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Interaction of electromagnetic waves with liquid films

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The influence of an electromagnetic wave on the flow of a liquid film between two flat plates is considered. It is shown that the electric field intensity vector has an effect on the double electric layer of the liquid at the surface of the plates. Due to vibration effects, the velocity of fluid movement increases..

Keywords: electromagnetic wave, liquid film, double electric layer, electroosmosis.

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Current thin films are used in equipment systems for chemical processing, coating, polymer processing, and microelectronic device cooling [1,2]. The motion of a thin film on a substrate — is a complex problem with no analytical solution. In addition, the uneven surface of the flowing liquid leads to non-uniformity of its thickness, which in turn leads to non-uniformity of cooling or other technological processes [3,4]. This problem can be circumvented by allowing liquid to flow between the two plates. In this case, the free surface will be absent, the equations describing the fluid flow will be greatly simplified, and the thickness of the fluid will be constant. However, the additional surface will inhibit the flow of fluid. To speed it up, we can use a combination of two physical phenomena: electro-osmosis and vibratory mechanics [5,6]. This is caused by a charged layer at the interface between two different substances. A layer of liquid adheres to a solid surface. The electric field acts on this layer and sets it in motion. Just as electroosmosis is explained by the action of a constant field on a charged layer setting it in motion, an alternating field acting on vibrational effects has been developed in a wide range of scientific activities [6–8]. Let us consider these effects in application to the flow of a liquid thin film. The possibility of such an increase in film flow rate is evidenced by the patent [9]. A method for measuring the power of electromagnetic radiation by exposing it to a capillary containing water is proposed in it. The capillary is orientated in the direction of the electrical component of the radiation, and the power is measured by the change in the velocity of the jet. The mechanism of such influence of electromagnetic wave on the velocity of liquid flow is not explained in any way, but it can be assumed that for both thin film and capillary this mechanism will be the same.

Let to a body of mass m, lying on a horizontal surface, a constant force F_C, which is less than the rest friction force, i.e. the body is at rest, is applied horizontally. If we now apply a horizontal force $F_0 \sin\omega t$ with frequency ω and amplitude F_0, greater than the rest friction force, the body will start moving. In vibration mechanics, an expression for the steady-state velocity [10] is derived:

$$U_0 = \frac{F_0}{m\omega}\cos\frac{k_+}{k_+ + k_-}\pi, \tag{1}$$

where $k_- = \frac{F_f + F_C}{mg} > k_+ = \frac{F_f - F_C}{mg}$, F_f — the maximum rest friction force.

Consider a flat liquid film between two solid surfaces flowing under the action of pressure difference. Let us mentally separate the liquid layer and consider the forces acting on it (Fig. $1, a$). The end surfaces are subjected to forces due to pressure differences $(P_1 - P_2)$, the side surfaces are subjected to viscous friction forces F_r. At steady-state flow, these forces balance each other, hence we can obtain an expression for the velocity distribution

$$U(x) = \frac{P_1 - P_2}{2\eta l}\left(a^2 - x^2\right), \tag{2}$$

where $2a$ — the distance between the surfaces, η — the dynamic viscosity coefficient. The immobile fluid layer immediately adjacent to the walls has a charge. If in this region somehow an alternating electric field along the axis z with the amplitude E_0 is created, then under the action of the alternating (vibration) force this layer will acquire the velocity U_0 (Fig. $1, b$). Then, the new formula of velocity distribution will be written in the form

$$U(x) = \frac{P_1 - P_2}{2\eta l}\left(a^2 - x^2\right) + U_0. \tag{3}$$

For evaluation, assume that the fluid flows between two vertical flat surfaces under the influence of gravity. Consider a fluid layer of thickness h, located directly at the wall. This layer is acted upon by gravity, adhesion force from the wall side and viscous friction force from the neighboring fluid layer.

When studying the motion of a thin film, it is more appropriate to consider forces acting per unit surface. For the water interface – glass, the adhesion force will be of the order $f_A \approx 100\,\mathrm{N/m^2}$ [11,12]. This force is similar to the F_f force in formula (1).

We now estimate the gravity forces f_g and viscosity forces f_τ, which for the fluid layer adjacent to the wall are

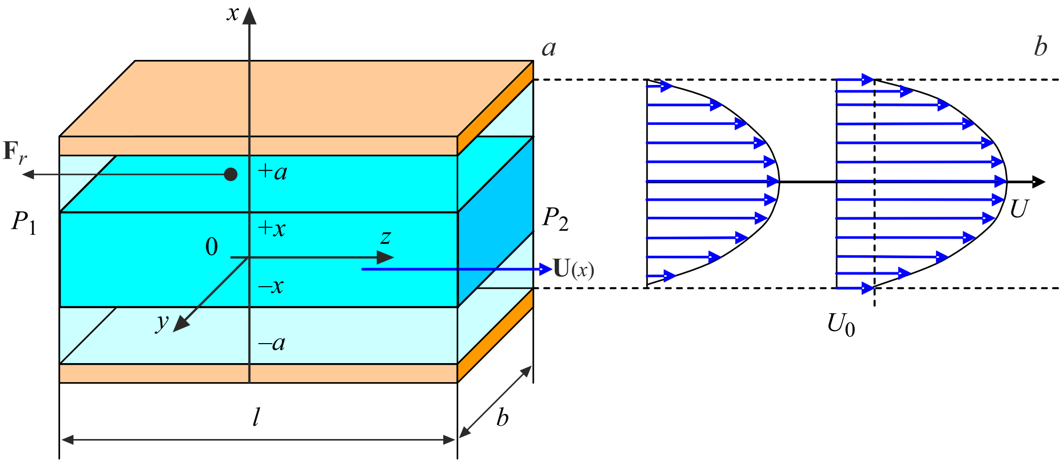

Figure 1. Liquid film motion.*a* — a liquid film between two flat dielectric plates;*b* — a velocity distribution in the cross section without (left) and with (right) vibration forces.

opposite to the adhesion force. Then, the force of gravity per unit of surface S, will be equal to

$$f_g = \frac{F_g}{S} = \frac{\rho blhg}{bl} = \rho gh. \tag{4}$$

Taking into account formula (2), the viscous force per unit surface will be equal to

$$f_\tau = -\eta \frac{dU(r)}{dr}\bigg|_{r=a} = \eta \frac{P_1 - P_2}{\eta l} a = \frac{\rho gl}{l} a = \rho ga. \tag{5}$$

Thus, the total force, which will make sense of the force F_C from formula (1), is the sum of forces (4) and (5):

$$f_C = \frac{F_C}{S} = f_g + f_\tau = \rho g(h + a). \tag{6}$$

Since the thickness of the liquid layer adhering to the pipe wall is of the order of hundreds of angstroms [11], the value of h can be neglected in formula (6). If the distance between the surfaces is 1 mm, the force $f_C \approx 10\,\mathrm{N/m^2}$ is an order of magnitude smaller than the adhesion force, i.e. it cannot move the liquid layer relative to the surface.

The amplitude of the electromagnetic force acting on a thin layer of liquid is proportional to the magnitude of the intensity E_0 and the surface charge density ρ_S. Then the thin film at the $\pm a$ boundaries will acquire an additional velocity in formula (3), which can be written explicitly using formula (1):

$$U_0 = \frac{\rho_S E_0}{h\rho\omega} \cos \frac{f_A - f_C}{2 f_A} \pi. \tag{7}$$

Using the estimation (6), from (7) we can obtain that $U_0 = \frac{\rho_S E_0}{\omega} \cdot 1.6 \cdot 10^3$ m/s.

The distribution of fields in the film also plays a role. You can create an alternating electric field in the film in various ways. The capacitor will produce a field perpendicular to the axis z, which is inefficient from the point of view of vibration mechanics. The use of external emitters is not always acceptable as space inside liquid film cooled devices is usually limited. Therefore, the most convenient variant of input of electromagnetic energy into the system as in a waveguide looks most convenient. Also with this approach, the fields will be evenly distributed. If we consider such a system as a three-layer rectangular waveguide, then the electric field strength component we need can be written using the vector potential $\mathbf{A}$ [13]:

$$E_{zj} = -i \frac{1}{\omega\varepsilon_0\varepsilon} \frac{\partial^2 A_{xj}}{\partial x \partial z}, \tag{8}$$

where $A_{xj} = \big(B_j \cos(k_{xj}x) + C_j \sin(k_{xj}x)\big) \sin(k_y y) e^{ikz}$, j — waveguide area number ($j = 1$— plate area, $j = 2$ — liquid area), k_{xj}, k_y — transverse wave numbers, k — wave propagation constant, d — thickness of the plates confining the liquid film, B_j, C_j — constant coefficients determined by the wave intensity. At the liquid – dielectric interface, the tangential components of the fields should be equal. Using such boundary conditions, we can obtain a system of equations for the coefficients B_j, C_j. The solution of the system is nontrivial if the dispersion equation [13] is satisfied:

$$\frac{k_{x1}\varepsilon_2}{k_{x2}\varepsilon_1} \operatorname{tg}(k_{y1}d) + \operatorname{tg}(k_{y2}a) = 0, \tag{9}$$

and transverse wave numbers are determined from the relations

$$k_{xj} = \sqrt{\frac{\omega^2}{c^2}\varepsilon_j - k_y^2 - k^2}, \ k_y = \frac{n\pi}{b}, \ n = 1, 2, \ldots. \tag{10}$$

By stitching the solutions of (8) at the boundaries and using (9), (10), the field distributions in the waveguide can be obtained. The results are obtained for longitudinal magnetic waves LM$_{mn}$ ($H_x = 0$). The following parameters are used in the calculations: $a = h = 0.5$ mm, $b = 3$ mm,

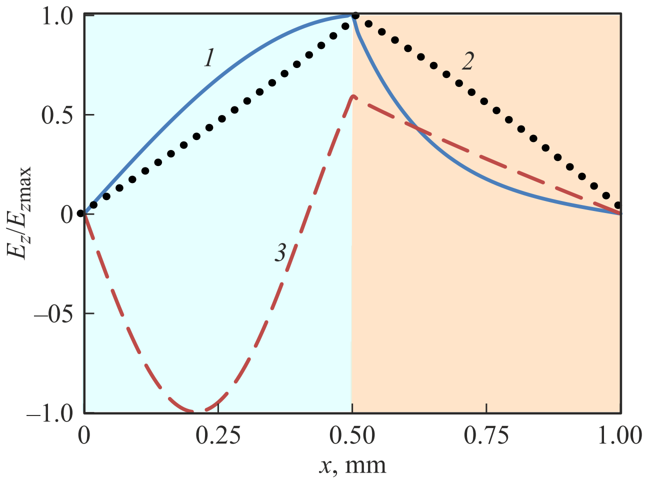

Figure 2. Field distribution. *1* — LM_{21}, $\varepsilon_2 = 60$; *2* — LM_{21}, $\varepsilon_2 = 6$; *3* — LM_{41}, $\varepsilon_2 = 60$.

$f = \omega/2\pi = 50\,\text{GHz}$, $\varepsilon_1 = 10$, $\varepsilon_2 = 6-60$ [14–16]. The frequency is determined by the size of the waveguide. The dielectric permittivity of water and aqueous solutions near this frequency is highly variable and temperature dependent. The results are presented in relative $E_z/E_{z\,\max}$ (Fig. 2), where $E_{z\,\max}$ is determined from the intensity of the electromagnetic wave. It can be seen that for different waves, the maximum of the electrical field strength will be at different locations. The geometry of the system will influence the field distribution. For example, for a capillary with water, the fields will be described by Bessel functions [17]. It is necessary to select the parameters so that the maximum electric field strength occurs at the – water boundary of the dielectric.

Thus, the paper suggests a possible mechanism of electromagnetic wave influence on the motion of flat liquid films when they are used as waveguides. Since the U_0 velocity is independent of the film thickness, the contribution„of the vibration“ velocity will decrease with increasing thickness, as can be seen from formula (3). Therefore, the thicker the film, the less noticeable the observed effect will be. Increasing the thin film flow rate can be applied not only to increase the cooling efficiency of electronic devices, but also to determine the parameters of liquid thin films, since the flow rate depends on the film charge, which is determined by the chemical composition of the liquid. Other possible mechanisms for increasing the flow velocity of the fluid, for example, due to a reduction in viscosity due to heating, cannot be completely ruled out. But the authors who carried out the experiment claim that the phenomenon is accompanied by a decrease in the adhesion forces of the capillary wall and the liquid [18,19], which is characteristic of vibration effects. Also, this effect is more noticeable at higher velocities of liquid flow, while water flowing through the field area will be less heated, which should, on the contrary, reduce the effect. The viscous force will increase, which should result in an increased effect in terms of vibration mechanics.

Conflict of interest

The authors declare that they have no conflict of interest.

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