Journal of Natural Gas Science and Engineering 58 (2018) 234–240

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Determination of stimulated reservoir volume and anisotropic permeability using analytical modelling of microseismic and hydraulic fracturing parameters

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ARTICLE INFO

Keywords:
Stimulated reservoir volume
Microseismic monitoring
Analytical modelling
Linear diffusivity equation
Tight gas reservoir
Anisotropic permeability

ABSTRACT

The concept of stimulated reservoir volume (SRV) provides a link between well productivity, the observed distribution of microseismic events and fracture networks that are created or enhanced during well completion. The SRV dimensions are affected by both reservoir geomechanical properties and hydraulic fracturing parameters. This research focuses on the determination of anisotropic permeability and the estimation of the SRV dimensions by refining the existing 3D linear diffusivity partial differential equation (PDE). The anisotropic permeability and the SRV are both calibrated using the analytical solution, based on determination of microseismic events that are inferred to be connected back to the horizontal wellbore. An improved analytical 3D linear diffusivity PDE model is proposed to simulate the anisotropic permeability and the SRV dimension with higher percentage of microseismic events. In a case study from western Canada, the proposed approach yields improved the prediction of the SRV dimension that consists 90% of microseismic events within the SRV, compared to the existing analytical solution predicts the SRV dimension that consists 70% of microseismic events within the SRV. The SRV anisotropic permeability is also estimated using the proposed model with the average values of 0.1897 mD (SRV length direction), 0.1112 mD (SRV width direction), and 0.0138 mD (SRV height direction) from 12 stages hydraulic fracturing. The simplicity of the proposed model allows the SRV dimensions estimation before hydraulic fracturing operations.

1. Introduction

Global gas consumption is increasing steadily by an estimated 1.6% per year (BP Statistical Review of World Energy, 2017). Considering that conventional gas production is in decline, there is an urgent need to optimize unconventional gas production to meet the increasing of the gas demand. Tight gas reservoirs are one type of unconventional gas reservoir that is becoming the focus of the natural gas production especially in the USA and Canada (e.g., Pedersen and Eaton, 2018). Stimulated reservoir volume (SRV) is defined as an induced network of hydraulic fracture and reopened natural fractures that generate microseismic events (Mayerhofer et al., 2010). The SRV serves as a correlation tool for a well performance, especially in low permeability formations where reservoir productivity is dependent on the SRV enhanced permeability. The microseismic event cloud corresponds to SRV dimension in which the reservoir height and area are estimated. However, large amount of microseismic field data is required and not always available in most of the hydraulic fracturing operation due to the costly microseismic monitoring operation (Yu and Aguilera, 2012). In this study, an analytical model based on linear diffusion equation is proposed in an anisotropic formation. A calibration coefficient is introduced to improve the SRV prediction and the model can be used to estimate SRV in tight case reservoirs with similar geomechanical properties.

An analytical model was first developed by Shapiro et al. (1997), based on a diffusion equation of pore pressure in a homogenous isotropic medium. This model has been applied is to represent the evolution of hydraulic fractures, where the equilibrium state of stress is

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https://doi.org/10.1016/j.jngse.2018.08.016
Received 4 June 2018; Received in revised form 31 July 2018; Accepted 18 August 2018
Available online 23 August 2018

Nomenclature

c	fluid compressibility, 1/Pa
c_f	formation compressibility, 1/Pa
c_t	total compressibility of the porous medium, 1/Pa
k	permeability component in system, m^2
P	pressure in porous medium, Pa
P_{trg}	minimum pressure required to trigger a seismic event at a given location, MPa
P_{inj}	injection pressure at wellbore, Pa
ΔP_{inj}	pressure difference induced by fluid injection, MPa
ΔP_{trg}	minimum pressure difference required to trigger a seismic event, MPa
t	time, minute or second
η	diffusivity coefficient, m^2/s
μ	viscosity of the injected fluid, Pa.s
φ	effective porosity

Subscript

i	initial
N	normalized
x	x-component of a vector
y	y-component of a vector
z	z-component of a vector
x'	reoriented x-component of a vector
y'	reoriented y-component of a vector
z'	reoriented z-component of a vector
ø	angle of reorientation
x_1	$\sqrt[6]{\frac{k_y k_z}{k_x^2}}x$
y_1	$\sqrt[6]{\frac{k_x k_z}{k_y^2}}y$
z_1	$\sqrt[6]{\frac{k_x k_y}{k_z^2}}z$

assumed to prevail until the effective normal stress is altered by increasing fluid injection pressure. The alteration of stress triggers the microseismic events; hence, according to this model, the hydraulic diffusivity coefficient is related to the spatio-temporal distribution of microseismic events. The model hs been developed for the determination of SRV permeability (Grechka et al., 2010; Shapiro and Dinske, 2009). However, in the case of anisotropic reservoirs, the model is unsuitable for the SRV dimension prediction as the assumption of isotropic properties is applied in the model.

Grechka et al. (2010) applied an inversion approach to determine the SRV permeability using microseismic events. The inversion approach involves the general 1D diffusion equation, which is parameterized by the average leak-off velocity across a hydraulic fracture, the hydraulic fracture width and the reservoir pressure. This method allows prediction of gas rate in tight sand formation with reasonable level of confidence. However, the proposed method is not applied for the determination of SRV dimension.

In a later research conducted by Yu and Aguilera (2012), a 3D analytical modelling based on linear diffusion equation was developed to analyze the geometry and the orientation of the SRV caused by hydraulic fracturing. In their work, diffusivity coefficients in 3D are determined by calibrating the model using microsesimic events. The obtained diffusivity coefficients allow the SRV dimension to be predicted. The SRV is a function of the injection pressure, the diffusivity coefficient, the injection time and the pressure required to trigger microseismic events. This model accounts for anisotropy, but the SRV predicted by the model is underestimated and the anisotropic permeability is not determined.

In this study, a similar approach is used to estimate the SRV dimension for 12 stages of a multi-stage hydraulic fracturing treatment of a horizontal well in a tight gas reservoir in Alberta, Canada. The microseismic dataset was acquired during openhole completion operations as part of the Hoadley Flowback Microseismic Experiment (Eaton et al., 2014). The data were acquired using a 12-level downhole toolstring deployed just above the reservoir zone. Details of the experiment are given by Eaton et al. (2014). Here, the diffusivity coefficient is validated with the microseismic events and a calibration coefficient is introduced to improve the accuracy of SRV dimension predicted by the existing model for the 12 stages hydraulic fracturing. The enhanced permeability within the SRV is then calculated.

2. Methodology

2.1. Reorientation of microseismic events

The initial step in the procedure is to determine apparent diffusivity coefficients for each hydraulic fracturing stage. In this case, the 3D distribution of microseismic events for 12 stages are used and the quality check is performed. A reorientation of microseismic events with respect to the actual orientation (N45E) is required to facilitate the determination of diffusivity coefficient. Fig. 1 shows data for a single stage, using Cartesian coordinate system where the *x'*-axis represents the direction in which microseismic clouds propagate actively. The reorientation is applied using a 2D rotation matrix

$$x' = x\cos ø + y\sin ø \quad (1)$$

$$y' = y\cos ø - x\sin ø \quad (2)$$

where *x* and *y* represent the original x-coordinates and ø represents the angle of reorientation.

2.2. Determination of diffusivity coefficient

The microseismic events for each direction are plotted against the corresponding propagation time (diffusivity, or *r-t,* plot) in Fig. 2. The straight line represents the inferred triggering front of the stress-induced microseismic events. The obtained slope from diffusivity plot of each direction is substituted into the existing analytical model for the calculation of diffusivity coefficient in three different directions using Equation (12) to Equation (14). The slope is determined based on the microseismic event 90% cutoff. 90% of the microseismic events are covered by the area under the slope (Urbancic and Baig, 2013).

2.3. Derivation of analytical model

Determination of the SRV dimensions for each hydraulic fracture stage requires the derivation from the original nonlinear PDE diffusion equation. The 3D diffusivity equation is given by

$$\frac{\partial}{\partial x}\left(\rho\frac{k_x}{\mu}\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(\rho\frac{k_y}{\mu}\frac{\partial P}{\partial y}\right)+\frac{\partial}{\partial z}\left(\rho\frac{k_z}{\mu}\frac{\partial P}{\partial z}\right)=\frac{\partial}{\partial t}(\rho\varphi). \quad (3)$$

This can be rearranged as (Yu and Aguilera, 2012)

$$\frac{k_x}{\mu}\left[\frac{\partial^2 p}{\partial x^2}+c\left(\frac{\partial P}{\partial x}\right)^2\right]+\frac{k_y}{\mu}\left[\frac{\partial^2 p}{\partial y^2}+c\left(\frac{\partial P}{\partial y}\right)^2\right]+\frac{k_z}{\mu}\left[\frac{\partial^2 p}{\partial z^2}+c\left(\frac{\partial P}{\partial z}\right)^2\right]$$
$$=\varphi\mu(c_f+c)\frac{\partial p}{\partial t}, \quad (4)$$

where *c* represents fluid compressibility and c_f represents formation compressibility. The partial differential equation is simplified by assuming the insignificance of nonlinear terms, which leads to

$$k_x\frac{\partial^2 p}{\partial x^2}+k_y\frac{\partial^2 p}{\partial y^2}+k_z\frac{\partial^2 p}{\partial z^2}=\varphi\mu c_t\frac{\partial p}{\partial t}\,. \quad (5)$$