Experimental studies in heating oil-saturated rock with high-frequency electromagnetic field

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Abstract. The paper describes a test bench for studying the interaction between electromagnetic fields and oil-saturated porous mediums. Dielectric parameters of the targets have been determined. Results of experimental studies in heating oil-saturated rock with high-frequency electromagnetic field are given.

1. Introduction
Development of new and improvement of existing production methods applicable to high-viscosity oil and natural bitumen is a pressing challenge, as their resources are more plentiful than those of light oil and according to forecasts their share in the general structure of hydrocarbon resources is going to increase. Due to that, there are intensive studies for new efficient technologies for production of high-viscosity oil and natural bitumen deposits throughout the world, as the currently used methods are either non-profitable or environmentally unsafe. Deposits of unconventional oil are characterized with complex geological structure, low permeability of formations, high viscosity of oil [1–15].

Thermal methods, based upon reducing the viscosity of oil with heat are potentially applicable on an industrial scale. Among such methods is heating the formation with the energy of electromagnetic field; this is the mechanism studied in this paper. A distinctive feature of RF electromagnetic heating is that distributed heat sources appear buried in the formation. Due to dielectric losses in the medium, the energy of electromagnetic waves is transformed to heat, resulting in increased temperature and decreased viscosity of liquid in the formation.

High frequency heating of dielectrics is relatively mature and successful technology, applied in various industries and technologies. As far back as 1950-60s, both Russian and foreign scientific literature published research results on possibility of applying RF electromagnetic frequency for heating bottomhole zone of oil wells [9]. Petr Leonidovich Kapitsa proposed an idea of transmitting the RF oscillation energy through the pipes in the ultra-high frequency (UHF) range: «Electrical energy of high enough frequency may be directed uninsulated through the tubing into boreholes and thus heat ground at significant depths, which may be helpful in production of sulfur, heavy oils, etc.» [10]. In 1980s, laboratory studies of EM treatment of BHZ with subsequent field tests were conducted at Bashkir State University [12].
When RF EM waves propagate through oil, there is a dispersion of dielectric parameters (specific permittivity $\varepsilon'$, loss tangent of a dielectric $\tan\delta$) of the oil-saturated medium due to the orientation polarization of nano-scale polar components of oil. Under the action of RF EM field, additional heat is released in the medium (in addition to Joule heat) due to effects of electric polarization. Absorption (dissipation) of EM field energy is accompanied with release of heat, as distributed heat sources arise. The process has a volumetric nature, the characteristic dimensions of the volume are defined by the frequency and structure of the EM wave, as well as by dielectric parameters of the medium.

With respect to electromagnetic processes, high-viscosity and ultra-high viscosity oils are weakly conducting, non-magnetic polar dielectrics. Dependence of the dielectric parameters on the thermohydrodynamic state of the medium and field frequency is usually determined experimentally, by measuring specific permittivity and loss tangent of the dielectric depending on the temperature, pressure and frequency of the RF EM field. These features were taken into account when selecting the operating frequency of the EM generator.

2. Test bench description

The test bench developed during this research is intended for studying the interactions of EM fields with oil-saturated porous mediums and consists of three main units (Figure 1): a model of bottomhole zone of the formation, a generator with a radiating antenna, generator power supply.

The model of bottomhole zone of the formation was developed on the analogy of the model described in [12] and consists of a vertical cylindrical cover 1 with a diameter of 200 cm and a height of 130 cm, build of brick and lined with asbestos thermal insulation material 2 on the inside. Inside the heat insulated cover there is a layer of sand 3 (effective pay), squeezed between an upper layer (formation top 4) and a sublayer (formation bottom 5) consisting of wet clay. The thickness of the effective pay is 70 cm, that of the formation top and bottom is 30 cm each. The model of the effective pay is a layer of quartz sandstone divided vertically into two parts. One part is saturated with pure oil; another is saturated with 70% oil and 30% formation water.

From the point of view of RF electrodynamics, the brick wall is a lossy dielectric that prevents reflection of EM waves and appearance of standing waves inside the effective pay, thus allowing for thermal field distribution evaluation through the formation with higher reliability. In the center of the formation model, there is a wellbore model 6 - a pipe of dielectric material (glass-fiber reinforced plastic) with a diameter of 150 mm. The tripping part of generator 7 with radiating antenna 8 are put inside this well.

Recording of thermal field in the effective pay employed high accuracy thermocouples; this type of thermocouples is characterized with high accuracy and relatively small diameter of conductor, thus allowing decreasing induced eddy currents near the alloy, as well as near the conductor itself. In the end, it significantly reduces localized thermal heat, which differs significantly from propagation of the thermal field due to the action of RF EM field.
Figure 1. A diagram of model for studying the interaction between electromagnetic fields and oil-saturated porous mediums. 1 – vertical cylindrical concrete and brick cover; 2 – thermal insulation material; 3 – formation; 4 – formation top; 5 – formation bottom; 6 – wellbore; 7 – generator; 8 – electromagnetic radiator; 9 – power supply; 10 – a system of thermocouples; 11 – multichannel recorder; 12 – PC; 13 – RF cable.

3. Research Results
Figure 2 shows temperature distribution curves in the formation model for RF EM heating at a 60 minute mark. Figure 3 shows the dynamics of temperature changes in the formation model at a distance of 2 cm from the radiator.

From Figures 2 and 3 it is evident that applying a harmonic EM field from the VChD-2,5-13 generator with the output power of 1 kW to the samples leads to volumetric heating of the samples with an intensity of 1.2 °C/min for the flooded part and 0.6 °C/min for water-free part of the model over the temperature range of 23-40°C. At higher temperatures, the intensity reduces, which may be explained by a reduction in tgδ in this temperature range (Figure 4). The «rock+oil+water» system is heated more
intensively than the «oil+rock» system, which is explained by a correspondence between dielectric parameters of the first system to the conditions of resonance interaction with the EM field (Figure 5).

**Figure 2.** Distribution of temperature in the mini-model of formation under RF heating. Heating time: 60 min.

**Figure 3.** Dynamics of temperature change in the formation mini-model at a distance of 2 cm from the radiator.
Figure 4. Loss tangent of the dielectric as a function of temperature.

Figure 5. Loss tangent of the dielectric as a function of temperature.

For the same power of the radiator, when water cut in the formation increases, the conditions for formation heating improve and the rate of heat penetration to the depth of the formation increases. This may be explained by an increase in dielectric parameters of the «rock+oil+water» system with higher water content in the formation model (Figure 6).
Figure 6. Loss tangent of the dielectric as a function of EM field frequency.

4. Conclusions
The studies of features of heating the oil-saturated rock with EM field provided by an RF generators revealed that dielectric parameters (specific permittivity and loss tangent of the dielectric) of the samples experience dispersion over the frequency range of 13-15 MHz. Consequently, the range of efficient operating frequency for the EM wave generator was determined as being 13-15 MHz. Dependency of the loss tangent of dielectric has a resonance nature, that is, until 40 °С the value of tg increases, while above 40 °С it drops abruptly. The «rock+oil+water» system is heated more intensively than the «oil+rock» system, which is explained by a correspondence between dielectric parameters of the first system to the conditions of resonance interaction with the EM field.

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