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On the theory of explosive boiling of a transparent liquid on a laser-heated target

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Abstract

The possible manifestations of thermodynamical instability (explosive vaporisation) are discussed for different regimes of laser heating of the metal/transparent liquid system. The present calculations show that the explosive vaporisation in the metastable region may occur if the nucleation rate is high enough. This condition is achievable if the surface tension of the superheated liquid tends to zero near the spinodal. It is also shown that the dependence of the phase explosion time on laser intensity markedly changes its behaviour when the water temperature reaches the spinodal.

Keywords: Laser heating; Explosive vaporisation; Spinodal

1. Introduction

Superheated or supercooled states are one of the characteristic features of the first-order non-equilibrium phase transitions. The phase transition of a superheated metastable liquid into vapour is accompanied by a sharp pressure increase and for this reason called "explosive boiling" [1]. A deep enough penetration into the metastable region is the condition for the explosive boiling to occur. It may be achieved, for instance, by increasing the temperature, while the pressure remains constant or changes insignificantly (see ref. [2] and references therein). Since the upper and lower metastability boundaries (binodal and spinodal) depend on pressure, penetrating into the metastable region can be also realized by a pressure drop at a relatively constant temperature [3,4]. Fast heating of a liquid is unavoidably associated with the pressure increase. That is why the temperature rise as well as the pressure decrease (after its initial increase) under pulsed laser action can provoke the explosive boiling [5]. Different modes of explosive boiling over a large range of laser intensities and pulse durations were discussed in several papers [6–15]. Nevertheless, as far as we know, a comprehensive analysis of explosive boiling has not yet been carried out. For example in ref. [8] devoted to experimental investigation of the mercury boiling-up in an optoacoustic cell under laser irradiation of its surface, the superheated metastable states are mentioned, but along with this, the authors locate the mercury boiling-up process at the contact surface with the glass on the binodal. In ref. [10] the possibility of appearance of a superheated metastable state in a transparent liquid in the vicinity of the laser-heated substrate surface is not treated.

In the present paper, the conditions for realisation of the explosive boiling are considered, depending on the laser pulse intensity and duration.

2. Mathematical model

It is suggested that the substrate thickness l_1 and the thickness of the adjacent transparent liquid layer l_2 are large enough as against the spatial length of the generated acoustic pulses. In this case, the temperature and pressure behaviour of the liquid/substrate system can be described by a complete system of hydrodynamic equations for the substrate and the liquid located in the right-hand $z > 0$ and in the left-hand side $z < 0$, respectively. Linear approximations of the continuity,

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Euler and energy equations [7] are applied to obtain analytical expressions for the pressure signals

$$\frac{\partial \rho}{\partial t}+\rho_0\frac{\partial v}{\partial z}=0, \qquad \rho_0\frac{\partial v}{\partial t}+\frac{\partial P}{\partial z}=0, \tag{1}$$

$$\rho_0 T_0\frac{\partial s}{\partial t}=\frac{\partial}{\partial z}\left(\kappa\frac{\partial T}{\partial z}\right)+\alpha I, \tag{2}$$

where P, ρ, T, s and v represent the pressure, density, temperature, entropy and velocity perturbations related to their unperturbed values P_0, ρ_0, T_0, s_0 and $v_0 = 0$, while κ, α and I are the thermal conductivity and absorption coefficients and the absorbed radiation intensity $I = I_0(t)\,e^{-\alpha z}$, respectively.

It is obtained directly from Eqs. (1) and (2) that

$$\frac{\partial^2 P}{\partial z^2}=\frac{1}{v_s^2}\frac{\partial^2 P}{\partial t^2}-\frac{\varepsilon}{c_P}\left\{\frac{\partial}{\partial z}\left(\kappa\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial t}\right)\right)+\alpha\frac{\partial I}{\partial t}\right\}, \tag{3}$$

since, accordingly to the state equation $\rho = \rho(P, s)$ and Eq. (2)

$$\begin{aligned}\frac{\partial^2 \rho}{\partial t^2}&=\left(\frac{\partial \rho}{\partial P}\right)_s\frac{\partial^2 P}{\partial t^2}+\left(\frac{\partial \rho}{\partial s}\right)_P\frac{\partial^2 s}{\partial t^2}\\&=\frac{1}{v_s^2}\frac{\partial^2 P}{\partial t^2}-\frac{\varepsilon}{c_P}\left\{\frac{\partial}{\partial z}\left(\kappa\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial t}\right)\right)+\alpha\frac{\partial I}{\partial t}\right\},\end{aligned} \tag{4}$$

where v_s is the sound velocity in the medium $v_s^2=\left(\frac{\partial P}{\partial \rho}\right)_s$, c_P the heat capacity at constant volume and $\varepsilon=-\frac{1}{\rho_0}\left(\frac{\partial \rho}{\partial T}\right)_P$ is the matter thermal expansion coefficient. In deriving Eq. (4) it was taken into account that

$$\left(\frac{\partial \rho}{\partial s}\right)_P=\left(\frac{\partial \rho}{\partial T}\right)_P\left(\frac{\partial T}{\partial s}\right)_P=-\rho_0\varepsilon\left(\frac{\partial T}{\partial s}\right)_P=-\rho_0\varepsilon\frac{T_0}{c_P}. \tag{5}$$

If the thermal penetration depth into the substrate z_1 achieved in one laser pulse t (defined by the absorption length $1/\alpha$ or the temperature influence $\sqrt{\chi\tau}$ as $z_1 = \max(1/\alpha, \sqrt{\chi\tau})$, where χ is the temperature conductivity coefficient) turns out to be small compared to the characteristic wavelength $z_2 = v_s\tau$ of the generated acoustic pulse, matter density variation under pressure (term $\frac{1}{v_s^2}\frac{\partial^2 P}{\partial t^2}$ in Eq. (3)) in the heated zone may be neglected. In this limit, the expression for the pressure $P(z, t)$ in the region $z_1 \le z^* \le z_2$ follows from Eq. (3):

$$\begin{aligned}P(z^*,t)&=P_0+\int_0^{z^*}\int_{z'}^{z^*}\left(\frac{\partial^2 P}{\partial z^2}\right)dz''\\&=P_0+\frac{\varepsilon}{c_P}\left(\kappa\frac{\partial T}{\partial t}\bigg|_{z=0}+\frac{1}{\alpha}\frac{\partial I_0(t)}{\partial t}\right).\end{aligned} \tag{6}$$

In deriving Eq. (6), it was assumed that the absorbed laser pulse intensity, temperature perturbations and their related pressure perturbations in the region $z_1 \le z^* \le z_2$ can be put equal to zero.

Since the pressure $P(z^*, t) = P(t)$ in Eq. (6) is independent of z^*, it may be taken as a boundary condition for the acoustic wave which propagates inward in the substrate.

Once the substrate surface $z = 0$ is not free, then the value $P_0 \neq 0$ must be obtained by solving the complete hydrodynamic problem in the right-hand and left-hand sides under the condition of equality of pressures and densities at the interface. The interface drift velocity is determined by expansion of both media, $v_1=\varepsilon_1\int_{-z^*}^{0}\frac{\partial T_1}{\partial t}dz$ and $v_2=-\varepsilon_2\int_0^{z^*}\frac{\partial T_2}{\partial t}dz$, as well as by the acoustic pressures $P_1(-z^*, t)$ and $P_2(z^*, t)$ at the left (index "1") and at the right (index "2") to the interface, respectively. Taking into account the relation between pressure and velocity for the acoustic wave $P(z + v_{s1}t) = -(\rho_{01}v_{s1})v$ and $P(z - v_{s2}t) = -(\rho_{02}v_{s2})v$ at the left-hand and right-hand sides, the conditions for the velocity and pressure equality at the interface are:

$$\begin{aligned}&v_1-\frac{P_1(-z^*,t)}{a_1}=v_2+\frac{P_2(z^*,t)}{a_2},\\&P_1(0,t)=P_2(0,t)=P(0,t),\end{aligned} \tag{7}$$

where the symbols $a_1 = \rho_{01}v_{s1}$, $a_2 = \rho_{02}v_{s2}$, $P_1(-z^*,t)=P_1(0,t)+P_1^T$, $P_2(z^*,t)=P_2(0,t)+P_2^T$, $P_1^T=\frac{\varepsilon_1 K_1}{c_{P1}}\frac{\partial T_1}{\partial t}\big|_{z=0}$, $P_2^T=\frac{\varepsilon_2}{c_{P2}}\left(\kappa_2\frac{\partial T_2}{\partial t}\big|_{z=0}\right)+\frac{1}{\alpha}\frac{\partial I_0(t)}{\partial t}$ are introduced.

The pressure at the surface $P(0, t)$ and the pressure impulse in the substrate $P_2(t)$ are obtained from Eq. (7)

$$P(0,t)=P_0+\frac{a_1a_2}{a_1+a_2}(v_2-v_1)-\frac{a_1P_2^T}{a_1+a_2}-\frac{a_2P_1^T}{a_1+a_2}, \tag{8}$$

$$\begin{aligned}P_2(t)&=P_0(0,t)+P_2^T\\&=P_0+\frac{a_2(P_2-P_1)}{a_1+a_2}+\frac{a_1a_2}{a_1+a_2}(v_2-v_1),\end{aligned} \tag{9}$$

where

$$v_2-v_1=Q\left(\frac{\varepsilon_1}{\rho_{01}c_{P1}}-\frac{\varepsilon_2}{\rho_{02}c_{P2}}\right)+\frac{\varepsilon_2}{\rho_{02}c_{P2}}I_0(t), \tag{10}$$

$Q=\kappa_1\frac{\partial T_1}{\partial t}\big|_{z=0}=\kappa_2\frac{\partial T_2}{\partial t}\big|_{z=0}$ is the heat flux across the interface between the two phases and $P_0 = 1$ bar is the unperturbed pressure value. Note that given of the thermophysical parameters of both media have the same values, the apparent dependency on temperature in Eqs. (8)–(10) falls out.

If the contact heating of the transparent medium may be neglected ($\kappa_1 \ge 0$), Eqs. (8) and (9) become easier

$$\begin{aligned}P(0,t)&=P_0+\frac{a_1}{a_1+a_2}\frac{v_{s2}\varepsilon_2}{c_{P2}}I_0(t)-\frac{a_1}{a_1+a_2}\frac{\varepsilon_2}{c_{P2}}\\&\quad\times\left(\kappa_2\frac{\partial T_2}{\partial t}\bigg|_{z=0}+\frac{1}{\alpha}\frac{\partial I_0(t)}{\partial t}\right),\end{aligned} \tag{11}$$

$$\begin{aligned}P_2(t)&=P_0+\frac{a_1}{a_1+a_2}\frac{v_{s2}\varepsilon_2}{c_{P2}}I_0(t)+\frac{a_2}{a_1+a_2}\frac{\varepsilon_2}{c_{P2}}\\&\quad\times\left(\kappa_2\frac{\partial T_2}{\partial t}\bigg|_{z=0}+\frac{1}{\alpha}\frac{\partial I_0(t)}{\partial t}\right).\end{aligned} \tag{12}$$

For the general case, the temperature profile in a two-layer medium is given by the energy Eq. (2) under the condition of continuity at the interface for the temperature $T_1(0, t) = T_2(0, t) = T_0(t)$ and the heat flux $Q(t)$.