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30 June 1997

PHYSICS LETTERS A

Physics Letters A 231 (1997) 93–96

On gas-dynamic effects in time-dependent vaporisation processes

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Received 5 November 1996; revised manuscript received 26 December 1996; accepted for publication 17 March 1997

Communicated by M. Porkolab

Abstract

The linear response of a one-dimensional vaporisation process to modulated surface heating is considered with allowance for the back reaction of gas-dynamic perturbations in a subsonic vapour flow. It is shown that the gas-dynamic effects enhance the resonant behaviour of the response described earlier by Samokhin and Guskov [Phys. Lett. A 77 (1980) 344]. © 1997 Published by Elsevier Science B.V.

Keywords: Vaporisation; Knudsen layer; Gas dynamic; Vapour flow; Laser heating; Heat conduction

Vaporisation of condensed substances heated by laser or electron beams is widely used for various practical purposes. The theoretical description of these processes is complicated, in particular, due to the non-equilibrium nature of intense evaporation which manifests itself in metastable states of condensed and vapour phases as well as in Knudsen layer (KL) jumps adjacent to the evaporating surface. In the framework of fluid dynamics the KL is considered as a discontinuity where appropriate boundary conditions should be formulated to describe the

phase transition kinetics which depend on gas flow dynamics.

For sonic and supersonic vapour flow with Mach number $M \geq 1$ gas-dynamic effects are irrelevant to the condensed phase behaviour. The linear response of such vaporisation processes to a small modulation of the radiation intensity was considered in Ref. [1] in the framework of the one-dimensional heat conduction approach and it was shown that the surface pressure and temperature response has a resonant behaviour with respect to the modulation frequency. Resonances in laser penetration were observed later in different experiments [2–4]. Many effects can contribute to such a behaviour, e.g., plasma screening, melt expulsion [2–4]. In Ref. [4] it is shown that one-dimensional gas-dynamic effects at $M < 1$ also enhance the resonant-like response of the vaporisation

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tion process described earlier in Ref. [1] for the case $M = 1$.

Boundary conditions at the vaporisation front can be obtained from conservation laws for mass g_1 , momentum g_2 and energy g_3 fluxes if the nonequilibrium distribution function f_{ne} is known at the inner side of the KL. In phenomenological approaches f_{ne} is approximated by various model expressions [5–7]. Many papers (see, e.g., Refs. [5–11], and references therein) are devoted to theoretical and experimental investigations of the KL.

In Ref. [5] f_{ne} has the form of a shifted Maxwellian $f(n^*, u^*, T_z, T_{xy})$ with mean concentration n^* , mean velocity u^* along the z axis and two different temperatures T_z and T_{xy} for motion in the z direction and xy plane. These four parameters are subjected to three conditions: the mass $g_1^{(+)}$, momentum $g_2^{(+)}$ and energy $g_3^{(+)}$ fluxes evaluated with the help of f_{ne} in the positive velocity ($v_z \geq 0$) half-space should be the same as obtained with the help of the equilibrium (saturated) half-Maxwellian $f_0^{(+)} = f_0(n_s, T_s)$, $v_z \geq 0$, where n_s is the saturated vapour concentration at the surface with temperature T_s .

Another approach is used in Ref. [6] where the positive $f_{ne}^{(+)}$ part ($v_z \geq 0$) of f_{ne} is equal to $f_0^{(+)}(n_s, T_s)$, while $f_{ne}^{(-)}$ for particles moving to the surface $z = 0$ is proportional to the equilibrium shifted Maxwellian $f(n, u, T)$ at the outer side of the KL, $f_{ne}^{(-)} = \beta f(n, u, T)$, $v_z \leq 0$. The parameter $\beta(M)$ changes from 1 to 6.28 as M increases from 0 to 1. In this model g_1 , g_2 and g_3 have extrema at $M = 0.88$, 1.18, and 1.22 respectively, while in Ref. [5] all g_i have extrema at the same point $M = 1$.

This difference between Refs. [5] and [6] was pointed out in Ref. [7] where it was shown that a simple model with $f_{ne}^{(+)} = f_0^{(+)}(n_s, T_s)$ and $f_{ne}^{(-)} = \alpha^2 f_0(n_s, \alpha^2 T_s)$, $v_z \leq 0$ also gives extrema for all $g_i(M)$ at $M = 1$. The models with g_i extrema at $M = 1$ [5,7] seem to be more preferable than the model of Ref. [6].

Vaporisation boundary conditions determine $g_i(T_s, M)$ as functions of T_s and M . At phase equilibrium $M = g_1 = g_3 = 0$ and g_2 is the saturated vapour pressure $p_s(T_s)$. In the case of a time-dependent surface temperature $T_s = T_0 + \delta T_s e^{i\omega t}$, $\delta T_s < T_0$, the Mach number $M(t) = M + \delta M e^{i\omega t}$ is also modulated by the term δM which can be found from the

linearized gas-dynamic equations for a one-dimensional ideal adiabatic flow [12] above the evaporating surface $z = 0$,

$$\begin{aligned} i\omega\delta\rho + u\frac{\partial\delta\rho}{\partial z} + \rho\frac{\partial\delta u}{\partial z} &= 0, \\ i\omega\delta u + u\frac{\partial\delta u}{\partial z} + \frac{1}{\rho}\frac{\partial\delta p}{\partial z} &= 0, \\ (i\omega + u\partial/\partial z)(\delta p - u_c^2\delta\rho) &= 0. \end{aligned} \quad (1)$$

For perturbations of the gas pressure δp , velocity δu , and density $\delta\rho$ this procedure gives

$$\begin{aligned} \frac{\delta p}{p} &= A_1 e^{-ik_1 z} + A_2 e^{-ik_2 z}, \\ \frac{\delta u}{u} &= \frac{1}{\gamma M} (A_1 e^{-ik_1 z} - A_2 e^{-ik_2 z}), \\ \frac{\delta\rho}{\rho} &= \frac{\delta p}{\rho u_c^2} + A_3 e^{-ik_3 z}, \quad k_{1,2} = \frac{\omega}{u \pm u_c}, \quad k_3 = \frac{\omega}{u}, \end{aligned} \quad (2)$$

where $z > 0$ is the distance from the surface (or the outer side of the KL) and the modulation δV of the vaporisation front velocity V is neglected.

For subsonic flow $M < 1$ one should put $A_2 = 0$ because there are no perturbations going to the $z = 0$ surface from infinity. Using the linearized form of the vaporisation boundary conditions for $p(T_s, M)$ and $u(T_s, M) = Mu_c$, $u_c^2 = \gamma p/\rho$, one obtains

$$\begin{aligned} A_1 &= \left(\tilde{p}'_s + \frac{\gamma M}{2} \right) \frac{\delta T_s}{2T_s} + \left(\tilde{p}' + \gamma M + \frac{\gamma M}{2} \tilde{T}' \right) \frac{\delta M}{2M}, \\ A_3 &= \left(\frac{\gamma - 1}{\gamma} \tilde{p}'_s - 1 \right) \frac{\delta T_s}{T_s} + \left(\frac{\gamma - 1}{\gamma} \tilde{p}' - \tilde{T}' \right) \frac{\delta M}{M}, \\ \frac{\delta M}{M} &= \alpha \frac{\delta T_s}{T_s}, \quad \alpha = \frac{\tilde{p}'_s - \gamma M/2}{\gamma M(\tilde{T}'/2 + 1) - \tilde{p}'}, \\ \tilde{p}'_s &= \frac{\partial \ln p_s}{\partial \ln T_s}, \quad \tilde{p}' = \frac{\partial \ln p}{\partial \ln M}, \quad \tilde{T}' = \frac{\partial \ln T}{\partial \ln M}. \end{aligned} \quad (3)$$

If the $g_i(T_s, M)$ have extrema at $M = 1$ as it is the case for the models of Refs. [5,7] then A_1 and A_3 become independent of $\delta M \neq 0$ at this point where $\tilde{p}' = -5/4$ and $\tilde{T}' = -1/2$. From (3) it is also seen

that the gas-dynamic perturbations enhance the vaporisation process because $\alpha > 0$.

Consider now the time-dependent vaporisation process induced by surface heating with modulated intensity $I(t) = I + \delta I e^{i\omega t}$, $\delta I < I$. The temperature distribution in evaporated condensed matter is determined by the one-dimensional Stefan-like problem

$$\frac{\partial T}{\partial t} + V \frac{\partial T}{\partial z} = \chi \frac{\partial^2 T}{\partial z^2}, \quad c \rho_0 \chi \frac{\partial T}{\partial z} \Big|_0 + \rho_0 L V = I,$$

$$T(t, -\infty) = T_\infty, \tag{4}$$

where the thermal diffusivity χ , specific heat c , and density ρ_0 are supposed to be constant while the latent heat $L(T_s, M)$ as well as vaporisation front velocity $V = g_1/\rho_0$ depend on T_s and M . At $M = 1$ the front velocity $V(T_s) = V_B \exp[A(1 - T_B/T_s)]$, where T_B is the normal boiling temperature, $A \sim 3L/cT_B \sim 10$ and $V_B \sim (0.8 p_s/\rho_0 u_c) (\gamma/2\pi)^{1/2} \sim 1$ cm/s for metals, e.g. for Pb.

Despite this extra dependence of L and V on M the problem (4) after linearization can be reduced to that considered in Ref. [1] because $\delta M = \alpha M \delta T_s/T_s$. Taking into account this relation one obtains for δT_s the same expression as in Ref. [1],

$$\delta T_s = \frac{\delta T}{g} \phi, \quad \phi^{-1} = 1 + (n-1) \left(a - \frac{b}{1+n} \right),$$

$$n^2 = 1 + \frac{4i\omega\chi}{V^2}, \quad b = 2aT_s \frac{V'}{V} = \rho_0 c \Delta T \frac{V'}{g},$$

$$g = [(L + c\Delta T)\rho_0 V]', \quad \Delta T = T_s - T_\infty, \tag{5}$$

where the prime in the expressions for b and g now means total differentiation with respect to T_s ,

$$V'(T_s, V) \equiv \frac{\partial V}{\partial T_s} + \alpha \frac{M}{T_s} \frac{\partial V}{\partial M}. \tag{6}$$

At a given value of T_s this modification changes coefficients $a < b < 1$ and increases the maximum value ϕ_m of the response function modulus $|\phi(\omega_m)|$ which can be expressed approximately by the formula

$$\phi_m \approx [1 - b(1-r)^2]^{-1}, \quad r^2 = a/b. \tag{7}$$

The increase of ϕ_m is more pronounced at $M \ll 1$ and it is connected with the fact that the total derivative V' is greater than the partial derivative with respect to T_s . This difference tends to zero as M

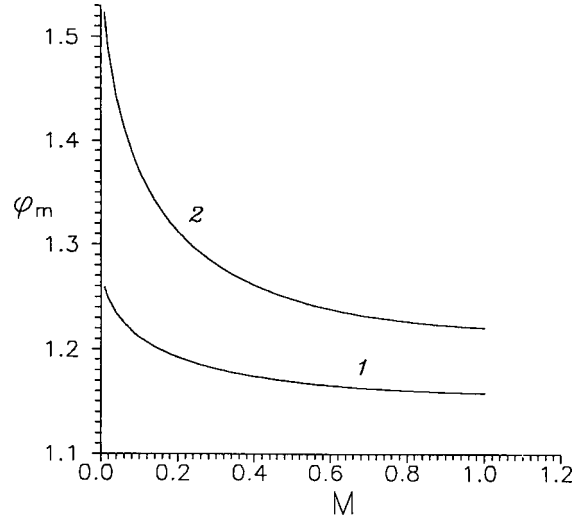


Fig. 1. Dependence of ϕ_m on M at $T_s/T_B = 1$ (1) and 2 (2).

approaches unity if the g_i have extrema at this point while at $M \ll 1$ the value of $\phi_m - 1$ is approximately twice that at $M = 1$.

The maximum ϕ_m and resonance frequency ω_m as functions of M are shown in Figs. 1 and 2 respectively for above boundary conditions [7] with the specific-heat ratio $\gamma = 5/3$ and for the same material constants as in Ref. [1].

It is worthwhile to mention in conclusion that such an enhancement of the vaporisation response due to the gas-dynamic reaction is in contrast to the Le Chatellier principle for equilibrium systems: the surface temperature modulation δT_s gives rise to the

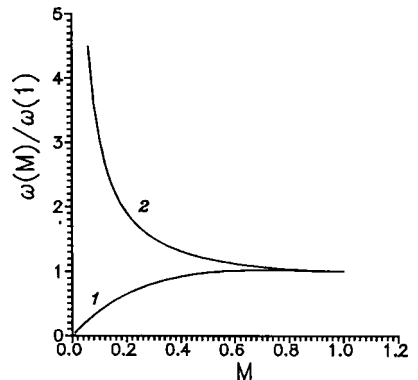


Fig. 2. Dependence of normalized resonance frequency $\omega(M)/\omega(1)$ on M at $T_s = T_B$ (1) and $I = \text{const}$ (2) with $T_s = T_B$ at $M = 1$.

Mach number change δM which increases the effect of δT_s on the vaporisation process. Such a behaviour is pertinent to unstable systems or processes. In fact, at $M < 1$ the vapour flow becomes unstable for the same reason which makes unstable the planar flame front in the slow combustion regime (Darreius–Landau instability). The stability problem of the vaporisation front at $M < 1$ will be considered elsewhere.

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