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Numerical simulation of enhancing shale gas recovery using electrical resistance heating method

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ABSTRACT

Gas production from shale gas reservoirs can be enhanced by increasing the temperature of the reservoirs due to the increased desorption of the adsorbed gas. However, limited techniques are currently available for practically introducing heat into such low permeability reservoirs. This paper investigates the feasibility of an electrical resistance heating method to promote shale gas production by increasing the temperature of the reservoirs. To achieve our research goal, a mechanistic numerical model is developed to describe electrical field, temperature field, and pressure field. To capture gas flow in a shale gas reservoir, non-linear flow, diffusion and adsorption/desorption which are all dependent on temperature are incorporated into a dual continuum media model. In our study, the gas production enhancement by electrical heating with two parallel horizontal electrode wells is evaluated using this model. We then assess impacts of the thermal properties of the formation, electrode length, electrical power, Langmuir volume and starting time of heating on gas production. The results indicate that the electrical heating method using two parallel horizontal electrodes can be an efficient method to enhance shale gas production. The heat capacity and conductivity of the formation have significant impacts on gas production. Reservoirs with low conductivity and low heat capacity tend to produce more gas due to heating. Meanwhile, shale gas reservoirs with high Langmuir volume also tend to yield more gas due to heating for. To maximize gas production, electrical power should be optimized based on the properties of shale gas reservoir and heating equipment. Longer electrodes heat more formations of the reservoir and thus lead to higher gas production by using the electrical heating method. In order to efficiently enhance shale gas production, electrical heating should start later in gas production, instead of earlier.

1. Introduction

The development of shale gas production has significantly changed the energy supply structure of the world in recent years. A shale gas reservoir is characterized by an organic-rich deposition with extremely low matrix permeability and clusters of mineral-filled nature fractures [1]. In shale gas reservoirs, natural gas is mainly composed of free gas stored in natural fractures and matrix pores as well as adsorbed gas on shale formation and organic components. About 20–85% of the total gas in the shale gas reservoir exists as adsorbed gas [2–4]. Compared with conventional gas reservoirs, shale gas production may include a considerable amount of gas desorbed from the shale [5]. Therefore, gas desorption is one of major gas production mechanisms and can be an important contributor to the improved gas recovery. Some studies have suggested that pressure drawdown may lead to a considerable additional shale gas production due to desorption. For both Barnett and Marcellus shales, for example, gas desorption could account for 5–15% of the total gas production at the end of 30-year production period [6]. Thompson et al. [7] observed that gas desorption may contribute to 17% increase in the estimated ultimate recovery in a Marcellus shale well. The ratio of adsorbed gas production to total gas production is lower than the proportion of the adsorbed gas to total gas storage. That is to say, a higher percentage of adsorbed gas is unrecoverable in a shale gas reservoir. In addition to pressure drawdown, increasing temperature of the reservoir is another method to desorb adsorbed gas from the matrix and organic matter [8–12]. Lu et al. [8] found that the adsorption of shale gas is highly temperature dependent. Ross et al. [12] estimated that adsorbed methane is lower than 0.01 cm^3/g when temperature increases to 400–423 K. In recent years, many researchers [13–16] have attempted to enhance shale gas production by increasing formation temperature. Over a production period of 20 years, more than 40% of additional gas production was achieved by increasing the temperature along with

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Nomenclature

B	volume factor
C_a	amount of adsorbed gas ($m^3\ m^{-3}$)
C_g	gas internal energy ($J\ kg^{-3}\ K^{-1}$)
D_k	diffusion coefficient ($m^2\ s^{-1}$)
E	intensity of electrical field ($V\ m^{-1}$)
H	enthalpy of shale gas ($J\ kg^{-3}\ K^{-1}$)
J	electrical current density ($A\ m^{-2}$)
k	permeability (D)
k_a	adsorption equilibrium constant (MPa^{-1})
L	fracture spacing (m)
M_g	molar weight of gas ($kg\ mol^{-1}$)
M_R	volumetric heat capacity ($J\ m^{-3}\ °C^{-1}$)
P	pressure (MPa)
P_E	electrical energy density ($J\ m^{-3}\ s^{-1}$)
q_{leave}	gas transfer rate ($m^3\ m^{-3}\ s^{-1}$)
q_p	source/sink term ($m^3\ m^{-3}\ s^{-1}$)
t	time (s)
T	temperature (K)
u_D	Darcy mass flow velocity ($kg\ s^{-1}$)
u_k	diffusion mass flow velocity ($kg\ s^{-1}$)

Greek letters

α	shape factor of fracture (m^{-2})
ϕ	porosity
φ	electrical potential (V)
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
μ	gas viscosity (mPa s)
ρ	density ($kg\ m^{-3}$)
σ	electrical conductivity ($S\ m^{-1}$)

Subscripts

f	fracture
g	gas
m	matrix
R	rock
sc	standard condition

the hydraulic fracture, compared with the hydraulic fracture alone [13]. Zhu et al. [14] also numerically proved that shale gas recovery can be enhanced by altering gas desorption behavior by hydraulic fracture heating. Wang et al. [15,16] designed a thermal treatment in hydraulically fractured shale formations to enhance gas production and discussed the formation temperature required in a fracture to get more benefits.

Despite the potential to enhance gas desorption by increasing shale gas reservoir temperature it is challenging to inject hot fluids into shale gas reservoirs due to the extremely low permeability. In the researches mentioned above, a constant temperature thermal source was often used to heat the reservoir [13–15]. An electrical heating technology can overcome low injectivity of the formation, and has shown promising potential to increase the formation temperature [16–19]. Formation can be heated by electrical resistance heating when low frequency electromagnetic waves are introduced into formation using a system of electrodes. Electrical heating recovery techniques have been theoretically and experimentally tested for gas reservoir recovery [16,21], heavy oil recovery [17–20,22–24], shale oil recovery [25] and soil remediation [26–29]. However, the electrical resistance heating method has not been assessed for its potential to enhance shale gas production. Wang et al. [21] have developed an electrical heating method to enhance shale gas desorption. They also investigated the effects of parameters of reservoirs and electrodes on heating and desorption efficiency. In their study, however, the effects of electrical heating methods on shale gas production were not addressed.

In this paper, we aim to develop a mathematical model to describe electrical field, temperature field and shale gas flow in a reservoir when electrical resistance heating is used to enhance shale gas production. The distributions of electrical field and temperature field in overburden, underburden and shale layers are considered in the model. Gas adsorption and non-Darcy flow are coupled with a dual porosity medium model to describe shale gas flow in a reservoir. The model is numerically solved by a finite difference method to calculate shale gas production enhanced by the electrical resistance heating method. The effects of electrode length, formation thermal properties, electrical power, Langmuir volume and the starting time of electrical heating on temperature distribution and gas production are investigated and discussed in the paper. The results of this study show the feasibility of enhancing shale gas production by the electrical resistance heating method and provide a foundation for further research efforts on electrical heating techniques to enhance the ultimate shale gas recovery.

2. Mathematical model formulation

Here, we consider a three-dimensional shale gas reservoir with natural fracture. Overburden or underburden, that lies above or below a shale layer to preserve gases in the shale layer, can have an important impact on the distribution of electrical field and temperature field, especially when the rock electrical and thermal conductivities are high. Both overburden and underburden layers are included in the shale gas reservoir model. In addition, the shale gas layer is considered as a dual porosity medium.

2.1. Mathematical model of shale gas flow in natural fracture

It is assumed that only single component methane exists in the matrix and natural fractures. Natural fractures are only occupied by free gas. Adsorbed gas and free gas coexist in the matrix pores. Fick diffusion is considered based on the actual flow mechanisms in matrix and natural fractures. The permeability of the fracture is independent on pressure and pore structure. The continuity equation of gas in natural fracture is written as:

$$-\nabla\cdot\left(\vec{u}_{D_f}+\vec{u}_{k_f}\right)+\rho_{gf}q_{leav}+\rho_{gf}q_p=\frac{\partial}{\partial t}\left(\rho_{gf}\phi_f\right) \tag{1}$$

where the subscript g represents gas, f represents fracture, ρ denotes density, μ represents gas viscosity, ϕ denotes porosity. The first term of Eq. (1) $\vec{u}_{D_f}$ represents gas mass flow in the natural fracture of a shale. If we neglect the gravity force, it can be written as

$$\vec{u}_{D_f}=-\rho_{gf}\frac{k_f}{\mu_{gf}}\nabla P_f \tag{2}$$

where k_f is the permeability of fracture, P_f is the pressure of fracture. The second term of Eq. (1) $\vec{u}_{k_f}$ represents gas mass flow caused by