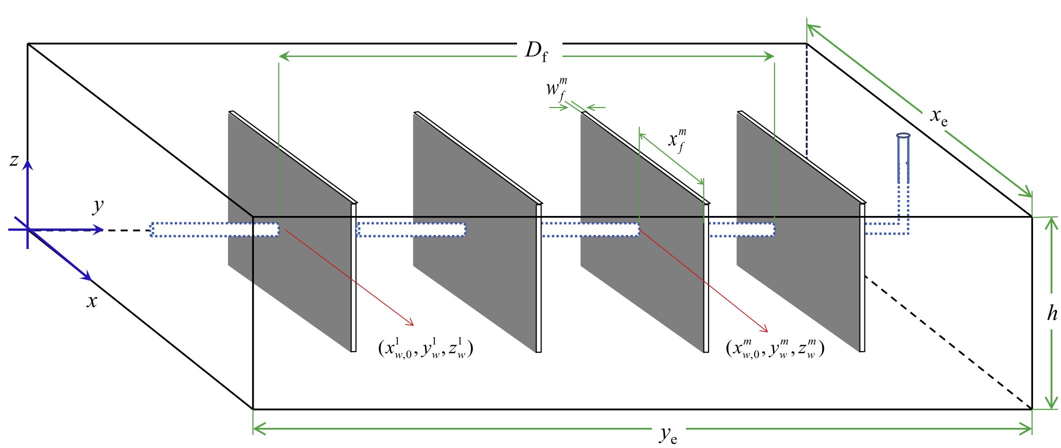

Fig. 1. Sketch of horizontal wellbore intersected by multiple transverse fractures in box-shaped reservoir.