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EXPERIMENTAL STUDIES OF THE INFLUENCE OF A HIGH-FREQUENCY ELECTROMAGNETIC FIELD ON THE CONVECTION OF FLUIDS IN A VERTICAL TUBE

M. A. Fatykhov and A. R. Zinnatullin

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Results of experimental studies of the influence of a high-frequency electromagnetic field on a change in the levels of fluids in a vertical tube are reported.

Formulation of the Problem. The investigation of convective phenomena in the case of electromagnetic action on different media is closely related to applied problems. Among those is, in particular, intensification of oil production from a productive oil stratum with the aid of the energy of a high-frequency (HF) electromagnetic field. Some advances are observed along this line that are indicative of the potentialities and efficiency of this method [1–5]. This technology of processing an oil stratum substantially differs from other known methods in the fact that an oil well serves not only as a tube through which oil is extracted to a surface but also as a waveguide or a coaxial line by which the energy of an HF electromagnetic field is transported to the oil stratum.

The thermal and hydrodynamic processes in an oil stratum in the presence of an HF electromagnetic field have been studied sufficiently in detail in [6–14]. However, in oil wells they have almost not been studied. Experimental studies are needed to elucidate the initial parameters describing heat and mass transfer in the media filling the shaft of an oil well in an HF electromagnetic field.

Description of the Experimental Setup and Procedure of Investigations. To study the influence of an HF electromagnetic field on the convection of dielectric fluids in a vertical channel we have worked out an experimental setup (Fig. 1).

Use is made of a generator of the VChD3-6/81 type (vibrational power 6 ± 0.6 KW, working frequency 81.36 ± 0.8136 MHz).

The energy of an electromagnetic field is concentrated between the plates of a plane horizontal capacitor and transferred from it by means of pin 2 and radio-frequency cable 3 to plane vertical capacitor 6 placed in metallic casing 11. Plane capacitor 6 is made of Duralumin plates with a thickness of 35 cm and width of 11.5 cm. Finger bushing 5 electrically and mechanically tightly connects radio-frequency cable 3 to the body of HF generator 1 on the one side and to the metallic casing on the other side. Plane vertical capacitor 6 is isolated from metallic casing 11 by two fluoroplastic-slotted electric insulators 10. The slots make it possible to change the distance between the capacitor plates and, consequently, to investigate the peculiar features of action of an HF electromagnetic field on a fluid in relation to different powers. The metallic casing and the HF generator are connected to substitute 13. Measuring cylindrical vessel 9 is placed between the plates of capacitor 6. Finger bushing 8 fixes cylindrical vessel 9 in the vertical position. The lower end of thermometer 7 mounted on holder 12 is on the level of the upper end of plane capacitor 6.

The investigation procedure consisted of recording the rise of a fluid level in the vertical tube in the presence of an HF electromagnetic field and investigating simultaneously the change in their temperature with time. The change in the level was determined visually against the scale of the measuring cylindrical vessel. The temperature of the fluids was controlled by thermometer 7.

Results of the Investigation and Their Analysis. Investigations were carried out with burning kerosene, toluene, transformer oil, oil, distilled and tap water, and acetone, and with a binary solution consisting of 50% tap water and 50% acetone. The physical properties of the investigated fluids are presented in Table 1.

Bashkir State University, Ufa; email: kaf_pfg@bsu.bashedu.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 75, No. 3, pp. 33–36, May–June, 2002. Original article submitted October 5, 2000; revision submitted October 30, 2001.

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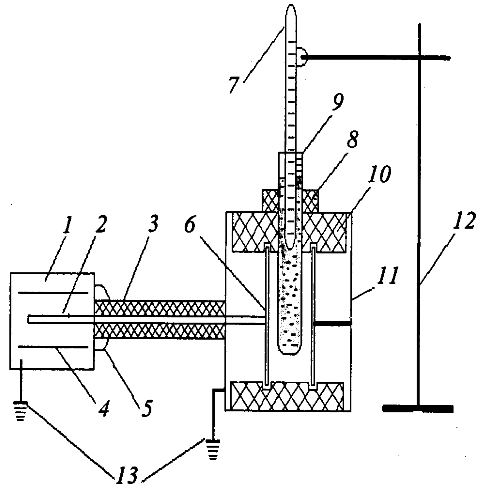


Fig. 1. Schematic of the experimental setup used for investigating the rise of fluid level in a high-frequency electromagnetic field.

TABLE 1. Physical Properties of the Investigated Fluids

Fluid	c	ρ	$\beta \cdot 10^6$	μ	ε'	tan δ	γ
Water	4200	1000	208	1004	$81^{*)}$	$0.0072^{*)}$	10–100
Kerosene	2085	820	900	1800	2.1	–	$4.6 \cdot 10^{10}$
Toluene	1730	867	1099	584	2.3	–	10^{10}–10^{12}
Transformer oil	1880	880	606	19800	2.5	0.01–0.0002	10^{10}–10^{13}
$\text{Oil}^{**)}$	2190	961	800	1253000	2.72	0.0157	$2 \cdot 10^4$
Acetone	2114	790	1487	322	20.74	–	$\sim 10^7$

Notes: *Taken from [15]; **The values correspond to the bitumen oil of the Mordovian–Karmal' deposit of bitumens of the Republic of Tatarstan, the dielectric parameters were measured by the present authors, the remaining parameters, by the concern TatNIPIneft' [16]; –) the values are not determined; the remaining parameters are taken from [17].

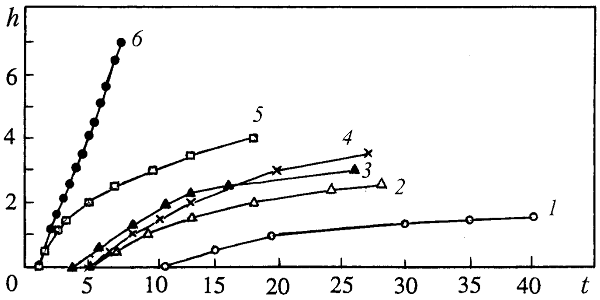
Results of the experimental studies are given in the form of plots in Figs. 2–5. The absolute error of measurements of temperature is 0.5 K and of a fluid level, 0.0005 m.

Figure 2 depicts the dependences of change in the levels of the investigated fluids in an HF electromagnetic field with time at the same voltage between the capacitor plates. As is seen from the figure, the times of the beginning of change in the levels differ substantially. For instance, this parameter for tap water and oil is equal to 60 sec, for the transformer oil and the binary solution, to 5 min, for kerosene, to 3 min 30 sec, and for toluene, to 10 min 30 sec. The largest change in the level is observed for tap water (up to 9 mm), while the least one, for toluene (about 2 mm). The level of acetone and distilled water for the time of conducting the experiment (about 40 min) virtually does not change in an HF electromagnetic field. These data are indicative of the predominant influence of an HF electromagnetic field on the convection of polar fluids that have the greater permittivity. A higher-polarity fluid (with the exception of acetone and distilled water) has a smaller time of the beginning of convection and a considerably larger height of fluid rise in a vertical tube than a fluid of less polarity.

Thus, a fluid level in the vessel of prescribed volume that is in an electrical field of the vertical plane capacitor arises. One of the physical mechanisms underlying this effect is as follows.

When a variable electromagnetic field of the form

$$\dot{\mathbf{E}} = \dot{\mathbf{E}}_0 \exp(j\omega t), \quad \dot{\mathbf{H}} = \dot{\mathbf{H}}_0 \exp(j\omega t) \qquad (1)$$



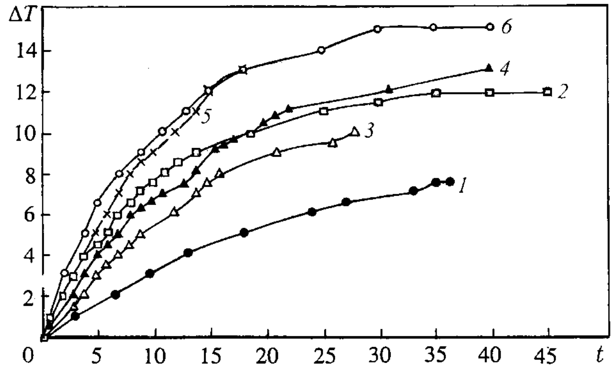


Fig. 2. Change in the level of fluids in an HF electromagnetic field with time: 1) toluene; 2) transformer oil; 3) kerosene; 4) binary solution; 5) oil; 6) tap water (the distance between the capacitor plates is 0.015 m). *h*, mm; *t*, min.

Fig. 3. Temperature variation of the fluids with time: 1) transformer oil; 2) distilled water; 3) kerosene; 4) toluene; 5) oil; 6) binary solution. Δ*T*, K; *t*, min.

acts on a medium, the energy of the electromagnetic field is converted into heat and the medium is heated and expands. This is evidenced by the experimental data in Figs. 3 and 4. It is seen that at the same voltage between the capacitor plates the investigated media are heated differently. In particular, tap water is heated more quickly by a factor of 15 than distilled water. Moreover, as follows from Table 1, unlike the data of the experiment (Fig. 2) on heating a substantially greater expansion of kerosene than of water should be expected. Consequently, these regularities point to the dissimilar and unusual absorption of the energy of an HF electromagnetic field by the investigated media. Indeed, the specific absorbed and converted to heat HF electromagnetic power

$$q^{(e)} = \frac{\omega \varepsilon' \varepsilon_0 \tan\delta}{2} (\dot{\mathbf{E}}_0 \dot{\mathbf{E}}_0^*) \qquad (2)$$

is determined by the distinctive features of change in the complex permittivity in an HF electromagnetic field

$$\dot{\varepsilon} = \varepsilon_0 \varepsilon' (1 - j \tan \delta) . \qquad (3)$$

In expressions (2) and (3), the symbols with a dot above the vectors and with an asterisk indicate their complexity and conjugation.

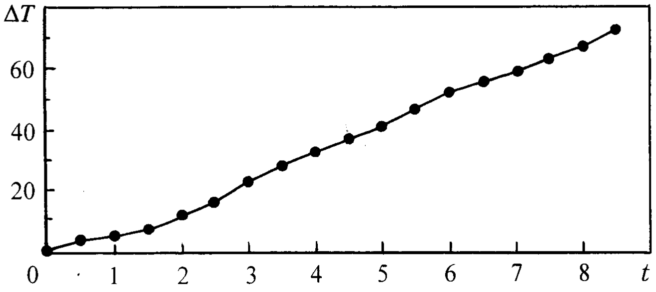
The quantities ε' and $\tan \delta$ at constant pressure depend on the frequency of electromagnetic oscillations and temperature of a medium, i.e.,

$$\varepsilon' = \varepsilon' (\omega, T) , \quad \tan\delta = \frac{\sigma (\omega, T) + \omega \varepsilon_0 \varepsilon'' (\omega, T)}{\omega \varepsilon_0 \varepsilon' (\omega, T)} . \qquad (4)$$

Dependences (4) are determined by experimentally known methods.

The specific features of heating of the media investigated in the present experiment are fully described by the regularities of change in ε' and $\tan \delta$ as a function of the frequency of electromagnetic oscillations in conformity with functions (4). In particular, results of the investigations of ε' and $\tan \delta$ for distilled water are reported in [15] and for bitumen oil of the Mordovian–Karmal’ deposit, in [18]. Apparently, the tap water is mineralized, possesses electric conductivity, and has a greater dielectric loss tangent, and by virtue of expression (2) the absorbed HF electromagnetic power and, consequently, the temperature of heating is substantially larger than in distilled water and others.

Table 2 provides values of the electromagnetic-field powers absorbed by the investigated fluids that have been calculated with use of the law of conservation of energy:



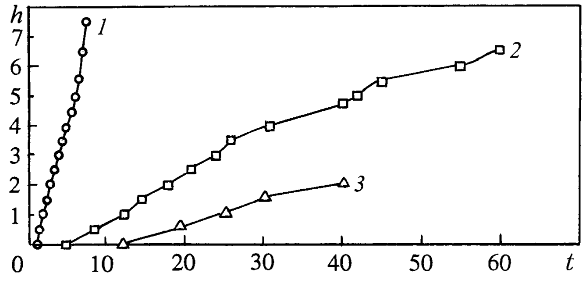


Fig. 4. Temperature variation of tap water versus the time of action of the electromagnetic field. ΔT, K; t, min.

Fig. 5. Level of tap water versus time at different powers of the electromagnetic field. 1) 9 W; 2) 1.1; 3) 0.3. h, mm; t, min.

TABLE 2. Electromagnetic-Field Powers Absorbed by the Investigated Media

Fluid	P_0	Fluid	P_0
Kerosene	0.148	Toluene	0.09
Transformer oil	0.112	Oil	0.385
Tap water	9.0	Distilled water	0.002
Binary solution	0.21		

$$P_0 = c\rho V \frac{\Delta T}{\Delta t} . \tag{5}$$

The larger the power, the higher the temperature of the medium. As is seen from Figs. 3 and 4, the temperature of tap water in an HF electromagnetic field is higher than that of other media. This is indicative of its greater capability to absorb the energy of an HF electromagnetic field.

At the same time, as the temperature rises the heat losses to the surrounding medium increase as well, which substantially influences the change in fluid levels. This is most distinctly manifested in the investigations of change in the fluid levels as a function of the absorbed power of an HF electromagnetic field (Fig. 5). The latter quantity was also evaluated by formula (5) and changed from 0.1 to 9 W. As is seen from the figure, the growth of power of the electromagnetic field decreases the time of the beginning of motion and increases the height of water rise. At a high power of the HF electromagnetic field (curve 1), the level of water changes sufficiently quickly and attains the regime with peaking. Here, the water boils up and its surface performs oscillatory motion with different amplitudes. The rate of change in the fluid level per unit power of the field amounts to 0.02 mm/(sec·W). At low powers, as curve 2 shows, this quantity is 0.002 mm/(sec·W). The level of water slowly ascends and attains a steady-state regime. Consequently, with an eightfold increase in the absorbed power the rate of water rise in the vertical tube is equal to 10. These regularities are, apparently, related to the substantially less loss of thermal energy to the surrounding medium since at high powers of the HF electromagnetic field the fluid in the capacitor does not succeed in exchanging heat with the surrounding medium. Thus, the temperature is nonuniformly distributed in the fluid: in the middle of the vessel it is higher than over its periphery. Therefore the temperature difference is established in the vessel relative to its middle, which leads, at the sacrifice of temperature-dependent density, to the appearance of the pressure gradient over the vessel height and, consequently, the force causing change in the fluid level in the vessel. Moreover, because of the dependence of the permittivity of the media on the temperature and its nonuniform distribution along the vessel the permittivity gradient appears and, consequently, the ponderomotive force, which is also directed upward.

A comparison of Figs. 2, 3, and 4 shows that no linear dependence exists between the changes in the fluid levels and their temperatures and, consequently, in the thermal expansion of the fluids. Thus, for instance, the thermal expansion coefficient is 1.8- and 1.5-fold larger and the coefficient of change in the levels is a factor of 1.4 and 1.75 less than those of the transformer oil and kerosene.

Apparently, the forces of gravity and friction exert an influence on the rise of fluid level in the vertical vessel. As the experiments show, the dependence of change in the levels of fluids on their viscosity, which is related to the friction force, is rather complicated and ambiguous. For instance, kerosene has a tenfold smaller viscosity but increases 1.75 times higher than the transformer oil, and the viscosity of toluene is three times smaller and has a twofold lower rise of level than kerosene.

Thus, in the fluid a nonuniform temperature field is formed. In the gravitational field, this leads to the appearance of the density difference between the median and upper layers of the fluid which gives rise to buoyancy (Archimedian) forces responsible for fluid motion. The intensity of this convection is essentially determined by the electrophysical properties of fluids and their dependences on the frequency of an electromagnetic field. The thermophysical properties of the media surrounding the investigated fluids cause temperature redistribution in the fluids, which, in turn, influences the excited convection. To analyze their contribution to the investigated phenomenon in detail theoretical studies are needed.

NOTATION

c, specific heat, J/(kg·K); ρ, density, kg/m^3; T, temperature, K; ΔT, change in the temperature, K; t, time, sec; Δt, time variation, sec; h, change in the fluid level, m; P_0, power of the electromagnetic field induced in the plane capacitor absorbed by the fluid, W; V, fluid volume, m^3; β, thermal expansion coefficient, 1/K; μ, dynamic viscosity of the fluid, Pa·sec; ε_0, dielectric constant, F/m; ε', relative permittivity; ε'', factor of dielectric loss; $\tan\delta$, dielectric loss tangent; γ, electric resistivity, Ω·m; σ, electric conductivity, 1/(Ω·m); $\omega = 2\pi f$, cyclic frequency, rad/sec; f, frequency, Hz; $\dot{\mathbf{E}}_0$ and $\dot{\mathbf{H}}_0$, complex amplitudes of the intensities of an electromagnetic field, V/m and A/m; j, imaginary unity.

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