Journal of Unconventional Oil and Gas Resources 12 (2015) 15–22

Contents lists available at ScienceDirect

Journal of Unconventional Oil and Gas Resources

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

Multi-stage hydraulic fracturing and radio-frequency electromagnetic radiation for heavy-oil production

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ARTICLE INFO

Article history:
Received 17 June 2015
Revised 30 July 2015
Accepted 19 August 2015
Available online 3 September 2015

Keywords:
Radio frequency electromagnetic heating
Hydraulic fracturing
Numerical modeling
Heavy oil
Heat sources

ABSTRACT

Numerical model results of heavy oil production through multi-stage radio-frequency electromagnetic (RF EM) heating from a well after fracturing and re-fracturing operations are given in this paper. We consider the inflow of heavy oil to the well through two perpendicular fractures filled with propping agent. The conductivity of fractures is substantially greater than the conductivity of the reservoir but the dielectric and thermal properties of the reservoir and fractures are considered identical. In the expression used for heat distribution, a correction for near-field is introduced, which is shown to improve the accuracy of the temperature distribution around the well. The calculations for different powers of EM emitters and length of fractures are also considered and compared to the base case (cold oil) production.

Introduction

In practice, it is often necessary to perform different operational schemes of hydraulic fracturing to increase the productivity of the production wells and better coverage of a reservoir. A common case, for example, is a development of a second fracture coming along a path that is different from the direction of the first (Siebrits et al., 1998; Li, 2008; Liu et al., 2008; Roussel and Sharma, 2010, 2012; Zhai and Abou-Sayed, 2011; Latypov et al., 2011, 2013). This is strictly controlled by the stress distribution in the field and the way operation is handled based this distribution. The use of geomechanical simulators to calculate the stress state of the reservoir in a modified pressure field and effect on stress reorientation was discussed by Fedorov and Davletova (2014) as well as the problems with calculating the stress field and the fracture growth during re-fracturing operations (Li, 2008; Roussel and Sharma, 2010, 2012; Latypov et al., 2013; Davletova et al., 2014).

On the other hand, the production of heavy oil using radio-frequency electromagnetic (RF EM) heating through vertical and horizontal wells was investigated in the past for different purposes (Abernethy, 1976; Islam et al., 1991; Dyblenko et al., 1981; Chakma and Jha, 1992; Kasevich et al., 1994; Sahni et al., 2000; Ovalles et al., 2002; Kovaleva and Khaydar, 2004; Carrizales et al., 2008; Davletbaev et al., 2011). Recently, RF EM heating and hydraulic fracturing concepts were combined and numerical model results of heavy-oil production with multi-stage electromagnetic (EM) heating from a well with a single fracture (Davletbaev et al., 2014; Davletbaev and Kovaleva, 2014a) and two perpendicular fractures were reported (Kovaleva et al., 2014; Davletbaev and Kovaleva, 2014b).

In the present study, we propose an improved version of this type of numerical modeling (first presented in Davletbaev et al. (2014) for a single stage-single fracture case), in which a well with two perpendicular fractures is considered. The present paper contains practically important additions to the model of this previous publication, namely, correction of heat sources (for near-field zone) and consideration of the well with two fractures developed through a multistage process. When calculating the distribution of heat, the correction for the near-field of reservoir was applied and the calculations for the cases with different power EM waves emitter and different geometry as well as different fracture conductivities were performed. The expression for distributed heat was obtained from an earlier work by Abernethy (1976). The corrections for the expression for heat distributed in the reservoir near-zone were adapted from Nasyrov (1992).

Formulations of the problem and basic equations

The system considered consists of two perpendicular fractures in a well located in a low permeability reservoir (Fig. 1). The first

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http://dx.doi.org/10.1016/j.juogr.2015.08.002
2213-3976/

fracture passes along the x-axis and the second fracture that forms after additional hydraulic fracturing operation lies perpendicular to the first, passing along the y-axis. Differential equations used to calculate the distribution of pressure and temperature in the fractures (zones $0 \leqslant x \leqslant x_{f_2}$, $0 \leqslant y \leqslant w_{f_2}/2$ and $0 \leqslant x \leqslant w_{f_1}/2$, $0 \leqslant y \leqslant x_{f_1}$) and in reservoir. The equation for fluid flow in the finite conductivity fractures is a combination of the Darcy's law, law of conservation of mass and equation of state. Assuming that the gravity effects can be neglected, pressure distribution in the fractures can be given by the diffusivity equation (Cinco-Ley et al., 1978):

$$\phi_f \beta_{ft} \frac{\partial P_f}{\partial t} = \frac{\partial}{\partial x}\left(\frac{k_{fx}}{\mu_o}\frac{\partial P_f}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{k_{fy}}{\mu_o}\frac{\partial P_f}{\partial y}\right) + \frac{1}{h}\left(\frac{R_{fx}}{w_{fx}/2} + \frac{R_{fy}}{w_{fy}/2}\right). \quad (1)$$

The pressure distribution in the reservoir is described by the diffusivity equation (Horner, 1951):

$$\phi_m \beta_{mt} \frac{\partial P_m}{\partial t} = \frac{\partial}{\partial x}\left(\frac{k_m}{\mu_o}\frac{\partial P_m}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{k_m}{\mu_o}\frac{\partial P_m}{\partial y}\right). \quad (2)$$

The unsteady-state energy equation was developed from the conservation of mass, Darcy's law and conservation of energy (Chekaluk, 1965; Valiullin et al., 2004, 2009; Duru and Horne, 2008, 2011). Assuming that the Joule-Thomson effect and adiabatic effect are small and can be neglected, the temperature distribution in the fractures and reservoir are defined as follows:

$$\alpha_{ft}\frac{\partial T_f}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{ft}\frac{\partial T_f}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{ft}\frac{\partial T_f}{\partial y}\right) - \rho_o c_o\left(\upsilon_{fx}\frac{\partial T_f}{\partial x} + \upsilon_{fy}\frac{\partial T_f}{\partial y}\right) + q^{(E)}, \quad (3)$$

$$\alpha_{mt}\frac{\partial T_m}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_{mt}\frac{\partial T_m}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_{mt}\frac{\partial T_m}{\partial y}\right) - \rho_o c_o\left(\upsilon_{m_x}\frac{\partial T_m}{\partial x} + \upsilon_{m_y}\frac{\partial T_m}{\partial y}\right) + q^{(E)}. \quad (4)$$

P_f, T_f, P_m, T_m are pressure and temperature in the fractures (f) and in the reservoir (m). ϕ_m, k_m are the porosity and permeability of the reservoir. $\phi_{fx} = \phi_{fy} = \phi_f$ are the porosity of fractures, which is considered to be equal in the x and y directions. k_{fx} and k_{fy} are the permeability of the first and second fractures. $\beta_{fxt} = \beta_{fyt} = \beta_{ft}$, β_{mt} are the total compressibility of the system in the fractures and reservoir. w_{fx} and w_{fy} denote the width (opening) of the first and second fracture, while x_f and y_f are the half-lengths of the first and second fractures.

The dimensionless conductivities of the first and second fracture are defined as $C_{fxD} = (k_{fx}w_{fx})/(k_m x_f)$ and $C_{fyD} = (k_{fy}w_{fy})/(k_m y_f)$. $\alpha_{fxt} = \alpha_{fyt} = \alpha_{ft}$, $\lambda_{fxt} = \lambda_{fyt} = \lambda_{ft}$, α_{mt}, λ_{mt} are volumetric heat capacity and thermal conductivity of saturated medium in the fractures and reservoir, respectively. ρ_o, c_o are the density and specific heat capacity of oil. h is the height of the fracture, which coincides with the height of the productive reservoir. Index f refers to fracture, m to reservoir (matrix), o to oil, t to total parameter of the system, and w to well. 0 is the initial value, d is the coefficients of damping, phase, and propagation of EM waves. Subscript D denotes dimensionless value and x and y are the coordinate axes.

The inflow/consumption of liquid at the boundary of reservoir and fractures is calculated by the following expressions:

$$R_{fx} = \int_0^{x_f} \frac{k_m}{\mu_o}\frac{\partial P_m}{\partial y}\bigg|_{y=w_{fx}/2} dy + \int_0^{w_{fx}/2} \frac{k_m}{\mu_o}\frac{\partial P_m}{\partial x}\bigg|_{x=x_f} dx$$
$$R_{fy} = \int_0^{y_f} \frac{k_m}{\mu_o}\frac{\partial P_m}{\partial x}\bigg|_{x=w_{fy}/2} dx + \int_0^{w_{fy}/2} \frac{k_m}{\mu_o}\frac{\partial P_m}{\partial y}\bigg|_{y=y_f} dy \quad (5)$$

Oil flow in the fractures and reservoir is described by the Darcy's law:

$$\upsilon_{fx} = -\frac{k_{fx}}{\mu_o}\frac{\partial P_f}{\partial x}, \quad \upsilon_{fy} = -\frac{k_{fy}}{\mu_o}\frac{\partial P_f}{\partial y},$$
$$\upsilon_{m_x} = -\frac{k_m}{\mu_o}\frac{\partial P_m}{\partial x}, \quad \upsilon_{m_y} = -\frac{k_m}{\mu_o}\frac{\partial P_m}{\partial y}. \quad (6)$$

The expression for the temperature dependent oil viscosity is presented as follows:

$$\mu_o = \mu_{o_0}\exp(-\gamma_o(T_j - T_0)), \quad (7)$$

where μ_{o_0} is a value of oil viscosity with initial viscosity $T = T_0$. γ_o is a coefficient taking into account the dependence of viscosity of oil on temperature, $j = f, m$.

Heat sources

If a cylindrical emitter is in the downhole, axially symmetric electromagnetic wave propagates in the adjacent zone of the reservoir (Semenov, 1973; Khabibullin, 2000). An exact expression for the heat flux for a monochromatic wave for an infinite cylinder is given as follows (Nasyrov, 1992; Khabibullin, 2000):

$$q^{(E)} = \frac{\alpha_d \beta_d N_0}{\pi r_d h}\frac{|H_0^{(2)}(k_d r)|^2}{\mathrm{Re}\left[ik_d^* H_0^{(2)}(k_d r_d) H_1^{(2)^*}(k_d^* r_d)\right]} \quad (8)$$

$k_d = \beta_d - i\alpha_d$ is a complex wave vector (coefficient of propagation rate of EM waves) defined by the damping factor α_d and phase β_d of EM waves in reservoir. i is the imaginary unit, N_0 is a power of EM wave emitter, r_d is a radius of EM wave emitter, $H_0^{(2)}, H_1^{(2)}$ are the Hankel functions, Re is the real part of the complex value, and index * denotes the complex conjugate.

Eq. (8) can be simplified for short and long distances by approximation (conversion) of the Hankel functions (Skuchik, 1976). Thus, if we use the approximation of the Hankel functions for "far zone of EM waves radiation," (in the exponential form) where $k_d r >> 1$, the following expression is obtained (Abernethy, 1976):

$$q^{(E)} = -\frac{\alpha_d N_0}{\pi r h}\exp(-2\alpha_d(r - r_d)). \quad (9)$$

If the approximation of the Hankel functions for "near zone of EM waves radiation" is used where $k_d r << 1$, then the following expression is obtained (Nasyrov, 1992):

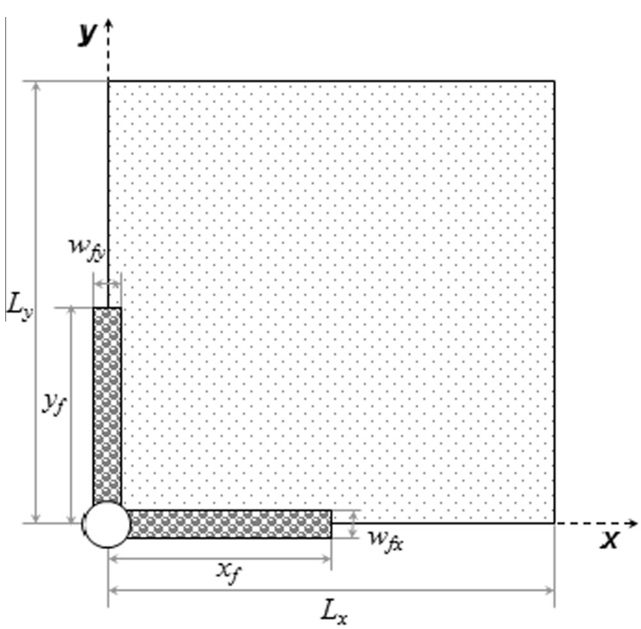

Fig. 1. Model of the reservoir zone studied.