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FILTRATION OF A HIGH-VISCOSITY OIL IN AN ELECTROMAGNETIC FIELD

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Results of experimental investigations of the time dependences of the change in the temperature of an oil pool and in the discharge of an oil "well" under the action of a microwave electromagnetic field are presented. An experimental setup is described. It is shown that the temperature is distributed nonuniformly over the thickness of the oil pool depending on the initial discharge of the well and the time of the microwave electromagnetic action on the face zone of the pool.

The action of a radio-frequency electromagnetic field on an oil pool makes it possible to intensify the extraction of high-viscosity bitumic and high-paraffin oil from the well [1–5]. This procedure is accompanied by the appearance of electrodynamic, thermodynamic, and hydrodynamic effects in the pool [6]. An investigation of them allows one to control the process of treatment of an oil pool with a radio-frequency electromagnetic field and estimate the efficiency of its action. These problems were theoretically investigated in a number of works [2, 4, 6–24]. However, the authors of these works used, for the most part, hypothetical parameters in the calculations. This is explained first of all by the fact that the results of experimental investigations of the effect of a radio-frequency electromagnetic field on an oil pool are covered very poorly in the literature. Therefore, there is a need for experimental investigation of electro-, thermo-, and hydrodynamic processes occurring in an oil pool subjected to an electromagnetic action.

In this connection, it should be noted that the effect of a radio-frequency electromagnetic field on an oil flow in a capillary and the dependence of this flow on the field intensity and the oil properties have been experimentally investigated in [25]. In [26], it has been established that the rate of flow of a dielectric liquid (kerosene) through a porous medium positioned in a coaxial cavity increases by a factor of two when the cavity is acted upon by a microwave electromagnetic field and that the rate of this flow stabilizes with time and depends on the temperature of the medium (increases with increasing temperature). However, the results of these investigations cannot be directly related to the processes occurring in the face zone of a well. Time dependences of the temperature of a porous medium saturated with an oil are presented in [2, 3, 27, 28]. Analogous investigations have been carried out under production conditions [1, 5, 25]. However, only the time dependences of the temperature inside tubing strings have been investigated in these works. By these dependences one can judge the regularities of heating an oil pool as a whole. Meanwhile, the study of the processes (not only the thermal ones) occurring beyond the tubing strings is of scientific interest. Clearly the solution of this problem under real conditions calls for material resources, since a large number of points positioned beyond the well should be controlled in this case. Therefore, in the present work, we experimentally investigated the filtration and temperature changes in an oil-pool model subjected to a microwave electromagnetic action.

It should be noted that, in the case under study, a radio-frequency electromagnetic action differs from a microwave electromagnetic action only by the methods of their generation and introduction into the working medium and there are no fundamental differences between them in the mechanism of interaction with it. Therefore, our reasonings for a microwave electromagnetic action will also be true for a radio-frequency one.

For experimental investigations of the filtration of a high-viscosity oil in a microwave electromagnetic field, we have developed a setup shown diagrammatically in Fig. 1. The setup comprises a metal case, a three-layer model of an oil pool, a "well" with an electromagnetic radiator positioned in it, an electromagnetic-energy source, and control meters.

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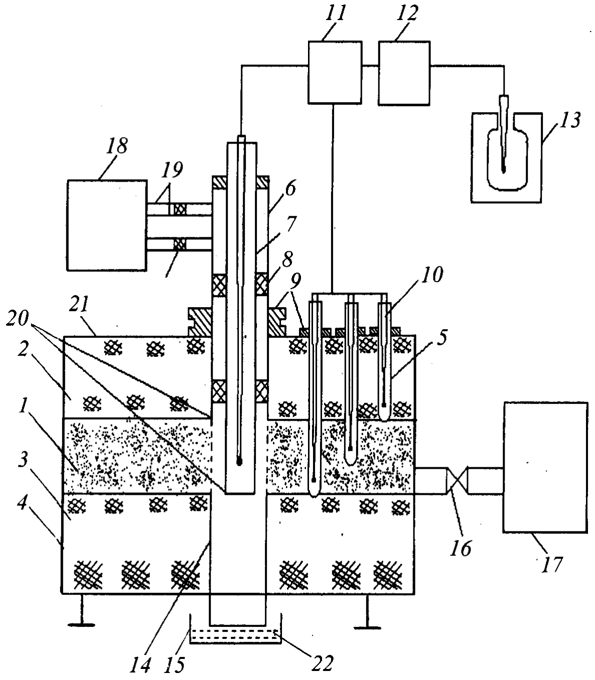


Fig. 1. Diagram of the experimental setup: 1) model of an oil pool, 2) roof, 3) floor, 4) metal case, 5) thermopockets, 6) "casing string", 7) "tubing string", 8) insulating washer, 9) collet, 10) thermocouples, 11) multiposition switch, 12) microvoltmeter, 13) Dewar vessel, 14) perforated dielectric tube, 15) graduated vessels, 16) valve, 17) pump, 18) microwave oscillator, 19) feeder, 20) electromagnetic radiator, 21) roof, 22) "produced" oil.

As the model of an oil pool, we used a quartz sand saturated with a bitumic oil from the Mordovo-Karmal'skoe oil deposit in the Republic of Tatarstan. A bentonite clay mixed with a mineralized water (containing 25% of sodium salt) to a doughy consistency was used for the roof and the floor. The radius of the model was determined from the condition

$$r > r_{\min} = \frac{1}{2\alpha} = \frac{\lambda}{2\pi\sqrt{\varepsilon}\tan\delta} .$$

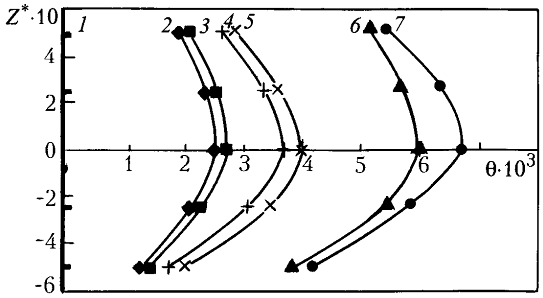
It has been experimentally determined, using known methods, that $\varepsilon = 7.5$ and $\tan\delta = 0.05$ for the saturated porous medium investigated under the conditions of our experiment. Consequently, the radius of the model is 0.147 m.

To exclude the influence of the walls of the pool model on the electromagnetic-field distribution, because of the reflection of electromagnetic waves from them, the radius of the model was taken to be 0.25 m. The thickness of the floor and the roof of the pool model was 0.28 m, which also excludes the influence of the bottom and the cover of the model because of the reflection of electromagnetic waves from them.

The thickness of the pool was selected such that the microwave oscillator was matched with the radiator; it was equal to 0.08 m.

One of the main elements of the setup is a unit for input of electromagnetic-field energy into the pool through the well. The unit contains a T-joint with a shorting plunger, a coaxial transmission line, and a radiator. The coaxial line consists of outer (brass) and inner (copper) tubes. All the elements of the input unit, through which electromagnetic-field energy is transmitted to the pool, have a wave resistance of 50 Ω corresponding to the cross sections of the conductors $d = 0.008$ and $D = 0.0215$ m. The nodes of the coaxial transmission line were centered with the use of fluoroplastic washers.

The electromagnetic radiator is a system comprising the ends of the outer tube and the inner tube extending beyond the outer tube.



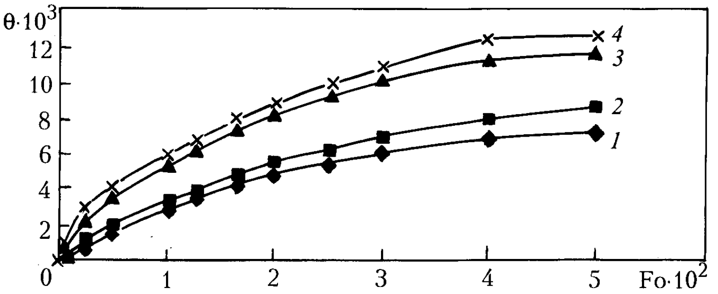


Fig. 2. Temperature distribution in the face zone of the pool subjected to an electromagnetic field at a dimensionless distance $R^* = 0.44$ from the well at different values of the Fourier parameter: 0 (1), 0.009 (2, 3), 0.025 (4, 5), and 0.032 (6, 7) in the presence of an oil inflow $Q_0 = 0.127$ (2, 4, 6) and in the absence of an oil inflow (3, 5, 7).

Fig. 3. Dependences of the change in the dimensionless temperature on the dimensionless time of the action and the initial discharge of the well model ($Z^* = 0.25$) at $R^* = 0.88$ (1, 2) and 0.44 (3, 4) and $Q_0 = 0.248$ (1, 3) and 0.127 (2, 4).

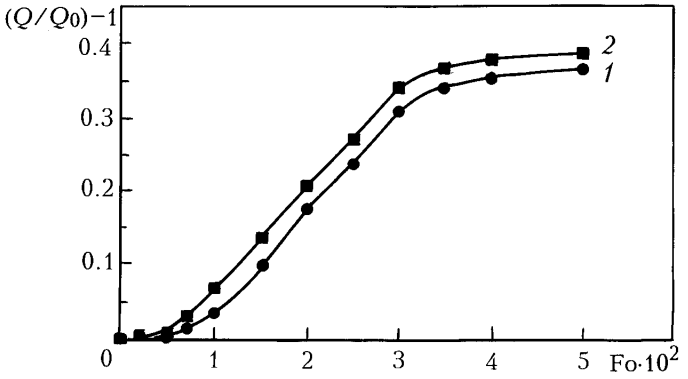


Fig. 4. Change in the discharge of the well model with time at initial discharges 0.248 (1) and 0.127 (2).

The electromagnetic-energy source is a "Parus" microwave oscillator generating oscillations at a frequency of (2375 ± 24) MHz. The power supplied to the transmission line was measured by a calorimetric method; it was equal approximately to (450 ± 10) W.

At first, the pool was completely saturated with a bitumic oil.

The experimental procedure involved the following stages: (a) recording of the temperature distribution in the pool model subjected to a microwave electromagnetic action in the absence of oil inflow to the well and (b) recording of the temperature distribution and measurement of the oil inflow in the pool model subjected to a microwave electromagnetic action on condition that the pressure in the pool is constant.

The temperature in the pool and at the interface between the pool and the roof and the floor was measured by copper-constantan thermocouples. Oil was dislodged from the pool by a pump. The investigations were carried out at two values of the pressure in the pool, corresponding to the rates of oil flow through the pool model (to the discharges of the well) in the absence of a field: about $(33.3 \pm 1.7)\cdot 10^{-9}$ m^3/sec and $(65.5 \pm 1.7)\cdot 10^{-9}$ m^3/sec.

Results of the investigations are presented in Figs. 2–4.

As is seen from Fig. 2, the temperature distribution over the thickness of the pool is nonuniform: the temperature at the center of the pool is higher than the temperature at the roof and at the floor. This nonuniformity increases with increase in the time of electromagnetic-field action, which is due to the heat losses in the roof and in the floor.

In the presence of an oil inflow, these features of the temperature distribution over the thickness of the pool are retained but become less pronounced: the temperature curve is less elongated and the temperature at the center of the pool is lower.

It follows from Fig. 3 that initially the temperature in the pool increases rapidly and then more slowly and tends to a constant value.

The data presented in Figs. 2 and 3 point to the fact that the temperature in the pool decreases with distance from the well. The temperature changes nonuniformly in equal space intervals. The temperature changes insignificantly in the vicinity of the well, increases with distance from it, and decreases at the periphery of the heated zone. As the distance from the well increases, the temperature at the center of the pool becomes markedly different from the temperature at the roof and the floor of the pool.

Figure 4 presents results of investigations of the change in the liquid inflow to the well. As is seen from the figure, initially the discharge of the well increases comparatively slowly; then it increases fairly rapidly, and the tendency for a steady-state inflow appears with time. The value of the steady-state inflow depends on the initial rate of the oil flow, i.e., on the rate of the oil flow through the pool model in the absence of a microwave electromagnetic action. The larger the initial discharge of the well model, the smaller the relative increase in the oil inflow into it. This is explained by the fact that the higher the rate of oil flow, the larger the amount of heat carried out by the filtrated oil.

CONCLUSIONS

1. The dynamics of the temperature distribution over the thickness of an oil pool subjected to a microwave electromagnetic field is substantially dependent on the discharge of the well. As it increases, the temperature distribution over the thickness of the pool becomes more uniform.

2. Both the temperature in the saturated porous medium and the discharge of the well change nonmonotonically with time. If initially the discharge of the well increases fairly rapidly, its steady-state value is established with time, and this time depends substantially on the oil-flow rate attained in the absence of a microwave electromagnetic action.

3. The results obtained by us allow one to estimate the efficiency of the use of radio-frequency and microwave electromagnetic fields for intensification of the inflow of a hydrocarbon liquid to a well. They can also be used for theoretical investigations of the process considered and verification of their results.

NOTATION

C and C_{oil}, specific heat capacity of the pool and the oil, J/(kg·K); d, outside diameter of the inner conductor, m; D, inside diameter of the outer conductor, m; $\text{Fo} = \chi t/\rho C h^2$, Fourier criterion; h, thickness of the pool, m; $Q = qC_{\text{oil}}\rho_{\text{oil}}/2\pi h\chi$, dimensionless oil-flow rate through the pool model subjected to a microwave electromagnetic field; Q_0, dimensionless discharge of the well model prior to the treatment of the pool with a microwave electromagnetic field; q, flow rate of the filtrated oil through the pool model, m^3/sec; N, power of the electromagnetic field generated in the pool, W; $R^* = r/h$, dimensionless radial distance; r, radial cylindrical coordinate, m; r_{min}, minimum radius of the pool model, m; T, temperature of the pool, $^{\text{o}}$C; T_0, initial temperature of the pool, $^{\text{o}}$C; $\Delta T = T - T_0$, change in the temperature, $^{\text{o}}$C; t, time, sec; tan δ, dielectric-loss tangent of the pool model; $Z^* = z/h$, dimensionless vertical distance; z, vertical cylindrical coordinate, m; α, coefficient of absorption of electromagnetic waves in the pool, m^{-1}; ε, relative permittivity of the pool model; $\theta = \Delta T h\chi/N$, dimensionless temperature; λ, electromagnetic wavelength in a vacuum, m; ρ and ρ_{oil}, specific density of the pool and the oil, kg/m^3; χ, heat-conductivity coefficient of the pool, W/(m·K). Subscripts: oil, oil; min, minimum.

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