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Numerical simulation of hydraulic fracturing coalbed methane reservoir

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HIGHLIGHTS

- A two-phase, three-dimensional model of fracturing coalbed methane is developed and coded.
- Impact of permeability, original volume density, porosity, Langmuir pressure constant on production is analyzed.
- Influence of hydraulic fracturing on production capability, desorption and diffusion is studied.

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ABSTRACT

Some coal seam is well known for its three low characteristics: low permeability, low reservoir pressure and low gas saturation. Thus stimulation measures must be taken during coalbed methane development stage to enhance its recovery. Hydraulic fracturing transformation technology is an effective method for increasing coalbed methane production.

This paper presents a two-phase, 3D flow and hydraulic fracturing model of dual-porosity media based on the theories of oil–gas geology and mechanics of flow through porous media.

Correspondingly, a finite difference numerical model has been developed and applied successfully to a coalbed methane reservoir. Well test data from one western China basin is utilized for simulation. Results show that hydraulic fracturing promotes desorption and diffusion of coalbed methane which in turn substantially increases production of coalbed methane.

1. Introduction

Hydraulic fracturing transformation technology is the primary means in enhancing production of coalbed methane wells. More than 90% of coal seam is improved through hydraulic fracturing among 14,000 multi-port coalbed methane wells in United States. There may be a number of far extended cracks in the internal of fractured coal seams. This can result in the pressure drop in a large area around borehole, thus gas desorption surface area of coal seam enlarged which guarantees the discharge of coalbed methane rapidly and sustainably. Coalbed methane production of fractured coal seams is 5–20 times of pre-fracturing condition.

Hao et al. [1] analyzed characteristics of pressure of coal seam fracturing and the relationship between depth and break pressure gradient. Zhang and Wang [2] introduced dynamic (potential) testing technique used for determination of fracturing azimuth, length and other parameters of coal seam. Yuan and Meng [3] used acoustic detection system to carry out seismic tomography tests before and after fracturing respectively in order to determine fracturing effect. Michael et al. [4] analyzed hydraulic fracturing design on the impact of ECBM (Enhanced Coal Bed Methane Recovery). Mc Dariec [5] firstly applied hydraulic fracturing techniques to the stimulation work of coalbed methane wells. Zhao et al. [6] described hydraulic fracturing technique for coalbed methane gas reservoirs with low permeability and also developed a set of optimal design software for low permeability hydraulic fracturing coalbed gas reservoirs. Boyer [7] conducted Laboratory and field tests to establish criteria for containment of an induced hydraulic fracture. Clarkson [8] provided a new workflows and analytical approaches for analyzing single and multi-phase flow of CBM from vertical, hydraulically-fractured wells and horizontal wells. Wright et al. [9] summarized a few enhancements for coal seam fracturing technology, as well as the present limitations and the necessary advancements required for superior coal seam fracture performance in future. Holditch [10] utilized hydraulic fracturing treatments to optimize recovery from most of the wells that drilled into deep coal seams.

Although many scholars had studied the exploitation of CBM (Coal Bed Methane) as well as the impact of hydraulic fracturing

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Nomenclature

v_g	gas area velocity of cleat, cm/s
B_g	gas volume factor of cleat
q_{vg}	gas production items, cm^3/(cm^3 s)
D	depth away from the datum, cm
q_{mfg}	gas diffusion rate of gas cross flow from matrix to cleat, cm^3/(cm^3 s)
ϕ_f	porosity of cleat, decimal
s_g	gas saturation of cleat, decimal
∇	Hamilton operator
k_f	permeability of cleat, μm^2
k_{rg}	gas relative permeability of cleat, decimal
p_{fg}	gas pressure of cleat, 10^{-1} MPa
μ_g	gas viscosity of cleat, mPa s
ρ_g	gas density of cleat, g/cm^3
k_{rw}	water relative permeability of cleat, decimal
B_w	water volume factor of cleat
μ_w	water viscosity of cleat, mPa s
ρ_w	water density of cleat, g/cm^3
p_{fw}	water pressure of cleat, 10^{-1} MPa
s_w	water saturation of cleat, decimal
$\overline{V}_m$	average concentration of gas in matrix element, cm^3/cm^3
V_E	gas concentration in the surface of matrix element, cm^3/cm^3
τ	desorption time of coalbed methane, s
μ_{mg}	gas viscosity of matrix element, mPa s
F_G	geometry-related factor
p_{fg}^0	initial reservoir pressure of coalbed methane, a given function
s_g^0	initial gas saturation of coalbed methane, a given function
r_w	radius of wellbore
k_{fx}, k_{fy}	permeability in different directions of cleat system
Γ	outer boundary of coalbed methane, n represents external normal direction of outer boundary
$p_e(x, y, z, t)$	known function related to pressure

on CBM, few had taken hydraulic fracturing into consideration in three dimensional and two phase coalbed methane reservoir. This paper is rightly to address this problem and presents a numerical simulation with independent fracture system. A computer program has been coded. Well test data from one western China Basin, which include all parameters needed in simulation work, prove that the model established in this paper is reasonable and feasible.

2. Mathematical model of coalbed methane reservoir

2.1. Gas seepage equation in the cleat system

According to continuity equation, Darcy's law, general form of water flow seepage equation is shown as follows:

$$\nabla\cdot\left[\frac{\rho_g k_f k_{rg}}{\mu_g}(\nabla(p_{fg}-\rho_g gD))+D_f\nabla\left(\frac{s_g}{B_g}\right)\right]+q_{vg}+q_{mfg}=\frac{\partial}{\partial t}\left(\frac{\phi_f s_g}{B_g}\right) \tag{1}$$

2.2. Water seepage equation in the cleat system

Similarly, water seepage equation in the cleat system can be described as follows:

$$\nabla\cdot\left[\frac{k_f k_{rw}}{B_w\mu_w}(\nabla(p_{fw}-\rho_w gD)\right]+q_{vw}=\frac{\partial}{\partial t}\left(\frac{\phi_f s_w}{B_w}\right) \tag{2}$$

2.3. State equation in the cleat system

Eqs. (1) and (2) are the second-order nonlinear partial differential equations which contain four unkowns: p_{fg}, s_g, p_{fw}, s_w. At the same time, p_{fg}, s_g, p_{fw}, s_w satisfy state equation as follows:

$$s_g+s_w=1 \tag{3}$$

$$p_{cgw}(s_g)=p_{fg}-p_{fw} \tag{4}$$

The $p_{cgw}(s_g)$ in Eq. (4) is called capillary pressure function, which is a given function.

2.4. Gas desorption and transportation equation in the cleat system

Considering the steady-state case, average gas concentration in the matrix is subject to desorption of adsorption gas, thus gas concentration changes during the process of gas desorption and transport in the matrix system can be expressed as the following equation:

$$\frac{d\overline{V}_m}{dt}=\frac{1}{\tau}[V_E(p_{fg})-\overline{V}_m] \tag{5}$$

Accordingly, from the matrix cell proliferation by channelling flow into cleat system, gases diffused and crossflowed from matrix unit to cleat system is:

$$q_{mfg}=-F_G\frac{d\overline{V}_m}{dt} \tag{6}$$

Here, while taking both free gas and adsorbed gas into account, gas concentration both in the surface and internal of the matrix element can be described as follows according to Langmuir equation and real gas law:

$$V_E(p_{fg})=\frac{V_L p_{fg}}{P_L+p_{fg}}+\frac{\phi_f M p_{fg}}{\rho_{sc}zRT} \tag{7}$$

$$\overline{V}_m=\frac{\phi_m M p_{mg}}{\rho_{sc}zRT}+\frac{V_L p_{mg}}{P_L+p_{mg}} \tag{8}$$

Eq. (7) linkes up average pressure and average concentration in the matrix system, then combined with Eq. (5) the pressure of matrix element can be got.

2.5. Initial conditions of the model

$$p_{fg}(x,y,z,0)=p_{fg}^0(x,y,z) \tag{9}$$

$$s_g(x,y,z,0)=s_g^0(x,y,z) \tag{10}$$

$$\overline{V}_m\big|_{t-0}=\frac{V_L p_{fg}^0}{P_L+p_{fg}^0}+\frac{\phi_f M p_{fg}^0}{\rho_{sc}zRT} \tag{11}$$

(1) Inner boundary conditions