Three-dimensional numerical simulation of enhancing shale gas desorption by electrical heating with horizontal wells

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ABSTRACT

Increasing temperature can significantly enhance gas desorption and hence improves gas production in shale gas reservoirs, but there are limited practical techniques that can be used to introduce heat into such low permeability reservoirs. This paper investigates the feasibility of an electrical heating method for shale gas desorption enhancement with a mechanistic numerical model. The model incorporated the mechanisms of shale gas adsorption/desorption as a function of low-frequency conduction heating. We evaluate the gas desorption efficiency of heating by two parallel horizontal electrode wells using this model. The electrodes are placed in the two parallel horizontal wells. The impact of the physical properties of formation, electrode length and distance between electrodes, electrical power, and Langmuir volume on gas desorption are investigated. The results indicate that electrical heating using two parallel horizontal electrodes can be an efficient method to enhance shale gas desorption. The temperature and gas desorption increase when the two horizontal electrodes get closer. However, the electrode length and formation resistivity have insignificant impact on gas desorption as long as the injected electrical power is maintained constant. The reservoir thermal properties (heat capacity and conductivity) have a significant impact on gas desorption. Reservoirs with low conductivity and heat capacity get more benefit from the method. The amount of desorbed gas is proportional to the Langmuir volume, so electrical heating method is more applicable to the shale gas reservoir with high Langmuir volume. Gas desorption is directly proportional to the electrical power, therefore, high enough electrical power is required to make the technique successful.

Keywords: shale gas; desorption; electrical heating; numerical simulation; horizontal well

1. Introduction

The development of unconventional shale gas in the world, especially in North America, has significantly changed the energy supply structure of the world in recent years. A shale gas reservoir is characterized of an organic-rich deposition with extremely low matrix permeability and clusters of mineral-filled nature fractures (Ross et al. 2008). The gas storage mechanisms in a shale reservoir are quite different from those in a conventional gas reservoir. In shale gas reservoirs, natural gas is stored as free gas in the porous space as well as an adsorbed gas on shale formation and organic components. Some studies (Schettler et al., 1991; Li 1992; Wu et al., 2014) have estimated that the amounts, range from 20% to 85%, of the total gas storage in shale gas reservoir exist as adsorbed gas. Therefore, enhancing gas desorption can significantly improve

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shale gas recovery.

At the early stage of shale gas recovery, gas production is dominated by free gas mainly stored in the high permeability fractures. However, gas production rate tends to decrease sharply due to the limited gas storage capacity of the high permeability fractures. At the later development stage, the absorbed shale gas will dominate gas production. In general, continuous gas production from wells leads to a pressure decrease in shale gas reservoirs, which would desorb shale gas as a result. However, the amount of desorbed gas solely from pressure drawdown may not be sufficient to sustain profitable gas production at this stage. Therefore, there is a need to find appropriate methods to enhance gas desorption. In addition to pressure drawdown, another key factor impacting shale gas desorption is temperature (Lu et al., 1995a, 1995b; Zhang et al., 2012; Chareonsuppanimit et al., 2012; Ross et al., 2007). Lu et al. (1995a) found that the adsorption of shale gas is highly temperature dependent. Ross et al. (2007) estimated that the adsorption capacity of methane is lower than $0.01 \text{ cm}^3/\text{g}$ when the shale gas formation temperature increases to 400-423K. In recent years, many researchers (Lin et al., 2015; Zhu et al., 2016; Wang et al., 2014; Wang et al., 2015) have investigated shale gas production enhancement by increasing formation temperature. Lin et al. (2015) assessed the effect of temperature on shale gas adsorption and numerically simulated how thermal stimulation affected shale gas production. Their results showed that increasing the temperature along with the hydraulic fracture could produce more than 40% additional gas for a period of 20 years, compared with the hydraulic fracture alone. Zhu et al. (2016) numerically investigated the effect of thermal recovery based on hydraulic fracture heating by assuming the hydraulic fracture temperature is an isothermal heat source. They proved that heating hydraulic fractures can actually enhance shale gas recovery by altering gas desorption behavior. Wang et al. (2014; 2015) proposed a method to evaluate desorbed gas as a function of pressure and temperature in shale formations. They provided a guidance to design thermal treatment in hydraulically fractured shale formations and proposed the degree of thermal stimulation temperature required in a fracture to promote an economically viable return on production.

Although increasing formation temperature has been recognized for its potential to enhance gas production, very limited information is available on how to introduce heat into the formation. In the mathematical models mentioned above, the thermal source is often assumed to provide a constant temperature (Lin et al., 2015; Zhu et al., 2016; Wang et al., 2014). Unlike conventional oil reservoirs, shale gas reservoirs are often of extremely low permeability, which makes it difficult to inject hot fluids into them. In this case, electrical heating overcomes low injectivity of the formation and may have promising potential in increasing the formation temperature (Wang et al., 2015; Bientinesi et al., 2013; Bera et al., 2015; Sandberg et al., 2014; Zhu et al., 2013). The electrothermal processes convert electrical energy to heat, so that the formation can be heated by means of ohm losses of electric current using a system of electrodes to induce currents to flow through the formation. By properly adjusting operating frequency and electrodes spacing, considerable control can be made over the path taken by the currents and hence over the temperature profiles that will develop in the formation. In addition, a reservoir can be heated relatively uniformly if the optimization of electrical heating systems is made to reflect specific reservoir lithology. Electrical heating recovery techniques have been theoretically and experimentally tested in gas reservoir recovery (Wang et al., 2015), heavy oil recovery (Bientinesi et al., 2013; Bera et al., 2015; Sandberg et al., 2014; Zhu et al., 2013; Baylor et al., 1990), shale oil recovery (Symington 2006; Symington et al., 2009) and soil remediation (Martin et al., 2011; Hegele et al., 2014; Munholland et al., 2016). However, electrical heating has not been assessed

for its potential to heat shale gas reservoirs and thus enhance gas desorption.

In this paper, we propose a method to enhance shale gas desorption by electrical resistance heating according to the mechanism of shale gas adsorption/desorption and low-frequency conduction heating. A mathematical model of enhancing shale gas desorption by electrical heating is developed, and is numerically solved to calculate the distribution of the electrical and temperature field in overburden, underburden and shale layers. The desorption efficiency of shale gas is calculated by Langmuir isotherm equation from the temperature distribution. Based on the developed model, effects of electrode length and spacing, reservoir resistivity, formation thermal properties, electrical power and Langmuir volume on gas desorption are investigated and discussed in the paper. The results of this study show the feasibility of enhancing shale gas desorption by electrical heating method and give a foundation for further research efforts on electrical heating techniques to enhance the ultimate shale gas recovery.

2. Mathematical model formulation

2.1. Physical description

There are three electromagnetic heating methods commonly used for an oil reservoir, including radio frequency heating, induction heating, and low-frequency conduction heating (Mcgee et al., 2007). This paper only discusses low-frequency conduction heating. At low frequencies, electrical resistance heating occurs when an electric current flows through the reservoir. Because of the extremely low permeability of shale gas reservoir, horizontal wells often having larger contact area between formation and wellbores are often employed to produce shale gas (Olorode et al., 2013; Jiang et al., 2014). Obviously, it is easier to heat a reservoir by using horizontal electrode wells. Fig.1 shows the process of electrical resistance heating reservoir using two horizontal electrode wells. Two electrodes are placed parallel to each other in two horizontal wells. When electrical energy is imported into the formation by cable, there are currents flowing through the formation between electrode wells drilled into the shale gas formation. Electrical energy is converted to heat within the reservoir in proportion to the resistance of the formation along the current pathways. The adsorbed shale gas will desorb from the matrix and organic matter with the increase of formation temperature when electrical energy is converted to heat.

Fig.1 Diagram of electrical resistance heating shale gas reservoir using horizontal electrode wells

As the electrical current can go beyond the shale gas reservoir itself, an overburden and underburden layers are included in the model. The rock above and below the shale gas reservoir can have an important impact on the distribution of electrical field and temperature field,

especially when the rock conductivity is high.

2.2. Mathematical model of electrical field

In theory, the full form of Maxwell's equations, along with appropriate boundary conditions, can be used to calculate the electric field for any physical configuration at any frequency. At low frequencies, electrical resistance heating occurs when an electric current flows through the formation. The simplified assumptions employed in developing the mathematical model of electrical field include: 1) the quasi-static approximation is used, which neglects electric fields produced by the changing magnetic fields; 2) the displacement current is neglected when the voltage frequency used is low enough; 3) the electrical resistivity does not depend on the strengths of the electric fields, temperature, water saturation and organic distribution; and 4) the electrical resistivity is isotropic. But the distribution of electrical resistivity of the formation can be heterogeneous. With the above assumptions, the flow of electrical current in a shale gas reservoir satisfies the following conservation equation of electrical current (Hascakir et al., 2008; Hiebert et al., 1986)

$$\nabla \cdot \vec{j} = 0 \quad (1)$$

where $\vec{j}$ represents electrical current density. The relationship between $\vec{j}$ and electrical field intensity $\vec{E}$ is written as

$$\vec{j} = \frac{1}{R} \vec{E} \quad (2)$$

where R is the resistivity of shale gas formation. The relationship between electrical field intensity $\vec{E}$ and electrical potential φ is written as

$$\vec{E} = -\nabla \varphi \quad (3)$$

Combining Eq.(3) and Eq.(2) gives

$$\vec{j} = -\frac{1}{R} \nabla \varphi \quad (4)$$

Substituting Eq.(4) into Eq.(1) yields the equation of electrical potential in shale gas reservoir as

$$\nabla \cdot \left(\frac{1}{R} \nabla \varphi \right) = 0 \quad (5)$$

Assuming all the electrical energy distributed in the formation is converted to heat energy, the time rate of energy generation in per unit volume of formation (electrical energy density) can be written as

$$P_E = \frac{1}{R} \vec{E} \cdot \vec{E} \quad (6)$$

Eq.(6) can be regarded as the source term in energy conservation equation.

The electrical field discussed here have two boundary conditions constraining the solution. On the surface of the electrode, the potential function φ satisfies

$$\varphi = V_{\text{const}} \quad (7)$$

where V_{const} is the voltage applied on the electrode, which forms the inner boundary condition.

At the outer surface of the shale gas reservoir, an insulated boundary condition is formed and denoted as

$$\frac{\partial \varphi}{\partial n} = 0 \quad (8)$$

2.3. Mathematical model of temperature field

The following simplified assumptions were employed in developing the mathematical model for the temperature field: 1) the thermal conductivity is isotropy; 2) there is only a gas phase in the pores of the shale; 3) the transfer of heat between solid and gas phases is instantaneous; 4) the thermal conductivity is independent of the electrical and temperature fields; and 5) gas flow and phase transition are neglected. The energy conservation equation can be written as (Hiebert et al., 1986)

$$\nabla \cdot \lambda \nabla T + P_E = \frac{\partial}{\partial t} (\phi \rho_g C_g T + (1 - \phi) M_R T) \quad (9)$$

where λ is the thermal conductivity of shale, T represents the formation temperature, ϕ represents the rock porosity, ρ_g represents the gas density, C_g is the gas internal energy, M_R represents the volumetric heat capacity of the shale rock. The energy source term P_E is calculated using Eq. (6).

At the outer surface of the shale gas reservoir, the boundary condition of the temperature field satisfies the following equation

$$\frac{\partial T}{\partial n} = 0 \quad (10)$$

The initial condition of the temperature field is a constant temperature field

$$T_{t=0} = T_{\text{const}} \quad (11)$$

2.4. Shale gas adsorption model

The gas adsorption depends on the amount of organic matter, diagenesis, rock texture, and reservoir pressure and temperature (Li, 1992; Lane et al., 1991; Lane et al., 1989; Lu et al., 1995; Zhang et al., 2012; Chareonsuppanimit et al., 2012). It is hard to include all these factors in a mathematical model of shale gas adsorption. This study mainly focuses on the effect of temperature on shale gas adsorption. The Langmuir isotherm equation derived from the theory of kinetics and thermodynamics fits the measured shale gas data (Lu et al., 1995b; Ruthven 1984; Adamson, 1982). This model is a simplified model of gas/solid adsorption which is based on four assumptions (Wang et al., 2014): 1) all of the adsorption sites are equivalent and each site can only accommodate one molecule; 2) the surface is energetically homogeneous and adsorbed molecules do not interact; 3) there is no phase transition; and 4) at the maximum adsorption, only a monolayer is formed. The Langmuir isotherm equation is written as

$$C_a = C_{a\text{max}} \frac{k_a(T)P}{1 + k_a(T)P} \quad (12)$$

where C_a represents the amount of adsorbed gas at pressure P and temperature T per unit volume of shale, $C_{a\text{max}}$ is the Langmuir volume, i.e., the maximum amount of adsorbed gas per unit volume of shale, $k_a(T)$ is the adsorption equilibrium constant as a function of temperature. This constant can be expressed as

$$k_a(T) = k_{a0} T^{-\frac{1}{2}} \exp\left(-\frac{E}{RT}\right) \quad (13)$$

where k_{a0} is a constant independent of temperature, E is the characteristic adsorption energy, and R is the universal gas constant. It can be seen that the amount of adsorbed gas decreases with increasing temperature. When the temperature distribution is known, one can calculate how much gas is desorbed from the formation using Eqs.(12) and (13).

Fig.2. Flowchart of the numerical solution

2.5. Numerical solution of the mathematical model

The finite difference method is used to solve the above mathematical models of electrical field and temperature field. Assuming the electrical resistance of shale formation is independent of the electrical field and temperature field, the electric field model is only solved once as long as the electrical potential applied to the electrodes does not change. The distribution of electrical energy density defined by Eq.(6) is obtained by numerically solving the electric current conservation equation (Eq. (5)). A fully implicit finite difference scheme is used to numerically solve the mathematical model for the temperature field. A center difference scheme is used to the left side and a forward difference scheme is used to the right side of Eq.(9). Both the difference equations of electrical field and temperature field are solved using successive over-relaxation (SOR) method with relaxation factor $\omega=1.5$. The iteration is converged if the new iteration satisfies

$$\left| \frac{x^{l+1} - x^l}{x^l} \right| \leq 1.0 \times 10^{-6} \quad (14)$$

where x represents the electrical potential or temperature, and l represents the iteration number. Both the electrical field and temperature field are calculated for the whole system including overburden, underburden, and shale layers. The effects of overburden and underburden layers on the distribution of electrical field and temperature field can be discussed.

After the temperature field of the shale layer is obtained by solving the energy conservation equation, the amount of desorbed shale gas is calculated using Eqs.(12) and (13). The procedure continues until it reaches the specified time. The flowchart of the procedure is shown in Fig.2. This sequence is found to be adequate for solving the equations with good accuracy.

2.6. Model validation

In order to validate the model, the numerical results of temperature are compared with the measured data of a 3D physical model experiment of heavy oil reservoir heated by electrical method using single vertical electrode well (Wang, 1999). The schematic diagram of the experiment is shown in Fig.3. The experimental system was a $40 \times 40 \times 35 \text{ cm}^3$ cubic model with overburden, underburden and oil layers. The electrode well was placed vertically in the center of the oil layer. Nine moll thermopiles were located on the center plane of oil zone to measure the temperature of the formation. The model parameters are listed in Table 1. The model was discretized uniformly by $41 \times 41 \times 35$ gridblocks. The temperature of the formation was calculated using the above mathematical model.

Fig.4 shows the measured and simulated temperature of the formation at two different times. Because most electrical energy is distributed around the electrode well, the formation temperature around the well increases sharply. The simulation results (solid curves) match the experimental data with reasonable accuracy except the two data points around the well after one-minute of heating. From the statistical point (Zendehboudi et al., 2011a, 2011b; Montgomery, 2008), we can see that the relative error (i.e. a ratio of the difference between a measured value and the corresponding simulated value to the measured value) of the nine measured data points after heating one minute, ranges between 0.01% and 27.31%, with higher error occurring very close to the electrode. The average relative error of the nine points after heating one minute is 7.68%. The errors come from three sources: 1) the 3D physical model is filled with sands by hand, which would lead to heterogeneity in physical properties of the layers such as electrical resistivity, thermal conductivity, and heat capacity, all of which, however, are assumed to be homogeneous in the numerical simulation model; 2) the water vaporization heat is not accounted for in the mathematical model; and 3) there are experimental errors caused by measurement error in temperature, distance and different starting time for electrical heating and data collection. As the process continues, the differences between measured and simulated values tend to become smaller. The predicted temperature values are in good agreement with the experimental data when heating time reaches 90 minutes. For the nine measured data points, the relative error ranges from 0.11% to 6.12%, with higher error at the point close to the electrode. The maximum relative error is much smaller than that of heating one minute. The average relative error of the nine points after heating 90 minutes is 3.86%. This indicates that the mathematical model captures the main factors that control the distribution of electrical field and temperature field.

Fig.3. Schematic diagram of the physical experiment

Table 1 Basic parameters of the physical model.

Parameter	value
Electrode diameter d	0.6[cm]
Electrode length L	3.75[cm]
Oil zone thickness h_o	13.5[cm]
Electrical power P_{Etotal}	50.0[W]
Porosity ϕ	35.0[%]
Initial temperature T_0	8.0 [°C]
thermal conductivity λ	2.61[W m ⁻¹ °C ⁻¹]
Resistivity of oil zone R_s	14.30[Ω m]
Resistivity of overburden R_o	1.32[Ω m]
Density of formation ρ_R	1755[kg m ⁻³]
volumetric heat capacity of formation M_R	2.04 × 10 ⁶ [J m ⁻³ °C ⁻¹]

Fig.4. Comparison between numerical results and experimental data

3. Results and discussion

In this section, we investigate the efficiency of enhancing shale gas desorption by electrical heating. In addition, the impact of the parameters of horizontal well, electrical and thermal properties of the formation, electrical power, and amount of adsorbed shale gas on desorption efficiency are also discussed. The geological model is a 3D system with three layers as shown in Fig.1. The size of the model is 150m×150m×150m. The thickness of each layer is equal to 50m. Two well configurations are considered. The first well configuration consists of two horizontal wells as shown in Fig. 1 and the second well configuration is an inverted 5-spot with vertical wells

as shown in Fig.5. For the first well configuration, the two 100m long electrodes are located at the middle plane of the shale gas formation. The distance between the two electrodes is 50m. The simulation model consists of a $51 \times 51 \times 29$ grid. Along the horizontal well direction, the formation is discretized uniformly with 3m grid size. To simulate the sharp change of the electrical field, the shale gas reservoir geometry in x - z plane is discretized into a computational domain through non-uniform gridblocks. The diagram of grid size in x - z plane is shown in Fig.6. The grid becomes gradually sparse from electrode to boundary to simulate the sharp change of the electrical field around the electrodes. For the second well configuration, all five electrodes have a length of 38m and are located at the same level of the formation. The x - y plane is discretized uniformly with 3m grid size and the grid size along the z direction is as same as the first well configuration. The four negative electrodes are located at the corners: (5, 5), (5, 47), (47, 5) and (47, 47) in x - y plane, respectively. The positive electrode is located at the center, (26, 26) in x - y plane. The electrical properties and adsorption parameters are measured using core samples from a shale gas well in China. The basic parameters are listed in Table 2.

The distribution of electrical energy density, temperature, and gas amounts of desorption are simulated with an electrical power injected into the formation at 100kW for the both well configurations.

Fig.5. diagram of electrical resistance heating shale gas reservoir using 5-spot vertical electrode wells

Fig.6. Diagram of the grid system in x - z plane

Table 2 Basic parameters of the synthetic model.

Parameter	value
Porosity ϕ	0.0219
Initial temperature T_0	50.0[°C]
thermal conductivity λ	2.312[W m ⁻¹ °C ⁻¹]
Resistivity of shale zone R_s	200.0[Ω m]
Resistivity of overburden R_o	200.0[Ω m]
Resistivity of underburden R_u	200.0[Ω m]
Density of formation ρ_R	3.0 [kg m ⁻³]
volumetric heat capacity of formation M_R	2.04×10^6 [J m ⁻³ °C ⁻¹]
Adsorption constant k_{a0}	0.013[MPa ⁻¹]
Characteristic adsorption energy E	-15.648[kJ mol ⁻¹]
Maximum amount of adsorption C_{amax}	10.38[m ³ m ⁻³]
Initial pressure P_0	10.0[MPa]
Length of parallel electrode L	100[m]
Distance of parallel electrode d	50[m]
Electrical heating power P_{Etotal}	100[kW]
Length of the reservoir L_s	150[m]
Width of the reservoir W_s	150[m]
Thickness of overburden zone h_o	50[m]
Thickness of shale layer h_s	50[m]
Thickness of underburden zone h_u	50[m]

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319 *3.1. Evaluation of electrical heating with horizontal electrode wells*

320 The electrical energy density distributions in the formation of the two well configurations are
 321 shown in Fig.7. To show the electrical energy density distribution clearly in 3D space, especially
 322 the distribution near the electrodes, the distribution of electrical energy density on some slices of
 323 the formation is plotted. The electrical energy density distribution along the two parallel horizontal
 324 electrodes is shown in Fig.7a using an enlarged color scale. It is noticed that the areas of high
 325 power intensity are located near the electrodes, especially in the areas near the end of the wells,
 326 due to a large voltage gradient near the electrode. The high energy intensity concentrated at the
 327 end of the electrodes may cause high temperature and damage the electrode assembly. As the
 328 current flow area with horizontal wells is much larger than that of vertical wells, the electrical
 329 energy density near the parallel wells is significantly less than that of vertical wells when the same
 330 amount of electrical energy is introduced into the formation. Therefore, horizontal well
 331 configuration may heat more formations and help desorb more gas and hence yields better gas
 332 recovery than vertical wells.

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Fig.7. Electrical energy density distribution of formation

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Figure 8 shows the temperature fields after 10 years of heating. Because all electrical energy is converted to heat energy as an assumption, temperature field has the same feature as the electrical

energy density field. In the horizontal well configuration, the maximum temperature is reached along the parallel wells, especially at the ends of the well (Fig.8a). The maximum temperature at the end of the parallel wells is 140°C, while the temperature in the formation midway between the two parallel electrodes is 70°C at which more than 12.0% absorbed gas is desorbed. Note that the initial temperature is 50°C. Therefore, all the formations between and around the two electrodes are heated sufficiently to desorb the gas. In the case of vertical wells, the maximum temperature of the positive electrode is over 200°C. But the temperature of the formation decreases sharply with the increasing distance from the positive electrode. The temperature 30m away from the positive electrode decreases to about 60°C. The maximum temperature of the negative electrodes is only 73°C (Fig.8b). This indicates that more electrical energy dissipates near the positive electrode in vertical electrode wells case. The formation volume with temperature over 70°C is less than that of horizontal electrode well case. Comparing the two well configurations, the horizontal well case yields higher gas desorption. The same conclusion can be drawn from the shale gas desorption ratio.

Fig.8. Temperature distribution of formation after 10 years

Fig.9. shale gas desorption ratio of two electrical heating pattern

The shale gas desorption ratio is defined as

$$f_d = \frac{N_d}{N_{a0}} \quad (15)$$

where f_d represents shale gas desorption ratio, N_{a0} represents the total amounts of the adsorbed gas at initial condition, N_d represents the amounts of gas desorbed by electrical heating. N_{a0} and N_d can be calculated from Eqs.(12) and (13) according to the initial and

heated temperature field of the shale layer. Fig.9 shows the shale gas desorption ratio for both well configurations. After 10 years of heating, 5.85% of the adsorbed shale gas is desorbed from the shale when parallel electrode wells are used. But only 5.20% of the adsorbed shale gas is desorbed from the shale when an inverted 5-spot vertical electrode pattern is used. It is indicated that the two parallel horizontal electrodes heating configuration is more efficient to enhance gas production. The parametric study will focus on the electrical heating system with two parallel horizontal electrode wells.

3.2. Effects of parameters of heating system on shale gas desorption

3.2.1. Effect of distance of two parallel horizontal electrodes

The distance of the two parallel electrodes is a key factor to determine the distribution of electrical and temperature fields, as well as the desorption efficiency. With an increasing electrode spacing, electrical current flows through more area in y-z profile, and, as a result, more electrical energy will dissipate in the overburden and underburden layers. To investigate the effect of electrode spacing, 5 different cases with 20m, 40m, 60m, 80m, and 100m spacing are run. To quantitatively show the electrical energy distribution in shale, overburden, and underburden zones, we define

$$\eta(h) = \frac{P(h)}{P} \quad (16)$$

where $P(h)$ is the electrical power dissipated in the central formation with thickness h , P is the total electrical power introduced into the whole formation, including overburden zone, shale gas zone, and underburden zone. When h equals the thickness of the shale layer, $\eta(h)$ is defined as the electrical heating efficiency, which represents the rate of the electrical energy dissipated in the shale zone to the total electrical energy injected into the whole formation. Fig.10a shows the electrical heating efficiency for different electrode distance. The horizontal coordinate is the dimensionless formation thickness, h/h_{Total} . Here h_{Total} is the total thickness of the formation which is equal to 150m. The dimensionless formation thickness of the shale gas zone equals to 1/3. We can see that the electrical heating efficiency increases from 0.87 to 0.98 when the distance of the electrodes decreases from 100m to 20m. Such a result means that more electrical energy is lost into overburden and underburden zones with the increase of electrode distance, which tends to decrease the heating performance. Fig.10b shows the temperature distribution along x direction of the center line at the middle plane on which electrode wells are placed after 10 years of heating. The temperature of the gridblocks containing electrode increases from 117°C to 149°C, and the temperature of the midpoints between the two electrode wells increases from 54°C to 106°C, when the distance of electrodes decreases from 100m to 20m. The desorption ratio reflecting the desorption efficiency of electrical heating is almost same when the electrode distance ranges from 20 m to 40 m. In the range of 40-100 m, however, the desorption ratio decreases with increasing electrode distance regardless of heating time.

(a) Electrical heating efficiency

(b) Temperature

(c) Desorption ratio

Fig.10. Effect of distance of electrode on electrical heating efficiency, temperature and desorption ratio

3.2.2. Effect of electrode length

The length of an electrode determines the electrical current flowing area between formation and the electrode. If the injected electrical power is constant, more area would be heated with increasing electrode length and the temperature would decrease accordingly. Fig.11 shows the temperature distribution of the central horizontal plane on which electrode wells are placed after 10 years of heating. With the increase of electrode length, electrical energy dissipates to a larger area, which causes more formations being heated, leading to an increase in the desorption efficiency. Meanwhile, increasing electrode length decreases the temperature of the heated areas, decreasing the desorption efficiency. When the electrode length increases from 60m to 120m, for example, the temperature of the gridblocks containing the electrodes decreases from 190°C to

120°C, and the temperature at the midpoint between the two electrodes decreases from 77°C to 67°C. According to the above discussion, it is apparent that the net effect of electrode length on gas desorption is dependent on the volume of the heated shale area and the temperature in the area. As shown in Fig.12, the desorption ratio for an 80-m electrode is slightly higher than those for other tested electrodes. The result also shows that electrode length has no obvious effect on desorption ratio if the injected electrical power is constant. In addition, a short electrode well may cause exorbitant formation temperature near the electrode well, which may result in vaporization of formation water and damage to the electrode well. A short the horizontal well is not desired due to the low production of the shale gas.

Fig.11. Temperature distribution in central horizontal plane with different electrode length

Fig.12. Effect of electrode length on desorption ratio

3.2.3. Effect of resistivity of the formation

The formation resistivity affects the distribution of the electrical energy. Many researches have noted that shale resistivity depends on electrical property of the shale, water saturation, and organic matter content and maturity (Kamalia et al., 2004; Passey et al., 1990). The measurement data of the shale resistivity indicates a range from $10 \Omega \cdot m$ to $1000 \Omega \cdot m$. In this paper, dimensionless formation resistivity is defined as the ratio of the resistivity (R_s) of shale gas zone to that (R_o) of overburden or underburden zone. Fig.13a shows the electrical heating efficiency of different formation resistivity. The results indicate that a large resistivity of shale layer causes a little larger fraction of total power to be dissipated in the shale zone. Because both the electrodes are located in the shale layer, most of the currents flow through the shale layer from the positive electrode to the negative electrode. More resistance would produce more heat energy. The effects of resistivity on the temperature field of the shale layer between the electrodes and beyond are different. Fig.13b shows the temperature distribution along x direction of the center line at the middle plane on which electrode wells are placed after 10 years of heating. The temperature of the shale layer between the two electrodes increases with increasing shale resistivity. However, the temperature of the shale layer outside the two electrodes decreases with the decrease of resistivity of the shale. Fig.13c shows the effect of formation resistivity on the desorption ratio. The shale gas desorption ratios are almost the same regardless of dimensionless formation resistivity. In summary, the resistivity of the formation is not a key factor affecting the shale gas desorption enhanced by electrical heating.

(a) Electrical heating efficiency

(b) Temperature

(c) Desorption ratio

Fig.13. Effect of formation resistivity on electrical heating efficiency, temperature and desorption ratio

3.2.4. Effect of heat capacity of the formation

The heat capacity is related to the formation composition, porosity, water saturation, temperature, and pressure. When constant electrical power is introduced into the formation, the heat capacity of the formation determines the temperature increment of the reservoir. Fig.14a shows the impact of formation heat capacity on temperature distribution along x direction of the center line at the middle plane on which electrode wells are placed after 10 years of heating. The temperature of the whole reservoir increases with the decrease of the formation heat capacity. The temperature of the gridblocks containing the electrodes and of the midpoints between the two electrode wells increases from 117°C to 139°C and from 59°C to 83°C , respectively, when the heat capacity decreases from $4.08 \times 10^6 \text{J}/(\text{m}^3 \cdot \text{K})$ to $1.02 \times 10^6 \text{J}/(\text{m}^3 \cdot \text{K})$. Higher temperature results in more shale gas desorbed from the shale. Fig.14b indicates that the desorption ratio increases from 3.24% to 10.00% when the heat capacity decreases from $4.08 \times 10^6 \text{J}/(\text{m}^3 \cdot \text{K})$ to $1.02 \times 10^6 \text{J}/(\text{m}^3 \cdot \text{K})$. In summary, the smaller the heat capacity is, the more gas desorbed from the shale when the same amount of energy is injected into formation.

(a) Temperature

(b) Desorption ratio

Fig.14. Effect of heat capacity on temperature and desorption ratio

3.2.5. Effect of heat conductivity of the formation

Heat conductivity of the formation determines the speed of the heat conduction in the formation. Although most of electrical energy is dissipated in the shale layer, some heats may be transferred to overburden and underburden layers by heat conduction. The heat loss can reduce the heating efficiency of the shale layer. Here, we assume the overburden, underburden and shale layers have

the same heat conductivity. Fig.15a shows the temperature distribution along x direction of the center line at the middle plane on which electrode wells are placed after 10 years of heating. The temperature of most part of the shale layer decreases with increasing heat conductivity due to greater heat lost to overburden and underburden layers. However, it should be noted that the temperature of the shale close to the boundary increases slightly with the increase of the heat conductivity, which is caused by the heat conduction from high temperature zone of shale layer to low temperature zone near the boundary. Fig.15b shows the temperature distribution along z direction of the central formation of the reservoir after 10 years of heating with different heat conductivities. As expected, the temperature of the overburden and underburden layers increases with the increase of the heat conductivity. The reason that temperature of the shale does not monotonically change with heat conductivity is the interaction of heat conduction along x and z directions. As shown in Fig.15c, the desorption ratio decreases from 6.43% to 4.92% when the heat conductivity increases from 1.20W/(m·K) to 4.75 W/(m·K). If a very high temperature zone is formed near the well, however, high heat conductivity may lower the temperature level of the zone to avoid the equipment damage caused by high temperature.

(a) Temperature along x direction

(b) Temperature along z direction

Fig.15. Effect of heat conductivity on temperature and desorption ratio

3.2.6. Effect of electrical power

Electrical power is a very important factor for shale gas desorption in the electrical heating method. Fig.16a shows the temperature distribution of the center line along x direction at the middle plane on which electrode wells are placed after 10 years of electrical heating. It is noted that electrical power has a very large effect on the temperature of the formation. The temperature of the formation near the electrodes and the midpoint between the two electrodes is about 88°C and 59°C , respectively, when 50kW electrical power is introduced into the formation. In comparison, the temperature increases to 436°C and 144°C , respectively, when the electrical power increases to 500kW. Therefore, the volume of heated zone and its temperature increase when more electrical energy is introduced into the formation. Fig.16b shows the effect of electrical power on shale gas desorption ratio. Shale gas desorption ratio at the end of 10 years increases from 2.59% to 25.83% when the electrical power increases from 50kW to 500kW. It should be pointed out that high temperature near the electrodes caused by high electrical power may result in water vaporization and damage to equipment. Therefore, electrical power should be optimized based on the properties of shale gas reservoir and heating equipment if electrical heating method is used to enhance shale gas desorption.

Fig.16. Effect of electrical power on temperature and desorption ratio

3.2.7. Effect of Langmuir volume

The Langmuir volume is related to the composition of shale, water saturation, and organic matter content and maturity. It reflects the shale formation's intrinsic adsorption capacity and

determines the amount of gas that can be ultimately desorbed from the formation by electrical heating. When the Langmuir volume is $4.66\text{m}^3/\text{m}^3$, $10.38\text{m}^3/\text{m}^3$, and $26.80\text{m}^3/\text{m}^3$, the amount of gas desorbed from shale is $2.27 \times 10^5\text{m}^3$, $5.05 \times 10^5\text{m}^3$ and $13.00 \times 10^5\text{m}^3$, respectively, during the 10-yr period of electrical heating (Fig.17a). It is obvious that the amount of desorbed gas is proportional to the Langmuir volume. Our result also shows that the desorption ratios are same regardless of Langmuir volume (Fig.17b). It seems that electrical heating is more applicable to shale gas reservoirs with high Langmuir volume for enhancing gas desorption. Generally, high organic matter content leads to high Langmuir volume.

Fig.17. Effect of Langmuir volume on amount of desorption and desorption ratio

3.2.8. Discussion of the effects of the parameters on shale gas desorption

Fig.18 shows the effects of the parameters of heating system on the amount of gas desorbed from shale after 10 years of heating using a tornado chart. It clearly shows that electrical power is the most important factor among the parameters discussed above to desorb the gas from the shale by electrical heating. It should be pointed out that high electrical power may cause high temperature near the electrodes which may result in damage to electrodes. Therefore, electrical power should be optimized based on the properties of shale gas reservoir and heating equipment if electrical heating method is used to enhance shale gas desorption. The second important factor affecting gas desorption is Langmuir volume which reflects the shale formation's intrinsic adsorption capacity. The amount of adsorbed gas for almost shale gas reservoirs in the world ranges from $2.06\text{m}^3/\text{m}^3$ to $29.7\text{ m}^3/\text{m}^3$ (Arthur et al. 2008). The electrical heating method is more applicable to shale gas reservoirs with high adsorbed gas. The next two parameters that are important to desorb shale gas by electrical heating are heat capacity and heat conductivity. These two parameters depend on the thermal property of the formation which has little variance in general. The last three parameters, electrode distance, resistivity and electrode length, are less sensitive to desorb the gas compared with the above parameters. Resistivity is determined by the electrical property of the formation which can be changed by hydraulically fracturing the shale and filling the fractures with electrically conductive material. Electrode distance and length depend on the well configuration. These two factors can be adjusted to improve the gas desorption although their impact is small compared to other factors. For a real shale gas reservoir, all parameters should be optimized to enhance shale gas desorption by electrical heating according to the formation properties and well configuration.

Fig.18. Tornado chart of the effect of heating system parameters on shale gas desorption

4. Conclusion

In this study, an electrical heating method is proposed to enhance shale gas desorption. A mathematical model is developed to describe shale gas desorption enhanced by electrical heating according to the mechanism of shale gas adsorption/desorption and low-frequency conduction heating. The mathematical model was numerically solved by the fully implicit finite difference method. The temperature model is then validated using the measured data of a 3D physical model experiment of heavy oil reservoir, in which a single vertical electrode well is used to heat the system. The study indicates horizontal well configuration is more suitable to electric heating the shale gas reservoir than the inverted 5-spot vertical electrode wells heating pattern. The effects of the parameters of heating system with two horizontal electrodes wells on the heating and desorption performances are investigated. Based on this study, the following conclusions can be drawn:

1. Electrical resistance heating is an efficient method to enhance shale gas desorption. The numerical simulation model provides a rational approach to evaluate and optimize the scheme of the method.
2. The parallel horizontal well configuration is more efficient to desorb the shale gas compared with the inverted 5-spot vertical electrode heating pattern.
3. The parameters of the two horizontal electrodes should be considered to enhance gas desorption by electrical heating. More gas is desorbed with increasing electrode distance. A decrease in electrode length leads to an increase in temperature of the heated zone and a decrease in volume of heated zone. However, the net effect of electrode length on desorption ratio is not obvious if the injected electrical power is constant.
4. The formation resistivity is not a key factor affecting the shale gas desorption when two parallel horizontal electrodes heating pattern is used. The thermal properties have large effects on gas desorption. Lower heat capacity causes higher temperature of the formation and more gas is desorbed from the shale. Heat conductivity is related with heat losses to overburden and underburden layers. The desorption ratio decreases with the increase of heat conductivity.
5. Electrical power is a very important factor to enhance shale gas desorption by electrical heating method. Shale gas desorption ratio increases from 2.59% to 25.83% when the electrical power increases from 50kW to 500kW.
6. The amount of desorbed gas is proportional to the Langmuir volume. Electrical heating is more

applicable to shale gas reservoirs with high Langmuir volume for enhancing gas desorption.

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Nomenclature

ρ	density, kg/m ³
φ	electrical potential, V)
λ	thermal conductivity, W/ m K
η	electrical heating efficiency, dimensionless
ϕ	porosity, dimensionless
C_a	amount of adsorbed gas, m ³ /m ³
C_g	internal energy of the gas, J/kg K
E	electrical field intensity, V/m
f_d	gas desorption ratio, dimensionless
h	thickness, m
j	electrical current density, A/m ²
k_0	adsorption equilibrium constant, 1/MPa
M_R	volumetric heat capacity of shale, J/m ³ K
N_{a0}	amount of the adsorbed gas at initial condition, m ³
N_d	amount of the desorption gas, m ³
P	pressure, MPa
P_E	electrical energy density, J/m ³
R	resistivity of formation, Ω
T	temperature, °C
t	time, s
V	voltage, V

References

- Adamson, M., 1982. Physical chemistry of surfaces. Fourth Edition, John Wiley and Sons, New York City.
- Arthur, J. D., Langhus, B., Alleman, D., 2008. An overview of modern shale gas development in the United States. All consulting, 1-21.
- Baylor, B.A., Maggard, J.B., Wattenbarger, R.A., 1990. Improved calculation of oil production response to electrical resistance heating (ERH). In: Annual Technical Conference and Exhibition of the Society of Petroleum Engineers. Society of Petroleum Engineers.
- Bera, A., Babadagli, T., 2015. Status of electromagnetic heating for enhanced heavy oil/bitumen recovery and future prospects: A review. Applied Energy 151, 206–226.
- Bientinesi, M., Petarca, L., Cerutti, A., Bandinelli, M., 2013. A radiofrequency/microwave heating method for thermal heavy oil recovery based on a novel tight-shell conceptual design. Journal of Petroleum Science and Engineering 107, 18–30.
- Chareonsuppanimit, P., Mohammad, S.A., Robinson, Jr L., Gasem, K.A.M., 2012. High-pressure adsorption of gases on shales: Measurements and modeling. International Journal of Coal

Geology 95, 34–46.

Hascakir, B., Babadagli, T., Akin, S., 2008. Experimental and numerical simulation of oil recovery from oil shales by electrical heating. *Energy & Fuels* 22, 3976–3985.

Hegele, P.R., Mumford, K.G., 2014. Gas production and transport during bench-scale electrical resistance heating of water and trichloroethene. *Journal of Contaminant Hydrology* 165, 24–36.

Hiebert, A.D., Vermeulen, F.E., Chute, F.S., Capjack, C.E., 1986. Numerical simulation results for the electrical heating of Athabasca oil-sand formation. *SPE Reservoir Engineering* 1, 76-84.

Jiang, J.M., Shao, Y.Y., Younis, R.M., 2014. Development of a multi-continuum multi-component model for enhanced gas recovery and CO₂ storage in fractured shale gas reservoirs. In: *SPE Improved Oil Recovery Symposium*. Society of Petroleum Engineers.

Kamalia, M.R., Mirshady, A.A., 2004. Total organic carbon content determined from well logs using ΔLogR and Neuro Fuzzy techniques. *Journal of Petroleum Science and Engineering* 45, 141–148.

Lane, H.S., Lancaster, D.E., Watson, A.T., 1991. Characterizing the role of desorption in gas production from Devonian shales. *Energy Sources* 13, 337-359.

Lane, H.S., Watson, A.T., Lancaster, D.E., 1989. Identifying and estimating desorption from Devonian shale gas production data. In: *Annual Technical Conference and Exhibition of the Society of Petroleum Engineering*. Society of Petroleum Engineers.

Li, F.C., 1992. Methane adsorption on Devonian shales. M.S. Thesis, Texas A&M University.

Lin, Y., Wang, H.Y., He, S., Nikolaou, M., 2015. Increasing shale gas recovery through thermal stimulation: analysis and an experimental study. In: *Annual Technical Conference and Exhibition of the Society of Petroleum Engineers*. Society of Petroleum Engineers.

Lu, X.C., Li, F.C., Watson, A.T., 1995a. Adsorption measurements in Devonian shales. *Fuel* 74, 599-603.

Lu, X.C., Li, F.C., Watson, A.T., 1995b. Adsorption studies of natural gas storage in Devonian shales. *SPE Formation Evaluation* 10, 109-113.

Martin, E.J., Kueper, B.H., 2011. Observation of trapped gas during electrical resistance heating of trichloroethylene under passive venting conditions. *Journal of Contaminant Hydrology* 126, 291–300.

Mcgee, B.C.W., Vermeulen, F.E., 2007. The mechanisms of electrical heating for the recovery of bitumen from oil sands. *Journal of Canadian Petroleum Technology* 46, 28-34.

Montgomery, D. C., 2008. Design and analysis of experiments. 7th ed., Wiley, New York.

Munholland, J.L., Mumford, K.G., Kueper, B.H., 2016. Factors affecting gas migration and contaminant redistribution in heterogeneous porous media subject to electrical resistance heating. *Journal of Contaminant Hydrology* 184, 14–24.

Olorode, O.M., Freeman, C.M., Moridis, G.J., Blasingame, T.A., 2013. High-resolution numerical modeling of complex and irregular fracture patterns in shale-gas reservoirs and tight gas reservoirs. *SPE Reservoir Evaluation & Engineering* 16, 1-13.

Passey, Q.R., Creaney, S., Kulla, J.B., Moretti, F.J., Stroud, J.D., 1990. A practical model for organic richness from porosity and resistivity Logs. *The American Association of Petroleum Geologists Bulletin* 74, 1777-1794.

Ross, D.J.K., Bustin, R.M., 2007. Shale gas potential of the Lower Jurassic Gordondale Member, northeastern British Columbia, Canada. *Bulletin of Canadian Petroleum Geology* 55,

- 51-75.
- Ross, D.J.K., Bustin, R.M., 2008. Characterizing the shale gas resource potential of Devonian–Mississippian strata in the Western Canada sedimentary basin: Application of an integrated formation evaluation. *AAPG Bulletin* 92, 87-125.
- Ruthven, D.M., 1984. Principles of adsorption and adsorption processes. John Wiley and Sons, New York City.
- Sandberg, C., Thomas, K., Hale, A., 2014. Advances in electrical heating technology for heavy oil production. In: *SPE Heavy Oil Conference-Canada*. Society of Petroleum Engineers.
- Schettler, P.D., Parmely, C.R., 1991. Contributions to total storage capacity in Devonian shales. In: *SPE Eastern Regional Meeting*. Society of Petroleum Engineers.
- Symington, W., 2006. In: *ExxonMobil's Electrofrac Process for in Situ Oil Shale Conversion 26th Oil Shale Symposium*. Colorado School of Mines.
- Symington, W.A., Burns, J.S., El-Rabaa, W., Otten, G.A., Pokutylowicz, N., Spiecker, P.M., Williamson, R.W., Yeakel, J.D., 2009. Field testing of Electrofrac™ process elements at ExxonMobil's Colony Mine. In: *29th Oil Shale Symposium*. Colorado School of Mines, Golden. Colorado.
- Wang, H.C., Rezaee, Saeedi, A., 2015. The interaction of reservoir properties and microwave heating – An experimental and numerical modelling study of enhanced gas recovery (EGR). *Procedia Earth and Planetary Science* 15, 542-548.
- Wang, H.Y., Ajao, O., Economides, M.J., 2014. Conceptual study of thermal stimulation in shale gas formations. *Journal of Natural Gas Science and Engineering* 21, 874-885.
- Wang, Y.D., 1999. Fundamental research on oil recovery enhanced by electrical field. M.S. Thesis, China University of Petroleum.
- Wu, Y.S., Li, J., Ding, D., Wang, C., Di, Y., 2014. A generalized framework model for the simulation of gas production in unconventional gas reservoirs. *SPE Journal* 19, 845-857.
- Zendehboudi, S., Chatzis, I., Shafiei, A., Dusseault, M. B., 2011a. Empirical modeling of gravity drainage in fractured porous media. *Energy Fuels* 25, 1229-1241.
- Zendehboudi, S., Chatzis, I., Mohsenipour, A.A., Elkamel A., 2011b. Dimensional analysis and scale-up of immiscible two-phase flow displacement in fractured porous media under controlled gravity drainage. *Energy Fuels* 25, 1731-1750.
- Zhang, T.W., Ellis, G.S., Ruppel, S.C., Milliken, K., Yang, R.S., 2012. Effect of organic-matter type and thermal maturity on methane adsorption in shale-gas systems. *Organic geochemistry* 47, 120–131.
- Zhu, G.P., Yao, J., Sun, H., Zhang, M., Xie, M.J., Sun, Z.X., Lu, T., 2016. The numerical simulation of thermal recovery based on hydraulic fracture heating technology in shale gas reservoir. *Journal of Natural Gas Science and Engineering* 28, 305-316.
- Zhu, Z., Zeng, F., Zhao, G., Laforge, P., 2013. Evaluation of the hybrid process of electrical resistive heating and solvent injection through numerical simulations. *Fuel* 105, 119–127.