



Evaporation of a highly superheated liquid



P.A. Pavlov*

Institute of Thermophysics, Ural Branch of the Russian Academy of Sciences, Amundsen Street 107a, Ekaterinburg 620016, Russia

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ABSTRACT

Methods of calculating processes of intensive evaporation in conditions where the vapor flux density j is limited by the evaporation kinetics and the heat supply have been considered. A convenient approximation of the superheat dependence of j based on the continual theory of a pressure jump stopped by a counter flow at the interface has been obtained. It has been found that a pressure jump may be assumed to be isentropic with a sufficient accuracy, which simplifies the calculations considerably. It is shown that calculations of the process of intensive evaporation by a continual model, without invoking molecular kinetics, practically coincide with calculations by the kinetic evaporation theory. A simple criterion of transition from the regime limited by the evaporation kinetics to that limited by the heat supply has been suggested from conjugation at the interface of heat and mass flows.

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1. Introduction

As is well known [1], under certain conditions a liquid may be superheated to a temperature that exceeds considerably that of equilibrium evaporation. For instance, in experiments on water at atmospheric pressure [2] the temperature of attainable superheat of water reached 583 K. A rapid opening of the free surface of such metastable liquids results in intensive evaporation. In this case in the thin near-surface layer (Knudsen layer) there forms a pressure jump from the pressure of saturated vapor p_s at the interface temperature T_s to the ambient pressure p'' (the pressure behind the Knudsen layer) [3].

No universal method of calculating the rate of intensive evaporation has been created because of the great variety of possible realizations of the vaporization process. The pressure ratio $z = p_s/p''$ can be conveniently taken as the determining parameter. Evaporation which is sluggishly going into a gas ($z - 1 \ll 1$) is usually retarded by the rate of vapor diffusion. Intensive evaporation in technical devices in most cases also proceeds at a value of z close to unity and is limited by the heat supply to the interface or the hydrodynamics of the vapor flow-off. The evaporation of a highly superheated liquid under a pulsed superheat may proceed at a considerable inequality $z > 1$ and be retarded only by the evaporation kinetics. In the latter case the evaporation kinetics is calculated, as a rule, at the molecular level [3].

Posed below is the problem of choosing a model of calculation of the evaporation rate limited by both the evaporation kinetics and the power of heat supply to the interface. Let us assume, for instance, that the surface temperature is kept constant and equal to T_s by laser heating, and the vapor pressure p'' remains unchanged. In such a simple formulation at $z = p_s/p'' > 1$ the vapor flux density may be evaluated by the Knudsen formula [3], which will be written as follows:

$$j = \alpha j_0 (1 - 1/z). \quad (1)$$

Here the vapor flow from the evaporation surface without allowance for the vapor return flow is equal to $j_0 = \rho_s'' \sqrt{RT_s} / (2\pi M)$, and α is the condensation coefficient [3]. It should be noted that the basis for the Knudsen theory is the equation of the ideal gas $\rho'' RT'' = Mp''$.

Formula (1) is used for evaporation regimes close to equilibrium when the vapor pressure p'' does not differ from the external pressure. The vapor temperature T'' is taken equal to that of the liquid surface T_s . With an increase in the liquid superheat such a simple model of evaporation is erroneous. Many non-essential specifications of formula (1) are known.

The situation changed considerably when it became clear that it was necessary to take into account in the model of intensive evaporation the conservation laws in passing through the Knudsen thin near-surface layer [3].

The theory development was mainly reduced to a more precise calculation of the vapor return flow. At present it is agreed that at the evaporation surface there forms a region of a gas-dynamic rupture, to which conditions that express the retention of mass, pulse

* Tel.: +7 343 267 88 10; fax: +7 343 267 8800.

E-mail address: p-pavlov@mail.ru

Nomenclature

Latin letters

a	thermal diffusivity, m^2/s
c	specific heat capacity, $J/(kg \cdot K)$
j	vapor flow density, $kg/(m^2 \cdot s)$
j_0	vapor flow density without allowance for the backflow (the return stream), $kg/(m^2 \cdot s)$
u	average velocity of vapor flow behind the Knudsen layer, m/s
t	evaporation time, s
T	temperature, K
T_S	interface temperature, K
T''	vapor temperature behind the Knudsen layer, K
T^*	attainable-superheat temperature, K
r	radius from the center of bubble, m
R	gas constant, $J/(K \cdot mol)$
R''	bubble radius, m
M	molecular mass, kg/mol
p	pressure, MPa
p_S	saturated vapor pressure at the interface temperature, MPa
L	heat of evaporation, J/kg
x	distance from the interface in the liquid, m
X	criterion of choice of the evaporation regime

Greek letters

α	condensation coefficient
ρ_S''	saturated vapor density at the interface temperature, kg/m^3
ρ''	vapor density behind the Knudsen layer, kg/m^3
γ	adiabatic index
λ	thermal conductivity, $W/(m \cdot K)$
ξ	velocity of sound in vapor behind the Knudsen layer, m/s
ε, ϕ	adjustment parameters

Subscripts

s	of the liquid surface, belonging to the saturation line
∞	temperature deep in liquid
v	unstopped compression shock

Primes

one upper prime	liquid properties
two upper primes	vapor properties

and energy are applied [3]. For a gas far from the interface use is made of the Maxwellian distribution with allowance for the average gas flow rate. A verisimilar correction of this distribution is chosen in the thin near-surface layer (Knudsen layer).

As a result, a rigorous system of three equations which specify the conservation laws is written formally. Such a method of calculation has been considered by many researchers [3–8].

Ref. [8] presents a universal method of taking into account deviations of the coefficient α from unity in various heterogeneous processes. In particular, with this method, for calculating the evaporating Knudsen layer at an arbitrary value of α it is necessary to make a simple recalculation of the vapor density at the interface ρ_S'' to the effective vapor density. The effective vapor density in this case proves to be dependent on j and α . Unfortunately, simple methods of analytical calculation of the coefficient α have not been developed. Used below are the results of a sufficiently rigorous, but quite simple and illustrative investigation [7], in which a return molecular flow was simulated by a function similar to that of the Maxwellian distribution. As a result, the following equations have been obtained:

$$\begin{aligned} \frac{T''}{T_S} &= \left(\sqrt{1 + v^2 m^2} - vm \right)^2, \\ \frac{\rho''}{\rho_S''(T_S)} &= \sqrt{\frac{T_S}{T''}} \left[\left(m^2 + \frac{1}{2} \right) \exp(m^2) \operatorname{erfc}(m) - \frac{m}{\sqrt{\pi}} \right] \\ &\quad + \frac{T_S}{2T''} \left[1 - \sqrt{\pi} m \exp(m^2) \operatorname{erfc}(m) \right], \\ \beta &= \left(2m^2 + 1 - m \sqrt{\pi \frac{T_S}{T''}} \right) \cdot \exp(m^2) \frac{\rho_S''}{\rho''} \sqrt{\frac{T_S}{T''}}, \end{aligned} \quad (2)$$

where $m = u\sqrt{M}/\sqrt{2RT}$, and u is the average vapor flow rate behind the Knudsen layer, $v = (\sqrt{\pi}/2) \cdot (\gamma - 1)/(\gamma + 1)$, and γ is the adiabatic index.

The distribution function for particles scattered backwards in this work is taken proportional to the function of distribution at the outer edge of the Knudsen layer (with a proportionality coefficient β). It is assumed that the equality $\rho''/\rho_S''(T_S) = p''T_S/(p_S(T_S)T'')$ is met in accordance with the ideal gas equation. The density of the

mass flow from the interface $j = \rho''u$ is determined numerically from the written system of equations. For calculations it is necessary to specify the temperature of the liquid surface and the pressure on the outside of the Knudsen layer p'' .

2. Simulation of the evaporation process

In the calculated model (2) the condensation coefficient α was assumed to be equal to unity. The method developed in Ref. [8] has been used to calculate the effective vapor density of the interface $\rho_S''(T_S) - (1 - \alpha)\alpha^{-1}j\sqrt{2\pi M/(RT_S)}$. Substitution of the effective density into Eq. (2) instead of ρ_S'' , after a number of transformations, has given a formula for the vapor flux density at an arbitrary condensation $\alpha \leq 1$.

$$j = \alpha j_0 [1 - H(m)] [1 - (1 - \alpha)H(m)]^{-1}, \quad (3)$$

where the following designation has been introduced:

$$H(m) = \left(1 - \sqrt{\pi} m \cdot \exp(m^2) \operatorname{erfc}(m) \right) \left(1 + 2m^2 - \frac{\sqrt{\pi} m}{\sqrt{1 + (vm)^2 - vm}} \right).$$

Formula (3) is supplemented with an equation for calculating the complex m through the value of z :

$$\begin{aligned} \frac{1 - (1 - \alpha)H(m)}{\alpha z} &= \frac{1 - \sqrt{\pi} m \cdot \exp(m^2) \operatorname{erfc}(m)}{2} \\ &\quad + \left[\left(\frac{1}{2} + m^2 \right) \cdot \exp(m^2) \operatorname{erfc}(m) - \frac{m}{\sqrt{\pi}} \right] \\ &\quad \times \left(\sqrt{1 + v^2 m^2} - vm \right). \end{aligned} \quad (4)$$

The value of the total reaction of the vapor recoil $g \cdot p_S(T_S)$ is connected with the vapor flux density by the well-known expression $g \cdot p_S(T_S) = j^2/\rho'' + p''$, hence with the use of formulae (3) and (4) we obtain the relative pressure of the recoil reaction:

$$g(z, \gamma) = \frac{\alpha}{2} \cdot \frac{1 + f(m, \gamma)}{1 - (1 - \alpha)H(m)}, \quad (5)$$

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