Mathematical modeling of high-viscosity index oil formation with a sonic field at various frequencies

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Abstract. The paper describes the process of acoustic wave absorption in the oil-saturated porous medium in the case of cylindrical wave propagation. Terms of thermal and viscous-inertial absorption are introduced; the total attenuation ratio of the acoustic waves is calculated for various sonic field frequencies. The expression for sonic field thermal sources previously developed by the author is used to present the graphs of heat source distribution through the deposit in the cylindrical system of coordinates. The paper also considers a combination of the sonic field with a high-frequency electromagnetic field and some cross effects accompanying such a combination. Thus, it has been discovered that the energy of the sonic field is converted into heat in a closer near field of the deposit as compared to the electromagnetic field. At that, increasing frequency of the field leads to increased absorption zone in the radial direction.

1. Introduction

Supporting the high level of oil recovery at oil fields in Russia and beyond as well as keeping the high oil production level requires implementing a complex of physical and physico-chemical stimulation techniques to be applied at the oil-bearing formations and bottom-hole zone of wells. Of special interest are the complex stimulation techniques combining the advantages of their component methods [1-4].

One of such combined stimulation techniques is simultaneous electromagnetic and acoustic treatment of the bottom-hole zone (BHZ) [1, 2].

At that, absorption of the acoustic wave energy by the medium and appearance of distributed heat sources are usually disregarded. Action of the acoustic waves on the BHZ of an oil deposit is seen as a means to increase the effective thermal conductance of the reservoir, increase porous medium's permeability to oil, reduce oil viscosity, increase well productivity and regulate the profiles of flow and injection capacity. At that, it is stated that the porous media are significantly dissipative, that is, they absorb the energy of the acoustic waves [1, 3, 5]. Due to this, in the case of medium treatment with the electro-magnetic (EM) field, there is a transformation of sonic field energy into heat, leading to appearance of distributed heat sources. Thus, simultaneous treatment of oil-saturated rock with electromagnetic and sonic field leads to appearance of joint heat sources due to transformation of both EM and acoustic fields into heat.

2. Formulation of the problem

The problem is examined in a cylindrical coordinate system with respect to the well. The temperature depends only on the radial coordinate r, directed along the oil-bearing formation. It is assumed that
simultaneously with sonic and EM treatment, the formation also undergoes formation-fluid drainage.

Thermal field of the formation is found from solving the plane radial equation of thermal conductance for the heat sources inside the formation due to absorption of sonic and EM fields by the oil-saturated porous rock medium [5]. Equations describing location of the heat sources in the formation when the sonic field is absorbed are of the following form [5, 6]:

\[
q_s = \frac{\alpha_s \beta_s N_{a0}}{\pi r_0 h} \left[ H_0^{(2)}(k_s r) \right]^2 \quad (1)
\]

\[
q_s = \frac{\alpha_s \beta_s N_{a0}}{\pi r_0 h} \left[ H_0^{(2)}(\hat{k}_s r) \hat{k}_s r \right]^2 \quad (2)
\]

where \( \alpha_s, \beta_s, \alpha_0, \beta_0 \) are attenuation ratio values and phases of sonic and EM waves propagating through the formation, respectively; \( N_{a0}, N_{a0} \) are powers of sonic and EM radiating elements; \( h \) is the thickness of the formation; \( r_0 \) is the wellbore radius; \( H_0^{(2)} \) is the Hankel zero-order function of the 2nd kind; \( H_1^{(2)} \) is the Hankel first-order function of the 2nd kind; \( \text{Re} \) is the real part of the complex value; index «*» denotes a complex conjugate value, \( j \) is the imaginary unit. Parameters marked with a dot are complex values.

Propagation constants of sonic and EM waves are found from the formulas [5]:

\[
k_s = \beta_s - j\alpha_s
\]

\[
k_s = \beta_0 - j\alpha_0
\]

3. Results and Discussion

Figure 1 shows power density values of the heat sources related to sonic and EM field at the bottom hole. It is evident that the power density values of the heat sources related to sonic and EM fields at the bottom hole are comparable in the range of 2 – 3 kHz at the power of \( N_{a0} = 10 \) kW and in the range of 9–16 kHz at the power of \( N_{a0} = 1.5 \) kW.

At a distance of 1 m from the wellbore wall (Figure 2, a), the released power of the sonic radiator \( N_{a0} = 10 \) kW is higher than the released power of the EM radiator \( N_{\text{d0}} = 40 \) kW for the sonic frequencies of \( f_s = 16 \) kHz and \( f_s = 22 \) kHz and comparable in the frequency range of 4 - 7.5 kHz.

At a distance of 5 m from the wellbore wall (Figure 2, b), the power values released during propagation of sonic and EM waves are comparable in the sonic field frequency range of 5 – 12.5 kHz and sonic radiator power values of \( N_{a0} = 10 \) kW and \( N_{a0} = 20 – 40 \) kW. At the same distance, there is more heat released due to the sonic radiator with the power of \( N_{a0} = 10 \) kW than due to the EM radiator with the power of \( N_{\text{d0}} = 40 \) kW at a frequency \( f_s > 12.5 \) kHz.

At a distance of 10 m from the wellbore hole (Figure 2, c) the released power values are comparable for the sonic field frequencies used in the work at \( N_{a0} = 10 \) kW and \( N_{a0} = 20 – 40 \) kW.
**Figure 1.** Frequency response of heat source power density values for sonic and EM radiators at the bottomhole. Horizontal lines correspond to EM emitter of $N_{e0}=20$ kW and 40 kW, respectively.

**Figure 2.** The ratio between the released power of sonic and RF EM waves through the formation depending on selected frequencies ($f_a=6$, 16, 22 kHz) and a distance from the wellbore $r$. Horizontal lines correspond to EM radiator of $N_{e0}=20$ kW and 40 kW, respectively. a) $r=1$ m; b) $r=5$ m; c) $r=10$ m.
4. Conclusion
The analysis shows that sonic waves are absorbed by the medium in the nearer zone of the formation, as compared with the EM waves. At that, the propagation distance of the sonic field thermal influence depends on the radiator’s power. Increasing the sonic field radiator frequency leads to a larger radius of the thermal influence zone, however, at frequencies higher than 20 kHz, the graphs become independent. It should be noted, that further studies of the frequency response are of significant practical value.

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