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To cite this version:

HAL Id: jpa-00220588
https://hal.archives-ouvertes.fr/jpa-00220588
Submitted on 1 Jan 1980

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RESPONSE OF RADIATION-INDUCED EVAPORATION TO THERMAL AND HYDRODYNAMIC PERTURBATIONS

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Abstract.- A linear response of the steady-state evaporation process is investigated for liquids absorbing intense radiation. Thermal and hydrodynamic perturbations are considered. In the case of the thermal perturbations due to intensity modulation the vaporization pressure response shows a resonant behaviour with respect to the modulation frequency. The hydrodynamic (ripplon-like) perturbation results in differential pressure recoil which plays an essential role in the stability problem of evaporating liquid surface. Dispersion relation is obtained for ripplons in rapidly evaporating liquids.

One dimensional heat conduction equation is widely used for description of radiation-induced phase transitions in absorbing condensed matter (see, e.g., [1] and references therein). However, applicability limits of the approach are not well defined. This approach also involves some essential hypothesis about nonequilibrium phase transitions which require further investigations both theoretical and experimental. For this reason it is useful to study such properties of the model which can directly manifest themselves in experiments.

Vaporization pressure behaviour is one of the sensitive characteristic of radiation-induced vaporization process. In this paper an expression for linear pressure response to harmonic modulation of the radiation intensity is derived. This expression shows some specific features pertinent to the conduction approach and can be verified experimentally.

If the radiation intensity $I_0\exp(i\omega t)$ is modulated near the constant value $I_0 \gg 1$ then the linearized conduction problem for the disturbed part of the temperature $\Delta T(x,t)$ can be written as follows:

$$\frac{\partial^2 \Delta T}{\partial t^2} - v \frac{\partial \Delta T}{\partial x} - X_\rho \frac{\partial \Delta T}{\partial x} = \frac{\partial^2 \Delta T}{\partial x^2} + \frac{C_0}{\rho_0} \Delta T \exp(\Delta \phi - i\omega t)$$

$$C_0 \frac{\partial^2 \Delta T}{\partial x^2} \bigg|_{x=0} = (\nu_x)^2 \Delta T_0, \quad T(\infty,t) = 0 \quad (4)$$

where $\Delta T_0(x)$ is unperturbed temperature distribution:

$$T_0 = T_0 \left( \frac{q - \Delta \phi}{q - \Delta \phi} \right) + A \exp(-\Delta \phi) \right), \quad q = \frac{1}{(\nu x/L+C T_0)} \left( \frac{q - \Delta \phi}{q - \Delta \phi} \right), \quad (2)$$

$$I_0 = \rho \nu (L + C T_0)$$

In (1) the reference frame is used which moves together with the vaporization front, its velocity $\nu \nu T_0 \Delta T_0$ being supposed to depend only on surface temperature $T_0$. Heat capacity $C_0$, thermal conductivity $\chi = \chi_0 C_0$ and diffusivity $\chi$ are approximated by the constants the latent heat of vaporsion $L$ depends on the surface temperature, prime ($\prime$)
means differentiating with respect to $T_{0}$. 
The absorption coefficients $\alpha_{0}$ and $\alpha$ for the main and modulated parts of the radiation may be different from each other.

For the steady-state surface temperature oscillations $T_{S}$ from (1) it follows

$$T_{S} = \frac{1}{\rho} \exp(i\omega t) \rho [s(L+C\Theta_{0})]'$$

$$f = (q_{0} - \alpha_{0})v[L + q_{0}(p_{0} - \alpha_{0})]n_{4}(\alpha_{0} - \alpha_{0})n_{2}^{-1},$$

$$n_{4} = \alpha_{4}r(L+C\Theta_{0})/(i\omega + \alpha_{0} - \alpha_{0}),$$

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For large values $\varepsilon$, $f_{M}$ diverges as $\sqrt{\varepsilon}$ at $q=1$ and remains finite if $\varepsilon<1$. The divergence of $f_{M}$ is due to the one dimensional instability of the temperature distribution at $L^{+}c \leq 0$ and $\varepsilon \gg 1$.

In particular, if $L^{+}c>0$, $\varepsilon<1$ and $\varepsilon_{o}<\varepsilon$, then from (3) it follows

$$T_{S} = f \frac{1}{\rho} \exp(i\omega t) \rho [s(L+C\Theta_{0})]'$$

$$f = (q_{0} - \alpha_{0})v[L + q_{0}(p_{0} - \alpha_{0})]n_{4}(\alpha_{0} - \alpha_{0})n_{2}^{-1},$$

$$n_{4} = \alpha_{4}r(L+C\Theta_{0})/(i\omega + \alpha_{0} - \alpha_{0}),$$

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This expression shows explicitly the threshold meaning of the condition $L^{+}c = 0$.

A thermal expansion of irradiated liquid contributes as well to the total pressure recoil. This contribution $p_{E}$ can be estimated from the relation...
\[ P_e = \beta P_0 \omega T_s k^4 \]

where \( \beta \) is thermal expansion coefficient and \( h \) denotes an average thickness of the expanded layer.

For the surface absorption case \( k^2 \sim \chi / \omega \) so that \( P_e \) grows approximately as \( \omega^{1/2} \) while the surface pressure \( P \) diminishes like \( \omega^{-1/2} \) in the high frequency limit. These values of \( \rho \) and \( P_e \) become comparable with each other at frequency \( \omega = \rho / \rho \chi \) which can be as high as \( 10^8 \) s\(^{-1}\) if, e.g., \( \beta = 10^4 \), \( \rho = 10^4 \), \( \chi = 0.1 \), \( \rho = 10^4 \), in CGS units.

The corresponding frequency can be considerably lower for the bulk absorption \( \omega^2 = \rho \chi / \rho \beta \) provided the absorption coefficient is sufficiently small \( \chi < \omega / \chi \). In this case, however, the main features of vaporization process depend strongly on the behavior of superheated metastable liquid[2].

The available experimental data on radiation-induced pressure behavior[2-6] are too scarce to give a definite picture of the phase transition in superheated liquid with a free surface. Further investigations are needed, e.g., to distinguish between surface and bulk evaporation processes. The pressure response to the intensity modulation can be probably used for this purpose.

It is well known also that a planar phase front becomes unstable for the phase transitions which involve metastable states (see, e.g.,[7]).

Surface temperature response to the time- and space-modulated intensity \( I_{\exp}(\omega t - i \chi x) \) can be considered in the same way as described above. An expression for \( f(\omega, k) \) is obtained straightforwardly from eq. (3) after replacement of \( n_1 \) and \( n_2 \) by the factor \( 1 + i \omega / \chi \).

An existence condition for nontrivial solution \( T_s(\omega, k) \) at \( I = 0 \) gives a dispersion relation for thermal perturbations of the planar vaporization front. For liquids, however, the hydrodynamic motion of the surface adjacent layer should be taken into account [1].

The hydrodynamic motion modulates the surface temperature distribution, which gives rise to the differential pressure recoil. If the perturbation of a liquid velocity has a ripplon-like form

\[ u = u_0 \exp(i \omega t - i \chi x - i \varepsilon) \]  

then the linear response of the surface temperature is as follows

\[ T_s = \frac{\chi(\omega, k) u_0(x, 0, t)}{\omega}, \]

\[ Y = \frac{T_{0s}(F - E)}{\chi - \chi_0} \]

\[ E = \frac{\chi_0(q_0 - q_0)}{\omega + \chi_0(q - \phi)} + \frac{q_0(q_0 - q_0)}{\omega - \chi_0(q - \phi)} \quad \text{(8)} \]

\[ F = \frac{\chi_0(q_0 - q_0)}{\omega + \chi_0(q - \phi)} + \frac{q_0(q_0 - q_0)}{\omega - \chi_0(q - \phi)} \]

\[ q_1 = \chi + \chi_0, \quad q_2 = \chi + \chi_0. \]

For nonviscid and incompressible liquids this modulation results in dispersion relation for the surface waves.
\[ \omega^2 = \omega_0^2 - i \omega \kappa \rho \nu / \rho \nu' \quad (9) \]

where \( \omega_0(\kappa) \) is the unperturbed frequency of the surface waves.

Equation (9) can be analysed in general only numerically, though in some limiting cases stable and unstable analytic solution are also obtainable.

If, e.g., \( x_k \kappa \omega k \kappa^2 \) and \( q < \alpha \) then from (8), (9) one has

\[ \omega^2 = \omega_0^2 + i \omega \kappa \kappa^2 \alpha \quad (10) \]

This perturbation is stable because \( \alpha > 0 \).

In the case of small absorptivity \( \alpha < q \), one finds instead of (11)

\[ \alpha = \rho' C_T / \rho \nu [\alpha(L + c T_0)]' \quad (11) \]

This corresponds to the unstable case provided \( L' + c > 0 \). An absolute value of the parameter \( \alpha \) is much greater than unity because \( \rho' \gg \rho \nu^2 \). For intensive evaporation process the factor \( \rho' / \rho \nu^2 \) is proportional to the liquid-vapor density ratio \( \rho / \rho \nu \).

This factor shows clearly the important role of hydrodynamic movement in the stability problem of evaporating liquid surface. There is no such factor in the expression for thermal perturbations which are obtained without proper account of hydrodynamics.

It should be mentioned in conclusion that in the linearized approach the considered instabilities do not contribute to the surface pressure averaged over sufficiently large irradiation spot.

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