Instability of surface waves in a nonuniformly heated liquid

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The propagation of waves on the surface of a nonuniformly heated incompressible liquid is investigated. It is shown that on heating from the free-surface side, there exist in the liquid, besides the usual gravitational-capillary waves, "thermocapillary" waves produced by the action of thermocapillary forces and having a linear spectrum. When the density of energy flow at the surface of the liquid exceeds a certain threshold value, the gravitational-capillary waves become unstable. At sufficiently large flow densities, the instability growth rate is maximum in the region of intersection of the modes.

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1. INTRODUCTION

Physical phenomena due to excitation in a liquid of acoustic and shock waves under the influence of powerful laser radiation have been studied in considerable detail both theoretically and experimentally.[1] In the presence of a free surface on the liquid, besides these volume waves there also exist surface waves, excitation of which may change the conditions of reflection and absorption of laser radiation at the surface and may affect the processes of heat and mass transport in the liquid. The last fact is especially important in laser working of metals, when on their surface a melted layer forms, the transport processes in which may substantially affect the structure and composition of the material.

The existing experimental data indicate an anomalously rapid redistribution of impurities in the liquid phase during surface alloying of metals, which cannot be explained within the framework of ordinary diffusion and apparently is evidence of the occurrence of hydrodynamic flows in the laser melt.[2-4] The present paper investigates the stability of a horizontal layer of liquid heated from the free-surface side; it is shown that at a sufficiently large density of flow or radiation, there may occur in the liquid, under the influence of thermocapillary forces, a buildup of surface waves.

2. DISPERSION EQUATION

We consider a pure liquid, occupying the layer $\zeta > z > -h$, on whose free surface, at $z=\zeta(x)$, heat is absorbed with flow density Q. In a state of rest we have $\zeta \equiv 0$, and in the layer there is a constant temperature gradient

$$dT_0/dz = Q/\varkappa, \quad \varkappa = \rho c \chi, \tag{1}$$

where ρ is the density, c is the specific heat, and $\varkappa$ is the thermal conductivity of the liquid.

We shall investigate the stability of the stationary state of the layer with the temperature profile (1), supposing the liquid to be incompressible. For this purpose, we linearize in the usual way the Navier-Stokes and heat-conduction equations; introducing a scalar potential φ and vector potential $\mathbf{A}$ of the velocity, we get the system of equations

$$\Delta\varphi=0, \quad \frac{\partial}{\partial t}\mathbf{A}=\nu\Delta\mathbf{A}, \quad \operatorname{div}\mathbf{A}=0, \tag{2}$$

$$\frac{\partial}{\partial t}T_1+v_z\frac{d}{dz}T_0=\chi\Delta T_1, \quad \mathbf{v}=\nabla\varphi+\operatorname{rot}\mathbf{A}$$

with the boundary conditions at $z=0$[5]

$$\rho\frac{\partial^2\varphi}{\partial t^2}-\alpha\left(\frac{\partial^2 v_z}{\partial x^2}+\frac{\partial^2 v_z}{\partial y^2}\right)+\rho g v_z+2\eta\frac{\partial^2 v_z}{\partial t\,\partial z}=0, \tag{3}$$

$$\frac{d\alpha}{dT}\left(\frac{\partial^2 T}{\partial t\,\partial x}+\frac{dT_0}{dz}v_z\right)=\eta\frac{\partial}{\partial t}\left(\frac{\partial v_x}{\partial z}+\frac{\partial v_z}{\partial x}\right), \tag{4}$$

$$\varkappa\frac{dT}{dz}=Q. \tag{5}$$

At $z=-h$, we have $T=\text{const}$, $v=0$.

We shall seek a solution of the system (2) in the form

$$\varphi=\varphi(z)e^{ikx+\gamma t}, \quad A_y=A(z)e^{ikx+\gamma t}, \quad T_1=T_1(z)e^{ikx+\gamma t}.$$

Substituting these expressions in (2), we obtain the equations for the amplitudes:

$$\left(\frac{d^2}{dz^2}-k^2\right)\varphi(z)=0, \quad \left(\frac{d^2}{dz^2}-k_1^2\right)A(z)=0,$$
$$\left(\frac{d^2}{dz^2}-k_2\right)T_1(z)=-\frac{dT_0}{dz}\left(\frac{d\varphi}{dz}-ikA(z)\right). \tag{6}$$

Here $k_{1,2}=(k^2+\gamma/\nu,\chi)^{1/2}$; $\eta=\rho\nu$ is the viscosity of the liquid. By substituting the solution of the system of Eqs. (6) in the boundary conditions (3)–(5), it is not difficult to obtain a dispersion equation, which, however, is in general extremely cumbersome. Therefore we shall hereafter consider certain limiting cases.

3. WAVES ON THE SURFACE OF A DEEP LIQUID ($kh\gg 1$)

In the limiting case $kh\to\infty$, the dispersion equation has the form

$$-\frac{k^2}{\eta\chi}\frac{d\alpha}{dT}\frac{dT_0}{dz}\left[\frac{\chi}{\gamma}-\frac{1}{k_2(k_1+k_2)}-\frac{\omega_0^2+2\gamma\nu kk_1}{\omega_0^2+\gamma^2+2\gamma\nu k^2}\right.$$
$$\left.\times\left(\frac{\chi}{\gamma}-\frac{1}{k_2(k+k_2)}\right)\right]=2k^2\frac{\omega_0^2+2\gamma\nu kk_1}{\omega_0^2+\gamma^2+2\gamma\nu k^2}-k^2-k_1^2, \tag{7}$$

where $\omega_0^2=gh+\alpha k^3/\rho$ is the frequency of a gravitational-capillary wave. When $dT_0/dz=0$, (7) reduces to the usual equation for gravitational-capillary waves with damping.[5]

We shall seek a solution of (7) on the assumption that $\chi k^2/|\gamma|\ll 1$ but $P\equiv\nu/\chi\sim 1$. In the zeroth approximation, neglecting all terms that contain a small parameter, we get

$$(\gamma^2+\omega_0^2)(\gamma^2+c^2k^2)=0,$$
$$c^2=\frac{1}{\rho}\left|\frac{d\alpha}{dT}\right|\frac{dT_0}{dz}(1+P^{1/2})^{-1}. \tag{8}$$

This equation has solutions $\gamma_1 = \pm i\omega_0$ and $\gamma_2 = \pm ick$; γ_1 corresponds to the usual gravitational-capillary waves, whereas γ_2 represents the frequency of a new surface mode, which occurs only under nonuniform heating of the liquid, when $dT_0/dz > 0$. With the opposite sign of the temperature gradient, c becomes pure imaginary, which corresponds to the aperiodic thermocapillary instability of a liquid found by Pearson.[6] We note that, in contrast to a gravitational-capillary wave, during propagation of a "thermocapillary" oscillation with $c^2k^2 \ll \omega_0^2$ no displacement of the liquid surface occurs.

We shall find corrections for the discarded terms in the frequencies $\gamma_{1,2}$. Substituting in (7) $\gamma_1 = -i\omega_0 + \delta_1$, where $|\delta_1| \ll \omega_0$, we get

$$\delta_1 = -\nu k^2\left(2 + \frac{c^2k^2(P^{-1/2}+2)}{\omega_0^2 - c^2k^2}\right) + \frac{1}{2}\frac{c^2k^2(1+P^{1/2})\omega_0}{\omega_0^2 - c^2k^2}e^{-i\pi/4}\left(\frac{\chi k^2}{\omega_0}\right)^{1/2}. \quad (9)$$

It follows from (9) that when $\omega_0 > ck$, for waves with a prescribed value of k there is a threshold value of the density of heat flow, such that when it is exceeded the wave becomes unstable. The minimum threshold corresponds to an oscillation with $k = k_c = (5a)^{-1/2}$ and $\omega_c = \omega_0(k_c)$, where $a^2 = \alpha/\rho g$, and is equal to

$$Q_m = 2^{5/2}\eta\varkappa\left(\frac{\omega_c^3}{\chi k_c^2}\right)^{1/2}\left|\frac{d\alpha}{dT}\right|^{-1}.$$

Near the threshold of instability,

$$c^2k^2 \sim P\omega_0^2(\chi k^2/\omega_0)^{1/2} \ll \omega_0^2.$$

In this case, an expression for the growth rate (9) can be obtained from simple energy considerations. Namely, we assume that on the surface of the liquid there is propagated a gravitational-capillary wave described by the velocity potential

$$\varphi = \mathrm{Re}[\varphi_0 \exp(ikx - i\omega_0 t + kz)]. \quad (10)$$

The propagation of the wave is accompanied by a slight change of temperature of the liquid, $T_1 = T - T_0$, which is determined by Eq. (6) and the boundary condition (5):

$$T_1 = \mathrm{Re}\left[-i\frac{k\varphi_0}{\omega_0}\frac{dT_0}{dz}\left(e^{kz} - \frac{k}{k_2}e^{k_2 z}\right)\exp(ikx - i\omega_0 t)\right]. \quad (11)$$

With such a distribution of temperature, the surface of the liquid is heated nonuniformly, and there arises a thermocapillary force acting on the liquid

$$\frac{d\alpha}{dT}\frac{\partial T_1}{\partial x}.$$

The change of mechanical energy of the liquid under the action of this force is given by the expression

$$\frac{d}{dt}E_{\mathrm{mech}} = \int dx\, v_x \frac{d\alpha}{dT}\frac{\partial T_1}{\partial x}.$$

On substituting (10) and (11) and allowing for the usual viscous damping, we find for $\chi k^2 \ll \omega_0$

$$\frac{d}{dt}E_{\mathrm{mech}} = -\frac{d\alpha}{dT}\frac{k^2}{\sqrt{2}\rho\omega_0}\left(\frac{\chi k^2}{\omega_0}\right)^{1/2}\frac{dT_0}{dz}E_{\mathrm{mech}} - 4\nu k^2 E_{\mathrm{mech}} \quad (12)$$

It is easy to see that the expression for the instability growth rate that follows from (12) agrees with (9) when $c^2k^2 \ll \omega_0^2$.

Substituting in (7) $\gamma_2 = -ick + \delta_2$, we get

$$\delta_2 = \frac{\nu k^2 c^2 k^2}{\omega_0^2 - c^2k^2}\left(1 + \frac{1+P^{1/2}}{4P^{1/2}}\left(3 + \frac{\omega_0^2}{c^2k^2}\right)\right) - \frac{1}{2}\frac{ck(1+P^{1/2})}{\omega_0^2 - c^2k^2}e^{-i\pi/4}\left(\frac{\chi k^2}{ck}\right)^{1/2}\left(gk + \frac{\alpha}{\rho}k^3\right). \quad (13)$$

As follows from this expression, the surface thermocapillary mode is weakly attenuated at small k, i.e., $|\mathrm{Re}\,\delta_2| \ll ck$; and in the region where $c^2k^2 > \omega_0^2$, it becomes unstable.

In the region of intersection of the two modes, when $\omega_0^2 \approx c^2k^2$, the expressions (9) and (13) are no longer applicable. The instability growth rate increases abruptly on approach to resonance, and for $\omega_0^2 = c^2k^2$ it is given by the expression

$$\mathrm{Re}\,\delta = \frac{\omega_0}{2}(1+P^{1/2})^{1/2}\sin\frac{\pi}{8}\left(\frac{\chi k^2}{\omega_0}\right)^{1/4}. \quad (14)$$

The wave spectrum and growth rate in this case are shown in Fig. 1. The branches of the oscillations that have the larger frequency are unstable.

4. WAVES IN A LIQUID LAYER OF FINITE DEPTH

In the long-wavelength range, when $kh \lesssim 1$, the general dispersion equation can be simplified in the same way as was done in the preceding section for $h \to \infty$. Assuming that $(\chi k^2/\gamma)^{1/2} \ll 1$ and $(\chi/h^2\gamma)^{1/2} \ll 1$, we get instead of (7)

$$(\gamma^2 + c^2k^2 + 2\gamma\nu k^2 + c^2k^2\nu k^2(1+P^{1/2})/2\gamma P^{1/2})\left(\gamma^2 + \omega^2 + 2\nu k^2\gamma - \frac{k}{k_1}(\gamma^2\,\mathrm{th}\,kh + 2\nu k^2\gamma\,\mathrm{th}\,kh + \omega_0^2)\right) = (\omega_0^2 + 2\nu k k_1\gamma)\left(c^2k^2(1+P^{1/2}) \times \frac{k}{k_2}\left(1 - \frac{k}{k_1}\mathrm{th}\,kh\right) + 2\nu k^2\gamma\left(\mathrm{th}\,kh - \frac{k}{k_1}\right)\right), \quad (15)$$

where $\omega^2 = \omega_0^2 \tanh kh$.

We seek a solution of (15) in the form $\gamma = -i\omega + \delta_1$. For $\mathrm{Re}\,\delta_1$ we get the expression

$$\mathrm{Re}\,\delta_1 = -\frac{(\nu k^2\omega)^{1/2}}{\sqrt{2}\,\mathrm{sh}\,2kh} + \frac{c^2k^2\omega_0^2(1+P^{1/2})}{2\sqrt{2}\,\omega(\omega^2 - c^2k^2)}\left(\frac{\chi k^2}{\omega}\right)^{1/2}, \quad (16)$$

from which we can find the threshold value of the density of heat flow for excitation of a wave with wave number k:

$$Q_c(k) = \rho\varkappa g\left|\frac{d\alpha}{dT}\right|^{-1}\frac{(1+a^2k^2)\,\mathrm{th}\,kh\,(1+P^{1/2})}{k(1+(1+P^{-1/2})\,\mathrm{ch}^2\,kh)}. \quad (17)$$

Hence it follows that when

$$a^2 > h^2[1/3 + (1+P^{1/2})(1+2P^{1/2})^{-1}]$$

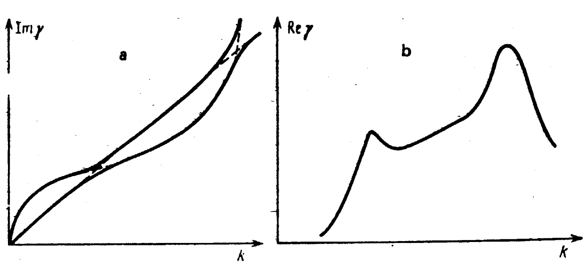

FIG. 1. Frequency (a) and instability growth rate (b) of surface waves for large excess of the density of energy flow above the threshold value.

the minimum value of the threshold is attained when $k=0$ and is

$$Q_c(0)=\frac{\rho\varkappa gh(1+P^{1/2})}{1+2P^{1/2}}\left|\frac{d\alpha}{dT}\right|^{-1}. \tag{18}$$

We note that under the conditions of applicability of the approximations made, i.e., $(\chi/h^2\omega)^{1/2}\ll 1$, the value of $Q_c(0)$ exceeds the value of the threshold power Q_m for an infinitely deep liquid. This is due to an increase of dissipation near the bottom. When

$$a^2<h^2(1/_3+(1+P^{1/2})/(1+2P^{1/2}))$$

the minimum value of the threshold power corresponds to a finite value of k, determined by the expression (17).

With increase of the density of heat flow, the frequency of gravitational-capillary waves may become less than ck; in this case $\mathrm{Re}\,\delta_1<0$, but the thermocapillary waves are unstable. The instability increment in the limit $c^2k^2\gg\omega_0^2\tanh kh$ is given by the expression (13) with ω_0 replaced by ω.

5. NONLINEAR STAGE OF DEVELOPMENT OF INSTABILITY

For small excesses over the instability threshold, it may be supposed that only one surface wave is formed and that the growth of its amplitude is described by the equation

$$\frac{d}{dt}|\varphi_k|^2=2\gamma|\varphi_k|^2. \tag{19}$$

The value of the growth rate γ in this expression can be expanded in powers of the amplitude[5]:

$$\gamma=\mathrm{Re}\,\delta_1+\beta|\varphi_k|^2+\dots. \tag{20}$$

In order to find the coefficient β, we shall use an energy method and shall calculate the difference between the workper unit time of the thermocapillary forces acting on the nonlinear wave and the power of the energy being dissipated. We consider the case $kh\gg 1$.

To solve this problem, it is convenient to go over to variables φ and ψ (the potential and the stream function), in terms of which the coordinates x and z in a reference system attached to the traveling wave are expressed as follows[7]:

$$kx=-\frac{k\varphi}{v_{ph}}-\varepsilon\exp\left(-\frac{k\psi}{v_{ph}}\right)\sin\frac{k\varphi}{v_{ph}}-A\varepsilon^2\exp\left(-\frac{2k\psi}{v_{ph}}\right)\sin\frac{2k\varphi}{v_{ph}}+\dots,$$
$$kz=-\frac{k\psi}{v_{ph}}+\varepsilon\exp\left(-\frac{k\psi}{v_{ph}}\right)\cos\frac{k\varphi}{v_{ph}}-\varepsilon+A\varepsilon^2\left(\exp\left(-\frac{2k\psi}{v_{ph}}\right)\cos\frac{2k\varphi}{v_{ph}}-1\right)$$
$$A=(2-k^2a^2)/2(1-2k^2a^2), \tag{21}$$

where $\varepsilon=k\zeta_0$, ζ_0 is the amplitude of the displacement of the surface, and v_{ph} is the phase velocity of the wave. In (21), terms of order ε^2 have been retained.[1)]

The heat-conduction equation in the variables φ and ψ takes the form

$$-\frac{\partial T}{\partial\varphi}=\chi\left(\frac{\partial^2}{\partial\varphi^2}+\frac{\partial^2}{\partial\psi^2}\right)T, \tag{22}$$

and the boundary condition at the surface, which expresses the law of conservation of energy, reduces to the expression

$$\left.\frac{dT}{d\psi}\right|_{\psi=0}=-\frac{Q}{\varkappa}\left.\frac{\cos\theta}{v}\right|_{\psi=0},\quad \cos\theta=v\frac{dx}{d\varphi}. \tag{23}$$

Here we have assumed that outside the liquid, the energy-flow vector remains constant.

The work per unit time by the thermocapillary forces, R_α, and by the viscous forces, R_η, can be transformed to the form

$$R_\alpha=\frac{d\alpha}{dT}\int dl\,v\frac{\partial T}{\partial l}=-\frac{d\alpha}{dT}\int d\varphi|v|\frac{dT}{d\varphi},$$
$$R_\eta=\eta\int d\varphi\frac{\partial v^2}{\partial\psi}, \tag{24}$$

where dl is an element of length of the distorted surface of the liquid. The modulus of the velocity $|v|$, which enters in (23) and (24), is expressed in terms of the variable φ ($\psi\equiv 0$)[7]:

$$|v|=v_{ph}\left[1+\frac{\varepsilon^2}{4}-\cos\frac{k\varphi}{v_{ph}}\left(\varepsilon+\frac{1}{8}\varepsilon^3-\frac{1}{2}M\varepsilon^3\right)\right.$$
$$\left.-\left(\varepsilon^2M-\frac{1}{4}\varepsilon^2\right)\cos\frac{2k\varphi}{v_{ph}}\right],\quad M=3/2(1-2k^2a^2). \tag{25}$$

Solving the heat-conduction Eq. (22) with the boundary condition (23) and substituting in (24), with the help of (25) we get an expression for the instability increment:

$$\gamma=2\nu k^2\left[\frac{Q-Q_t}{Q_t}+\frac{\varepsilon^2}{2^{1/2}}\frac{2-k^2a^2}{1-2k^2a^2}\left(\frac{3}{1-2k^2a^2}-\frac{1}{2}\right)\right.$$
$$+\frac{\varepsilon^2}{4}\left(\frac{1}{2}-\frac{3}{1-2k^2a^2}\right)-\frac{\varepsilon^2}{2}\left(\frac{3}{1-2k^2a^2}-1\right)$$
$$\left.-\frac{7\varepsilon^2}{32}\frac{8+k^2a^2+2k^4a^4}{(1+k^2a^2)(1-2k^2a^2)}\right]. \tag{26}$$

Here $Q_t(k)$ is the threshold value of the density of energy flow absorbed at the surface. For the value $k=k_c=1/a\sqrt{5}$, corresponding to the minimum threshold of the heat flow, one can get from (26)

$$\gamma_c=2\nu k_c^2\left(\frac{Q-Q_m}{Q_m}-2.7\,k_c^2\zeta_0^2\right). \tag{27}$$

As follows from this expression, in the system considered there occurs soft excitation of a surface wave, whose amplitude is limited by nonlinear hydrodynamic effects (basically in consequence of strong damping of the higher harmonics because of viscosity), at a level $\zeta_0\sim a(Q/Q_t-1)^{1/2}$.

It is easy to see that the development of instability of surface waves leads to a lowering ΔT of the temperature of the surface of the liquid; that is, to an effective increase of the coefficient of thermal conductivity in the surface layer. On averaging the value of the temperature along the surface, we find

$$\Delta T=-\varepsilon^2\frac{Q_t}{2\varkappa}\left(\frac{\chi}{2\omega}\right)^{1/2}.$$

We note that the expansion (26), (27) is correct under the condition $k^2\zeta^2\ll 1$, whereas $\zeta^2\omega/\delta$ may be arbitrary. Solution of the heat-conduction equation with this accuracy in powers of the surface displacement would require summing an infinite number of terms of a series of the form $\Sigma\, a_n(\zeta^2\omega/\chi)^{n/2}$. Transformation to the variables φ and ψ in Eq. (22) enabled us to avoid this.

6. CONCLUSION

We shall give estimates of the threshold for occurrence of instability of capillary-gravitational waves for values of the parameters typical for laser processing of metals.[2-4] Taking into account that in these experiments the thickness of the liquid film is usually less than the capillary constant, we shall use the expression (17) for estimates of Q_c. Thus in the case of iron with $h \sim 0.1$ cm, $hk \sim 1$ we get $Q_c \approx 3$ kW/cm^2, which is below the usually used densities of radiation flow.

In this paper we have neglected processes of evaporation from the surface of the liquid. As was shown in Ref. 8, allowance for evaporation leads to instability of the interference between phases at power flows larger than 10^6 W/cm^2 (for metals). As is shown by the estimate given, instability of the liquid surface may occur at considerably smaller densities of radiation flow.

We note that formation of capillary waves on the surface of a metal melt was observed in Ref. 3. We shall estimate the values of the wavelengths corresponding to the maximum instability growth rate for the conditions of the experiment of Ref. 3. The largest growth rate corresponds to waves that are in resonance, $ck \approx \omega_0$. Hence

$$k \approx \frac{Q}{\varkappa\alpha}\left|\frac{d\alpha}{dT}\right| \Big/ (1+P^{1/2}) \sim 5 \cdot 10^2 \text{ cm}^{-2}$$

for $Q \sim 5 \cdot 10^5$ W/cm^2. The instability growth rate corresponding to surface waves of such lengths is equal, according to (14), to $\mathrm{Re}\,\delta \sim 5 \cdot 10^4$ sec^{-1}. The wavelength values $\lambda = 2\pi/k \approx 3 \cdot 10^{-3}$ cm are close to those observed experimentally, while the corresponding instability growth rate exceeds the reciprocal of the time of action of the laser beam on the metal surface.[3] Thus we see that under the conditions of the experiment[3] the instability investigated in this paper could occur.

In conclusion, we note that at large excesses over the threshold radiation power, there may originate in the liquid nonlinear waves or turbulence of the surface waves. In both cases, this may lead to a substantial change of the conditions of reflection and absorption of radiation at the surface and may affect the processes of heat and mass transport in the liquid.

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[1)]In the calculation of $dx/d\varphi$ from (21), terms of the order ε^3 are proportional to sin $3k\varphi$ and, with the accuracy under consideration, make no contribution to the integral (24).

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