Two-stage stimulation of the oil formation

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Abstract. The article considers a two-stage exposure to the formation. At the 1st stage, the combined exposure of high-frequency (HF) electromagnetic (EM) and sonic fields on the oil formation are performed without simultaneous formation fluid withdrawal. At the 2nd stage, the HF EM field is affected on the formation and at the same time, a low-viscosity solvent is injected into it. At the 1st stage, the bottom-hole zone is strongly warmed up due to the total thermal effect of the fields and an increase in the effective thermal conductivity of the medium due to acoustic treatment on the formation. At the 2nd stage, the solvent injected into a formation withdraws heat from the bottom-hole formation zone (BHFZ) further into the field. The dependence of the oil displacement front by the solvent on the dispersion parameter of the porous medium is considered.

1. Introduction
A lot of research has been devoted to the heating method of productive oil-filled formations with an HF EM field. In the beginning, early works were justifying the application possibility of HF EM fields for heating oil formations and extracting high-viscosity oils and bitumens [1]. Experimental researches were conducted to determine the dielectric properties of productive formations and materials of oil technology in variable HF EM fields [2].

Many works have been published that suggest various methods and technologies for developing hydrocarbon accumulations by EM fields. Some works suggest a combined effect on the hydrocarbon formation. Thus, in [3], two stages of stimulation of the bituminous formation are envisaged. First, HF EM waves with a frequency of up to 20 MHz are emitted, then they are warmed up by high-frequency currents. In [2], simultaneous injection of the oxidizer into the formation and the effect of the HF EM field on it is proposed. Thus, an in-situ combustion source is created. Also of interest is the combined effect of HF EM radiation on the oil formation with simultaneous injection of a miscible agent into the formation. Experimental and computational work has shown that this combined effect in the case of high-viscosity oils gives the best results compared to other methods [4, 5]. In works [6–8] is proposed simultaneous exposure of the oil formation to EM and acoustic fields, since the acoustic field increases the effective thermal conductivity of the formation rocks and due to this, more uniform heating of the formation is realized.

2. Problem statement
In [2], it was noted that for heating the bottom-hole zone of wells using high-frequency electromagnetic oscillations, the most effective is a linear radiator placed on the well bottom-hole and
providing radial electromagnetic waves propagation deep into the formation. As a transmitting source, you can use the extension of oil-well tubing below the boring casing. Heating will be most effective if all the energy of high-frequency electromagnetic oscillations supplied to the transmitting source is transferred to the surrounding environment.

As a sound-emitting device, a garland of piezoceramic transcribers is used, the elements of which are evenly distributed throughout the entire formation thickness.

Due to the transmission losses of EM energy from the ground generator to the EM wave emitter in the formation, the radiant power is determined by the formula:

\[ N_{oe} = N_e \exp[-2(\alpha_1 + \alpha_2)H] \]  

(1)

Here \(N_{oe}, N_e\) is the radiant power of the EM wave and the generator power of the EM wave located on the earth's surface; \(\alpha_1, \alpha_2\) is the attenuation coefficient of EM waves in the annular tubes of the well - oil-well tubing (OWT) and boring casing; \(H\) is the occurrence depth of the heated formation.

The energy power \(W\) lost in the well is determined by the formula:

\[ W = 0,225 \left( \frac{N_e - N_{oe}}{\alpha_1 + \alpha_2} \right) \]  

(2)

The absorption coefficients of EM waves in the boring casing and oil-well tubing (OWT) can be determined from the formulas [3]:

\[ \alpha_1 = \frac{R_1}{2Z \ln(R_2 / R_3)} \cdot \frac{1}{R_2^2}, \alpha_2 = \frac{\pi f \mu_{asm}}{\sigma_m}, \quad Z^2 = \frac{\mu_0}{\epsilon_0} \]  

(3)

where \(R_s\) is the active surface resistance of the pipes, \(Z\) is the air wave resistance located in the casing-tubing annulus of the well; \(R_2\) is the outside radius of the tubing joint; \(R_3\) is the pipes inside radius of the boring casing; \(\mu_{asm}\) is absolute permeability of the well pipes; \(\sigma_m\) is the specific electrical conductivity of the well pipes.

When calculating the heating of the solvent moving in the oil-well tubing (OWT) to the bottom hole of the well. It is assumed that the energy part released in the oil-well tubing (OWT) due to non-zero effective resistance of the pipe material is used to heat the rocks surrounding the well. Part of it is spent on solvent heating. In this case, the temperature value to which the solvent is heated is determined by the formula:

\[ T_b = T_s + \frac{W}{c_s \rho_s g_s} \]  

(4)

where \(c_s, \rho_s, g_s\) is specific heat capacity, density, and flow rate of the solvent injected into the formation; \(T_s\) is the initial temperature of the injected solvent. In this case, the flow rate of the \(g_s\) solvent is determined by the filtration rate at the well bottom:

\[ g_s = 2 \pi r_0 h v \]  

(5)

Here \(h\) is the formation thickness; \(r_0\) is the well radius; \(v\) is the injection capacity of the solvent at the bottom.

At the first stage of formation stimulation, only the thermal conductivity equation is solved without the convective term, since the formation fluid withdrawal is not selected simultaneously with the HF impact. Therefore, the equation solved at the 1st stage has the form:

\[ \frac{\partial T}{\partial t} = \frac{1}{C_p r} \frac{\partial}{\partial r} \left( r \Lambda \frac{\partial T}{\partial r} \right) + \frac{q_{sc}}{C_p}, \]  

(6)
where \( q_{ae} \) is the total heat sources created by EM and acoustic influences on the formation; \( \lambda_a \) is the thermal conductivity factor, \( C_p \) is the specific heat per unit volume of the formation rocks.

At the 2nd stage of the formation stimulation, an equation system consisting of the equations of piezo-conductivity, thermal conductivity and diffusion is solved [2]:

\[
\frac{\partial P}{\partial t} = k_1 \frac{1}{r} \frac{\partial}{\partial r} \left( \frac{r}{\mu_{mx}} \frac{\partial P}{\partial r} \right); \quad k_1 = \frac{k}{m \beta_{mx} + \beta_0} \tag{7}
\]

\[
\frac{\partial T}{\partial t} = \frac{1}{C_p} \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda_0 r \frac{\partial T}{\partial r} \right) - \frac{v_{mx} \rho_{mx} C_{mx}}{C_p} \frac{\partial T}{\partial r} + \frac{q_{ae}}{C_p}; \tag{8}
\]

\[
m \frac{\partial C_j}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( D r \frac{\partial C_j}{\partial r} \right) - \frac{v_{mx}}{C_p} \frac{\partial C_j}{\partial r}
\]

\[
D = \delta (D_0 + \lambda v) \tag{10}
\]

Here \( j=1, 2 \) – component indices for the solvent and oil; \( C_{mx}, \rho_{mx} \) – heat capacity, the density of the oil mixture and solvent; \( P \) – pressure; \( C_j \) – component concentration, \( C_1+C_2=1 \); \( D \) – convective diffusion coefficient; \( m, k \) – porosity and permeability of the formation; \( \lambda \) – dispersion parameter of the porous medium; \( \beta_{mx}, \beta_0 \) – compression coefficients of the mixture and the rock matrix; \( D_o \ll \lambda v \) – molecular diffusion coefficient; \( \delta \) – an empirical coefficient, the value of which depends on the presence of an EM field, in the field absence \( \delta=1 \). In the diffusion equation, the solution is sought concerning the solvent concentration \( C_1 \).

The filtration rate of the solvent mixture and oil in the formation is determined from Darcy’s equation:

\[
v_{mx} = - \frac{k}{\mu_{mx}} \frac{\partial P}{\partial r} \tag{11}
\]

where \( \mu_{mx} \) is the dynamic viscosity of the oil mixture and solvent, determined from the well-known Kendall expression:

\[
\ln \mu_{mx} = C_1 \ln \mu_1 + C_2 \ln \mu_2 \tag{12}
\]

The solvent viscosity and oil depend on the thermal field and are determined from the formulas:

\[
\mu_1 = \mu_{10} e^{-\gamma_1 \Delta T}, \quad \mu_2 = \mu_{20} e^{-\gamma_2 \Delta T} \tag{13}
\]

where \( \mu_{10}, \mu_{20} \) are the initial solvent viscosities and oil (at temperature \( T=T_0 \)); \( \gamma_1, \gamma_2 \) is the temperature coefficients of the solvent and oil; \( \Delta T = T - T_0 \).

The initial and boundary conditions for the equation system (6) – (13) have the form: for the thermal conductivity equation:

\[
T(r,0) = T_0, \quad T(r_0,t) = T_0, \quad \frac{\partial T(r_0,t)}{\partial r} = 0 \tag{14}
\]

for the diffusion equation concerning the solvent concentration:

\[
C_1(r,0) = 0, \quad C_1(r_0,t) = 1, \quad C_1(r_0,t) = 0 \tag{15}
\]

for the piezo-conductivity equation:

\[
P(r,0) = P_0, \quad P(r_0,t) = P_0, \quad P(r_0,t) = P_0 \tag{16}
\]
3. Results and Discussion

The problem (9) – (13) with initial and boundary conditions (14) – (16) is solved by the numerical method of finite differences using an implicit scheme. Heat sources that occur in the formation when HF EM and acoustic waves propagate in it were calculated using the formulas:

\[ q_{\text{ac}} = \frac{\alpha N_{a0}}{\pi r h} \exp \left( -2 \alpha_e (r - r_0) \right) + \frac{\alpha N_{a0}}{\pi r h} \exp \left( -2 \alpha_e (r - r_0) \right) \]

where \( N_{a0} \) is the radiant power of the acoustic waves.

Consider how the solvent concentration distribution in a porous medium is affected by different values of the dispersion parameter of the porous medium \( \lambda \).

The following values were used in the calculations:

- \( T_0 = 12 \, ^{\circ}\text{C} \), \( f_e = 13.56 \, \text{MHz} \), \( \varepsilon = 7.5 \), \( \tan \delta = 0.05 \), \( \alpha_e = 0.0194 \, \text{m}^{-1} \), \( \lambda_0 = 1.28 \, \text{W/(mK)} \), \( h = 8 \, \text{m} \), \( r_0 = 0.05 \, \text{m} \), \( P_0 = 10 \, \text{MPa} \), \( T_r = 15 \, \text{K} \), \( r_0 = 15 \, \text{MPa} \), \( m = 0.3 \), \( k = 5 \times 10^{-13} \, \text{m}^2 \); \( Z = 376.8 \, \text{Ohm} \), \( H = 700 \, \text{m} \), \( \beta_{\text{max}} = 10^9 \, \text{PA}^{-1} \), \( \beta_0 = 10^{10} \, \text{PA}^{-1} \), \( R_2 = 0.03015 \, \text{m} \), \( R_3 = 0.0515 \, \text{m} \), \( \mu_{\text{m}} = 3.418 \times 10^6 \, \text{H/m} \), \( \alpha_m = 3.4 \times 10^6 \, \text{Ohm}^{-1} \, \text{m}^{-1} \), \( c_r = 2057 \, j/(\text{kg} \, \text{K}) \), \( \rho_r = 769 \, \text{kg/m}^3 \), \( \rho_{\text{max}} = 918 \, \text{kg/m}^3 \), \( c_{\text{max}} = 2024 \, j/(\text{kg} \, \text{K}) \), \( \lambda_0 = 1.28 \, \text{W/(m \, K)} \), \( \mu_0 = 1.73 \times 10^3 \, \text{PA}^{-1} \, \text{s} \), \( \mu_{02} = 0.2 \, \text{PA} \, \text{s} \), \( \gamma_1 = 0.0128 \, \text{K}^{-1} \), \( \gamma_2 = 0.042 \, \text{K}^{-1} \). The value of \( \lambda = 0.1 \, \text{m} \) is the dispersion parameter of a porous medium. And its value was not neglected the molecular diffusion coefficient due to its proximity to zero. The value \( D_0 = 10^{-8} \, \text{m}^2/\text{s} \) was used. In this connection, comparative calculations of the solvent concentration distribution at \( \lambda = 0.01 \, \text{m} \) and \( D_0 = 0 \) were performed. It turned out that with the HF EM field power \( N_{e0} = 40 \, \text{kW} \) and \( N_{a0} = 10 \, \text{kW} \) – the acoustic field power, the temperature field, and the pressure field do not depend on the parameter value of the dispersion. The solvent concentration distribution is shown in Figure 1.

![Figure 1. The solvent concentration distribution: N_{e0}=40 \, \text{kW}; N_{a0}=10 \, \text{kW} (full curves) and N_{a0}=0 (dotted line); \lambda = 0.01 \, \text{m}. D_{a0}=0 \, (black curves); \lambda = 0.1 \, \text{m}, D_{a0}=10^{4} \, \text{m}^2/\text{s} \, (red curves). 1 – t=25 \, \text{days}; 2 - t=30 \, \text{days}; 3 - t=35 \, \text{days}; 4-t=40 \, \text{days.}](image)

At \( \lambda = 0.01 \, \text{m} \) and forgetfulness the molecular diffusion coefficient due to its smallness, the curves \( C_1(r) \) in the case of values \( N_{a0}=0 \) and \( N_{e0}=10 \, \text{kW} \) merged, and at \( \lambda = 0.1 \, \text{m} \) and \( D_{a0}=10^4 \, \text{m}^2/\text{s} \) the curves \( C_1(r) \) in the cases of values \( N_{e0}=0 \) and \( N_{a0}=10 \, \text{kW} \) differ slightly. At \( N_{a0}=10 \, \text{kW} \), the solvent filtration is more intensive and it penetrates further into the depth of the formation. At \( \lambda = 0.01 \, \text{m} \) and neglecting the molecular diffusion coefficient, the \( C_1(r) \) curves are steeper and the solvent penetrates deeper into the formation at a lower depth. Approximately the same differences in the solvent concentration distribution are observed at another initial value of the oil viscosity – \( \mu_{02} = 0.8 \, \text{PA} \, \text{s} \).
4. Conclusion
The paper solves the problem of two-stage stimulation of the formation with high-viscosity oil. At the 1st stage, HF EM and formation acoustic heating are performed. At the 2nd stage, the formation continues to be heated by the HF EM field and at the same time, a low-viscosity solvent is injected. The solvent injection into the formation leads to a more severe transfer of heat from the bottom to the formation, namely, an increase in the formation heating radius by 1.5-2 times, where the oil viscosity is reduced by 1.5-1.7 times. At the same time, the temperature distribution becomes more uniform and the temperature at the bottom of the well decreases, which in practice will prevent negative consequences associated with overheating of the well bore.

The dispersion parameter changing of a porous medium practically does not affect the temperature and pressure distribution process, which is due to the predominance of molecular transfer heat and pressure in this case, but there are noticeable differences in the distribution of the solvent concentration, which indicates the convective transfer of the substance (solvent and oil) in the formation.

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