AMPLITUDE–FREQUENCY CHARACTERISTICS OF AN ELECTRODYNAMIC LOUDSPEAKER WITH MAGNETORHEOLOGIC SUSPENSION

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UDC 532.135

The thermal and mechanical characteristics of a loudspeaker with a magnetic gap filled with a magnetorheologic suspension (MRS) are numerically investigated.

The use of the magnetorheologic effect (MRE) [1] allows one to control hydrodynamic and heat-exchange characteristics of liquid media. Use of the MRE when the MRS is placed in a magnetic gap of the loudspeaker improves substantially its electroacoustic and power characteristics.

Method of Experimental Study. Some salient features of stationary and nonstationary heat exchange in the voice coil of a loudspeaker with magnetized liquids in a magnetic gap are considered in [2, 3]. An experimental study of the transient characteristics of heat exchange and of the motion of the voice coil of the 4GD-35 dynamic loudspeaker for excitation of the coil at the resonant frequency ($\nu_{res} \sim 40$ Hz) was performed on a setup, a diagram of which is given in Fig. 1. In the experiments, changes in the temperature and the parameters of motion of the voice coil were registered synchronously when the electric signal was applied to the coil. The coil was heated by a high-frequency signal ($\nu \sim 8000$ Hz) delivered concurrently with a low-frequency signal ($\nu_{res} \sim 40$ Hz), intended to preset the vibrations of the diffuser of the loudspeaker. Studies were conducted with a dynamic loudspeaker whose magnetic gap was filled with air, PMS-100 polymethylsiloxane liquid, and the MRS. The properties of these media are described in [2, 4].

Formation of the Thermomechanical Problem. We consider an electromechanical direct-radiation loudspeaker (Fig. 1) [5]. The motion of the loudspeaker coil is modeled nonstationary nonisothermal regimes under the condition that the width of the gap h in which the voice coil moves is much less than its length and radius of curvature. Therefore, the flow in the gap can be treated as plane Couette flow. The Reynolds number is small ($\mathrm{Re}_\omega = \rho\omega h^2/\eta_e \leqslant 1$), and the inertial forces when the coil moves can be neglected. In this case the tangential stress across the gap does not change and is determined by the shear velocity $\dot\gamma = (1/h)dX/dt$. The tangential stress $\tau(t)$ and the shear velocity $\dot\gamma$ are related via the rheological equation of state (RES) of the MRS [6]. The moving part of the loudspeaker is under the action of: the force of the mehcanical resistance ($r\dot X$), the reaction of the acoustic field (F_a), the elastic restoring force (F_e), the hydrodynamic resistance (τS) and the Lorentz force (αI, $\alpha = B_0 \ell$). The inductance of the coil at low frequencies is neglected [5]. The equation of motion for the moving part and the equation for the current in the circuit are written in the following way:

$$m\ddot X + r\dot X + F_a + F_e + \tau S + \alpha I = 0, \tag{1}$$

$$RI - \alpha\dot X = \mathrm{E}(t). \tag{2}$$

The reaction of the acoustic field F_a is negligible for a round flat piston at low frequencies when the wavelength exceeds considerably the size of the diaphragm [5]. Investigations conducted in [7] have shown that the factor of rigidity for an elastic restoring force for small displacements depends on the displacement and has two limiting values: for small and large displacements. Placement of the MRS in the magnetic gap of the loudspeaker further intensifies this effect. For small amplitudes of oscillation, the dependence of the restoring force F_e on the displacement is as follows:

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR. Belorussian Polytechnic Institute, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 53, No. 6, pp. 954-961, December, 1987. Original article submitted July 22, 1986.

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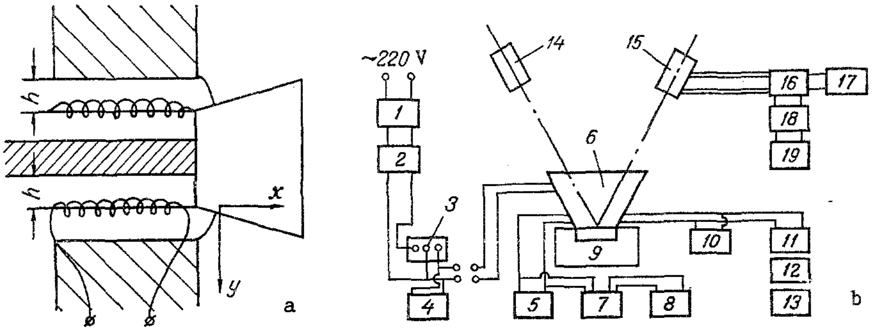

Fig. 1. Diagram of the loudspeaker (a) and experimental setup (b); 1) G6-26 audio-frequency generator; 2) power amplifier; 3) F-583 electronic wattmeter; 4) V3-13 voltmenter; 5) R-385 digital ohmeter; 6) 4GD-35 loudspeaker; 7) amplifier; 8) S8-13 storage oscillograph; 9) thermostat; 10) F-5043 frequency meter; 11) V3-13 voltmeter; 12) power amplifier; 13) oscillating frequency generator; 14) LG-55 laser; 15) photomatrix; 16) U7-1 differential amplifier; 17) S1-83 oscillograph; 18) Kh1-46 device for studying amplitude-frequency characteristics; 19) S8-13 storage oscillograph.

$$F_e = \left[K_\infty + \frac{K_0 - K_\infty}{1 + (X/Q)^2}\right]X, \quad K_0 > K_\infty. \tag{3}$$

During the long-term operation of the loudspeaker its thermal regime changes due to heat evolution in the liquid and thermal losses in the electric circuit. This results in the heating of the coil, the MRS, and the magnetic conductor. Estimates show that the dissipated energy released in the liquid during oscillations is much less than the heat evolution in the coil for the same period of time. We will consider heat processes of duration much greater than the characteristic time of propagation of the thermal wave h^2/A_* across the gap. In this case a transverse distribution of the temperature can be treated as a quasistationary one, and the time variation of the temperature of the coil and the liquid in the gap is determined by the equation of heat balance

$$\left(C_c M_c + \frac{C_1 M_1}{2}\right)\frac{dT}{dt} + \frac{C_1 M_1}{2}\frac{dT_0}{dt} = I^2 R - \frac{\lambda S}{h}(T - T_0). \tag{4}$$

The mean temperature of the liquid $T_\ell = (T_0 + T)/2$. In view of the linearity of the equation of conductive heat transport in a magnetic circuit, its slow heating is described by the following equation of heat balance:

$$\psi C_M M_M \frac{dT_0}{dt} = \frac{\lambda S}{h}(T - T_0) - \alpha_* S_* (T_0 - T_\infty). \tag{5}$$

In (5), a dimensionless coefficient ψ is introduced which allows for the distribution of temperature in the magnetic conductor. Its heating is assumed to be caused by heat transfer from the coil only. The parameter ψ is determined experimentally in the course of the slow heating of the magnetic conductor. It has been shown in [2] that the effect of its heating can be neglected for the relatively short time of operation of the loudspeaker. Therefore, the heat-regime calculations were later performed under the condition of constant temperature of the magnetic conductor, equal to the ambient temperature $T_0 = T_\infty$. The dependence of the electrical resistance of the coil on temperature is defined by

$$R = R_\infty [1 + \beta (T - T_\infty)]. \tag{6}$$

Thus, a nonstationary nonisothermal process of motion and heating of the coils is described by the system of equations (1)-(4), (6) with the initial conditions $X = \dot{X} = 0$, $T = T_\infty$ at $t = 0$. In order to obtain a closed system of equations it is necessary to have an

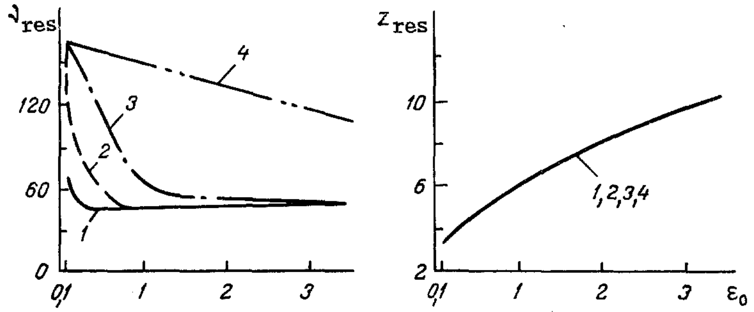

Fig. 2. Dependence of the resonance frequency ν and the complex impedance of the loudspeaker z on stress at $\tau_* =$ 430 Pa, $h = 0.15 \times 10^{-3}$ m, $\tilde{\theta} = 10^{-5}$ sec; $Q = 10^{-6}$ (1), 10^{-5} (2), 10^{-4} (3), 10^{-3} (4) m. ν_{res}, Hz; z_{res}, Ω; E_0, V.

RES of the MRS. At present the properties of the MRS are well known only for stationary shearing flow [1]. It is shown that the effective viscosity is approximated by a power law (n = 0.1-0.2). Since the effective viscosity of the MRS decreases with increase in the shear velocity to the value of the viscosity of the dispersive medium η_∞, the RES of the MRS is represented as follows:

$$\tau = \tau_1 + \tau_2; \quad \tau_1 = \eta_1(|\dot{\gamma}|)\,\dot{\gamma}, \quad \tau_2 = \eta_\infty\dot{\gamma}, \quad \eta_1 = \frac{\tau_*}{\dot{\gamma}_*}\left|\frac{\dot{\gamma}}{\dot{\gamma}_*}\right|^{n-1}. \qquad (7)$$

When the shear velocities are small, the contribution of the second component of the viscosity is insignificant. The value of τ_* determines a tangential stress at the shearing velocity γ_*. The viscosity of the MRS varies with the change in the temperature of the liquid T_λ in the magnetic gap of the loudspeaker. Its temperature dependence is just the same as that of the carrying agent [1]. The principle of superposition for temperature and time [1, 8], according to which the influence of the change in the temperature of the liquid on the tangential stress reduces to the change in the effective shear velocity is applicable to the MRS. Therefore, the temperature dependence of the viscosity of the MRS is determined by the reaction $\tau = f[|a(T)\dot{\gamma}|]$, where $a(T) = \eta_\infty(T_\ell)/\eta(T_\infty)$, $f(\gamma)$ is the dependence of the shear velocity at the temperature T_∞.

Estimate of Role of Relaxation Processes in MRS in Isothermal Regime. The 4GD-35 loudspeakers possess frequencies of electromechanical resonance of about 50 Hz. The mechanical relaxation time for the MRS is of order of $\tilde{\theta} \sim 10^{-3}$ sec [1], which is comparable with the period of oscillations of the moving part of the loudspeaker. In connection with this, an estimate of the influence of the relaxation processes in the MRS on the characteristics of the loudspeaker under isothermal conditions is performed for a side range of parameters: $m = 7.5 \times 10^{-3}$ -9.5×10^{-3} kg, $B_0 = 0.9$ T, $\ell = 3$ m, $R_\infty = 3$-9 Ω, $S = (3.6$-$6) \times 10^{-3}$ m², $r = 0.001$ - 0.570 kg/sec, $K_0 = 6075$ N/m, $K_\infty = 570$ N/m, $Q = 10^{-6}$-10^{-3} m, $h = (0.15$–$0.30) \times 10^{-3}$ m, $E_0 =$ 0.1-3.5 V, $\tau_* = 200$-430 Pa, $\gamma_* = 450$ sec⁻¹, $\eta_\infty = 0.1$ Pa·sec, $\theta = 10^{-5}$-10^{-2} sec. In order to describe the elastic properties of the MRS, we use the simplest RES of the type of White–Metzner [9], which has found wide application for dispersive systems. Then τ_1 is described from the relaxation equation with the right-hand side corresponding to the stationary equation (7)

$$\tau_1 + \tilde{\theta}\,d\tau_1/dt = \eta_1(|\dot{\gamma}|)\,\dot{\gamma}.$$

The system of differential equations (1), (2) was solved analytically. In order to determine the form of a resonant curve near the main resonance, the method of harmonic balance [10] has been used. For the voltage in the circuit $E = E_0 \cos(\omega t - \kappa)$, where κ is a phase shift, solution (1), (2) is presented in the form $X = A\cos\omega t$. By requiring that the error obtained be orthogonal to the functions $\cos\omega t$ and $\sin\omega t$, we arrive at the equation for determining the amplitude–frequency characteristics (AFC) of the loudspeaker

$$\left[-\frac{1}{2}mA\omega^2 + \Phi_{y,1} + \Phi_{r,1}\right]^2 + \left[-\frac{1}{2}\left(r + \frac{\alpha^2}{R_\infty}\right)A\omega + \Phi_{r,2}\right]^2 = \left(\frac{\alpha E_0}{2R_\infty}\right)^2. \qquad (8)$$

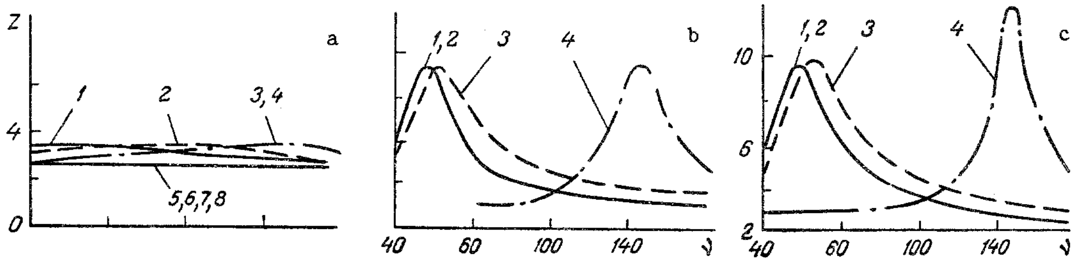

Fig. 3. Dependence of the complex impedance of the loudspeaker on frequency for a) $E_0 = 0.1$ V, $\tilde{\theta} = 10^{-5}$ sec, $\tau_* = 200$ (1-4), 430 (5-8) Pa, $h = 0.15 \times 10^{-3}$ m, $Q = 10^{-6}$ (1, 5), 10^{-5} (2, 6), 10^{-4} (3, 7), 10^{-3} m (4, 8); b), c) $E_0 = 1$ V, $\tau_* = 200$ Pa, $h = 0.15 \times 10^{-3}$ m, $Q = 10^{-6}$ (1), 10^{-5} (2), 10^{-4} (3), 10^{-3} m (4), $\tilde{\theta} = 10^{-5}$ (b), 10^{-3} sec (c).

Here

$$\Phi_{y,1} = 0{,}5K_\infty A + \varphi(A),\ \ \varphi(A) = (K_0 - K_\infty)(Q/A)^2(1 - 1/\sqrt{1+(A/Q)^2})A;$$

$$\Phi_{r,1} = \frac{\omega\tilde{\theta}}{1+(\omega\tilde{\theta})^2}\tilde{\eta}_1\frac{A\omega}{h}S,\quad \Phi_{r,2} = -\frac{A\omega}{h}S\left[\frac{\eta_\infty}{2} + \frac{\tilde{\eta}_1}{1+(\omega\tilde{\theta})^2}\right];$$

$$\tilde{\eta}_1 = \frac{\omega}{2\pi}\int_0^{2\pi/\omega}\eta_1\left(\left|\frac{A\omega}{h}\sin\omega t\right|\right)\sin^2\omega t\,dt = \frac{\tau_*}{\dot{\gamma}_*}\left(\frac{\omega A}{h}\right)^{n-1}\xi_n;$$

$$\xi_n = \frac{\Gamma(1+n/2)}{\sqrt{\pi}\,\Gamma\left(1+\frac{n+1}{2}\right)},\quad \Gamma(\ )\text{ is the gamma function.}$$

The results obtained were used later for calculating the modulus of the complex impedance of the coil of the loudspeaker z, which is its most important characteristic [5]. The numerical solution of the transcendental algebraic equation (8) with respect to A allows us to find the value of z from the following formula:

$$z = R_\infty/\left[\left(1+\frac{\alpha\omega A}{E_0}\sin\varkappa\right)^2 + \left(\frac{\alpha\omega A}{E_0}\cos\varkappa\right)^2\right]^{1/2},$$

$$-\frac{1}{2}mA\omega^2 + \Phi_{y,1} + \Phi_{r,1} = -\frac{\alpha E_0}{2R_\infty}\cos\varkappa.$$

The results of calculations allow us to analyze the influence of different factor on z(A). Thus, z increases with an increase of the voltage on the coil due to the growth of the external force, but the resonance frequency drops (Fig. 2). When the displacement of the coil increases, the stiffness of the coil approaches a constant value K_∞, and the resonance frequency tends to its limiting value. The type of behavior of the resonance frequency does not change with increasing Q. Only the value of voltage for which the frequency attains its limiting value changes. The value of the time of relaxation $\tilde{\theta}$ does not change qualitatively the nature of the behavior of the considered values. The increase in the width of the gap h from 1.5 to 3 mm leads to a decrease of the tangential stress due to a drop in the shear velocity and entails an increase in the resonance value z to 60% at $\tilde{\theta} \sim 10^{-2}$ sec. For small stresses (small displacements), the resistance force, which includes a mechanical component and a hydrodynamic component, exceeds the elastic force. Under these conditions, resonance is not observed (Fig. 3). With an increase in frequency the amplitude of oscillations decreases slowly. With an increase in the relaxation time $\tilde{\theta}$, the effective dynamic viscosity of the MRS drops, as a result, the hydrodynamic resistance decreases, and a resonance is observed on the frequency dependence of z. When the voltage E_0 increases, this phenomenon becomes more prominent. Calculations show that for $\tilde{\theta} \leq 10^{-3}$ sec, the relaxation process in the MRS associated with the change in the shear velocity, do not practically affect the amplitude—frequency characteristics of the loudspeaker (Fig. 3). Therefore, in order to calculate the characteristics, the data for the effective shear viscosity of the MRS in a

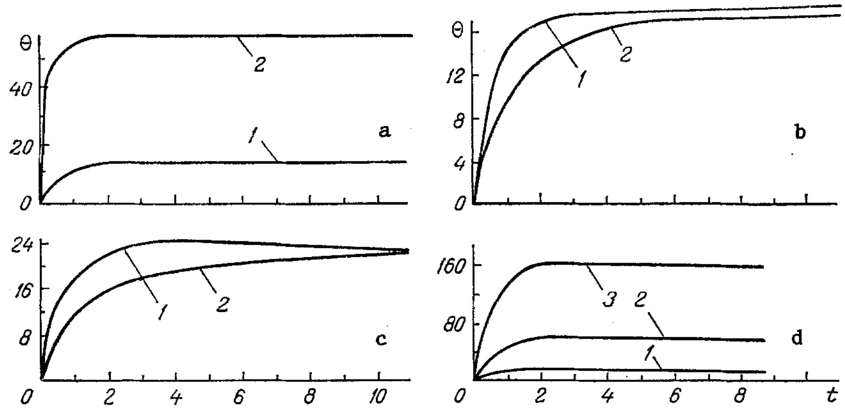

Fig. 4. Time variation of the coil temperature: (a) 1, MRS, 2, air; (b) 1, calculation curve for E_0 = 2.83 V, E_d = 2.81 V, R_∞ = 7.6 Ω, 2, experimental data for MRS; (c) 1, calculation curve for E_0 = 0.71 V, E_d = 5.5 V, 2, experimental data for PMS-100; (d) E_0 = 2.5 V, E_d = 6.25 (1), 14.5 (2), 25 (3), V, Θ, °C; t, sec.

stationary flow can be used, which allows one to specify the RES of the MRS in the form of the power law (7).

By neglecting relaxation processes in the MRS and inertial forces in the liquid ($Re_\omega \leqslant 1$) it becomes possible to considerably simplify calculation of the tangential stresses in the liquid for oscillating couette flow under nonisothermal conditions. It is shown in (8) that in this case the tangential stress for the nonisothermal conditions coincides with the corresponding value for the isothermal conditions with the temperature T_{equ}. The value of T_{equ} is determined by a cross profile of temperatures for the nonisothermal condition. In the given case, for a linear profile of temperatures and exponential dependence of the viscosity on temperature it is determined by the relation [8]

$$a(T_{equ}) = h \Big/ \int_0^h \frac{dy}{a(T(y))} = \frac{\alpha_B \Theta}{\exp(\alpha_B \Theta)[1 - \exp(-\alpha_B \Theta)]},$$

$$\Theta = T - T_0$$

<u>Nonisothermal Regime of Operation of the Loudspeaker</u>. We now turn to calculation of the concrete model of the 46D-35 loudspeaker. The formulated system of Eq. (1)-(4), (6), (7) contains the values r, K_0, K_∞, Q, which reflect its constructional features. For their determination, the experimental data has been used on measurement of the amplitude—frequency characteristics of the loudspeaker in the isothermal regime with air and MRS in the gap. The calculation has shown that for K_0 = 838.916 N/m, K_∞ = 751.122 N/m, Q = 0.38 × 10^{-3} m, r ~ 0.5 kg/sec. In order to analyze the transient characteristics of the loudspeaker when the heat regime varies, we specify the actual voltage in the form $E = E_0 \cos 2\pi\nu t + E_d \cos 2000\,\pi t$, where the high-frequency component is initiated 1.5 sec later. The component does not affect the motion of the coil directly, it only warms the coil. In the graphs on heating the coil, represented below, the origin of time coincides with the initiation of the second component of the voltage ($\Theta = T_* \bar{\Theta}$, $T_* = I_0^2/(\lambda S/h)$, $I_0 = \alpha^2 E_0/mR_\infty^2 2\pi\nu_0$, $t = \bar{t}/2\pi\nu_0$, $\nu_0 \approx 41$ Hz). The advantages of the introduction of the MRS in the gap in comparison with air are apparent from Fig. 4. The temperature of the coil with the magnetic gap filled with the MRS reduces by a factor of four due to the improvement in heat dissipation. In order to determine the effect of the thermal sensitivity of the viscosity on the amplitude of oscillations, we specified the value of α_B for the carrying medium of the MRS-100. In the interval of 20-60°C, α_B = 0.0205-0.0227 K^{-1} [4]. An increase in the coefficient of sensitivity of the viscosity α_B leads to an increase in the swing of the coil of the loudspeaker for the given law of the variation of the temperature of the coil with time. Thus, for example, the heating of the coil by 50°C results in an increase in the amplitude of oscillations by 15% and 19% for α_B = 0.0205 and 0.0227 K^{-1}, respectively.

The comparison of the experimental data on heating the coil of the loudspeaker with the magnetic gap filled with PMS and MRS and calculations perfomed on a computer for the same conditions are shown in Fig. 4. The heating of the coil depending on the value of the second component of the voltage E_d is shown in Fig. 4d.

The amplitude—frequency characteristics in a nonstationary nonisothermal regime are influenced strongly by the ratio of the mechanical resistance and the hydrodynamic resistance $A_{r\tau} = rh/\eta S$ at the initial temperature, value of E_0, and the ratio of the first and second components of the viscosity η_1/η_∞. In distinction to the Newtonian liquid, the value of $A_{r\tau}$ for the MRS depends on the amplitude of the voltage E_0. In particular, it may happen that for small voltages $A_{r\tau} \lesssim 1$, while for large voltages $A_{r\tau} \gtrsim 1$.

On heating, the value of $A_{r\tau}$ can increase and outgrow unity. We consider the two most important situations: $A_{r\tau} \lesssim 1$, $\eta_1/\eta_\infty \gtrsim 1$ and $A_{r\tau} \lesssim 1$, $\eta_1/\eta_\infty \lesssim 1$. For these situations the way the amplitude varies upon heating the coil differs significantly. In the second case, the amplitude increases due to the thermal variation in the viscosity of the dispersive medium only, while in the first case the increase in the amplitude is also dictated by a considerable fall-off in the effective viscosity with the increase in the shear velocity. If $A_{r\tau} \lesssim 1$, $\eta_1/\eta_\infty \gtrsim 1$ for the entire range of temperatures, then a nonlinear component of the effective viscosity affects decisively the value of the amplitude. The coil oscillates in the range where the non-Newtonian properties of the MRS are clearly defined. In case when $A_{r\tau} \lesssim 1$, $\eta_1/\eta_\infty \lesssim 1$, the value of the amplitude is decisively influenced by the second component of the effective viscosity, and the nonlinear properties of the MRS are weakly exhibited. When heating the coil by 50°C, the increase in the amplitude of oscillations due to the thermal sensitivity of the medium constituted 30% for the first case and 6.7% for the second case. It is essential to mention that depending on a particular situation of the heating, the sign in each of the inequalities $\eta_1/\eta_\infty \lesssim 1$ and $A_{r\tau} \lesssim 1$ can change. For $A_{r\tau} \gtrsim 1$ the amplitude of oscillations is crucially affected by the force of the mechanical resistance. If for the initial temperature of heating, $A_{t\tau} \gg 1$, then, irrespective of the ratio η_1/η_∞, the amplitude o oscillations is chiefly influenced by the mechanical resistance. Upon heating, the amplitude changes due to the increase in the electric impedance of the circuit only.

NOTATION

ρ, density of the liquid; η_e, effective viscosity; ω, circular frequency; X, displacement of the loudspeaker's coil; m, mass of the oscillating loudspeaker part; r, coefficient of the mechanical resistance of an empty loudspeaker; τ, liquid shear stress; S, wetted area of the coil surface; B_0, magnetic field induction in a gap; ℓ, length of the coil winding; I, curfent in the circuit; R, ohmic resistance in the circuit; K_0, K_∞, Q, parameters of the elastic restoring force; A_*, thermal diffusivity of the medium in a gap; T, T_0, coil temperature and magnetic circuit temperature, respectively; C_c, C_ℓ, specific heat capacity of the coil material and specific heat capactiy of the liquid, respectively; M_L, M_c, mass of the liquid and mass of the liquid and mass of the heated part of the coil; T_∞, ambient temperature; C_M, M_M, specific heat and mass of the magentic circuit; α_*, heat-transfer coefficient, S_*, area of the external heat transfer surface of the magnetic circuit; R_∞, resistance of the coil at the ambinet temperature; β, coefficient of temeprature resistance of the winding wire; α_v, coefficient of temperature dependence of the viscosity of the liquid; F_a, response of the acoustic field $\varkappa$, phase shift; $\tilde{\theta}$, relaxation time; A, amplitude.

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DIAGNOSTICS OF ELECTRO-GAS-DYNAMIC FLOWS OF A LOW-CURRENT HIGH-VOLTAGE DISCHARGE

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UDC 536.423.1:537.52

The results of an experimental investigation of the dynamic and energy characteristics of electro-gas-dynamic flows are presented.

In [1], in a study of the action of a low-current, high-voltage discharge on the kinetics of evaporation of a liquid, it was established that the process is significantly intensified (by one to two orders of magnitude) and the intensification depends on the strength of the discharge current, the form of the electrodes, and the polarity of the electrodes and their arrangement relative to the surface of evaporation as well as on the physical properties of the liquid. This effect is explained by the action of electro-gas-dynamic (EGD) flows forming in the zone near the electrode on the surface layer of the liquid and the entrainment of vapor by it into the discharge processes.

The purpose of this work is to determine the possible mechanism for the action of EGD flows on the kinetics of phase transitions and to determine their dynamic and energy characteristics. The investigations were performed on the experimental apparatus described in [2].

The discharge current varied from 0.5 to 100 μA and the voltage varied from 3 to 10 kV. The liquid was evaporated from thin tubes and flat volumes as well as from drop surfaces. The gas-dynamic flows were visualized with the help of the schlieren method for determining the nonuniformities of transparent materials (the point-source method) [3]. The EGD flow created in the point-ring system of electrodes (the ring diameter equalled 2.5 mm and the distance between the point and the plane of the ring equalled 1.5 mm) was probed with a parallel light beam. The investigations showed that a directed gas-dynamic jet 15-30 mm long and 2-3 mm in diameter is generated in the discharge gap of the point-ring electrode system.

The flow velocity was measured by the well-known method of [4], realized in a Pitot—Prandtl tube and modified for the specific case of EGD flows. It was established that the velocity on the axis of the flow depends on the strength of the discharge current and the polarity of the electrodes. For positive polarity of the electrode-tip and currents in the range 5-100 μA the velocity varied from 5 to 9 m/sec, and for a negative potential on the tip with the same discharge currents it varied from 2.5 to 4 m/sec. At distances of 1-1.2 mm from the axis of the flow the velocity decreases by a factor of 2.8-3.

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR. Belorussian Polytechnic Institute, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 53, No. 6, pp. 961-966, December, 1987. Original article submitted July 14, 1986.

 0022-0841/87/5306-1430$12.50