

DYNAMICS OF EXPLOSIVE BOILING OF DROPS AT THE SUPERHEAT LIMIT

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A physical model for explosive boiling of drops is presented. Loss of stability of the liquid-vapor interface results in occurrence of evaporation fronts. Their propagation in a metastable liquid is determined by the vapor recoil momentum. Detachment of drops from the interface is due to thermocapillary forces. The validity of the model is supported by comparison of calculations with experimental data.

In a liquid with no centers of evaporation, nearly limiting superheat temperatures can be attained. In this case, boiling occurs spontaneously and vapor bubbles form by fluctuations. At high superheat temperatures, the rate of evaporation of the liquid is so high that the boiling has an explosive nature. This process is called a *vapor explosion*. Under industrial conditions, vapor explosions can be extremely destructive. Vapor explosion hazards determine the practical importance of studies of physical processes involved in explosive boiling.

In experimental studies of the boiling dynamics for butane drops, Shepherd and Sturtevant [1] found that the explosive character of boiling is due to the loss of stability of the liquid-vapor interface. A series of single photographs of bubbles taken at various delay times gives a comprehensive idea of the development of evaporation. At the beginning of boiling, just one bubble always formed. It arose at the boundary of the drop, and Shepherd and Sturtevant [1] explained this by the nonuniformity of the temperature field in the drop. Instability of the interface developed at the early stage of bubble growth. The surface of the vapor formation growing in the drop has small-scale roughness with a large amplitude of irregularities. The volume occupied by the vapor formation was measured from the photographs. The measured volume was then set equal to the volume of a sphere, and the effective radius of the vapor formation was determined. The roughness of the interface was ignored therewith. It turned out that the growth rate of the effective radius of the vapor formation was constant in time. For butane at atmospheric pressure and a temperature of 105°C, it is 14.3 m/sec, which is much lower than the rate calculated from the Rayleigh formula

$$V_f = \sqrt{2\Delta P/(3\rho')}, \quad (1)$$

where ΔP is the pressure difference for the vapor and liquid phase and ρ' is the liquid density. This formula describes the stage of bubble growth at very small times when the liquid inertia is a determining factor. Shepherd and Sturtevant [1] studied the later times at which bubble growth is determined by the process of heat transfer. The theoretical calculations of [2] gave lower values of the growth rate compared to the experiment. From estimates of the density of material inside the vapor formation, Shepherd and Sturtevant [1] made the assumption of the presence of a considerable amount of liquid in the vapor. Frost [3] proved this assumption experimentally. During explosive boiling, fine liquid particles are detached from the interface.

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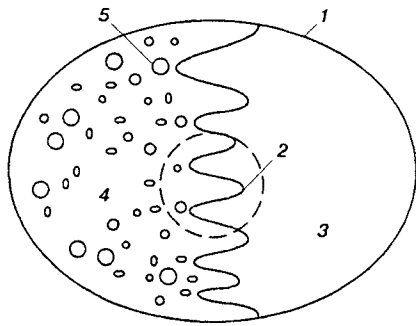


Fig. 1

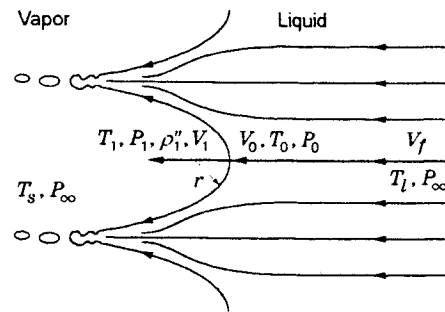


Fig. 2

With increase in the ambient pressure due to a decrease in the superheat temperature (with increase in pressure, the saturation temperature rises faster than the limiting temperature), loss of the stability of the bubble surface occurs at the later stages of bubble growth [3, 4]. At high pressures, instability of the interface was not observed during the entire stage of bubble growth in a drop.

A theory describing the dynamics of explosive boiling of drops is not yet available. This issue was the subject of only a few theoretical studies [5–7]. Nguyen et al. [5] and Lesin et al. [6] propose models in which the motion of the liquid–vapor interface is described by a modified Rayleigh equation allowing for the liquid compressibility and mass transfer through the interface. This equation has been employed previously [8] to describe bubble collapse in a liquid. Calculations using this model do not give a value for the bubble growth rate that is constant in time. The analysis of explosive boiling in [3, 7] using the Chapman–Jouguet condition has only an approximate character. The mechanism determining the flow of fine drops from the interface into the vapor region remains unknown.

We studied the dynamics of heterogeneous explosive boiling for metastability levels of liquids close to and much lower than the limit [9–14]. When the superheat temperatures prior to boiling exceeded the threshold values, (for example, 50 K for water at an ambient pressure of 3 kPa [11], 60 K for benzene at 9.8 kPa [10], and 40 K for Freon S318 at 260 kPa [12]) the bubble structure of evaporation also lost stability. As in the case of explosive boiling, the liquid–vapor surface became rough. At higher superheat temperatures, instability occurred at earlier stages of bubble growth. The development of instability of the interface was accompanied by an increase in liquid pressure [13].

In heterogeneous boiling, a liquid is metastable only near the heater. Therefore, the disturbances produced by the instability grew only in the wall overheated liquid layer. As in the case of homogeneous boiling, the growth rate of these disturbances is constant in time and is much higher than the bubble growth rate. For the frontal part of the vapor formation growing in a metastable liquid, we introduced the term an *evaporation front*. The effect of regime parameters (superheating of the heater wall with respect to the saturation temperature, pressure in the working volume, and underheating of liquids with respect to the saturation temperature) on the velocity of propagation of the evaporation front was studied in [10–14].

The physical model of [14, 15] was developed to describe the dynamics of explosive boiling in heterogeneous nucleation. The velocities of evaporation fronts for organic liquids calculated using this model were close to the experimental values. The objective of this paper is to show the suitability of this model for describing the dynamics of explosive boiling of drops.

The process of explosive boiling in a drop is shown schematically in Fig. 1. The frontal part of the vapor formation growing in the drop 1 will be called the evaporation front as in the case of heterogeneous explosive boiling. The evaporation front 2 moves in the liquid 3 at constant velocity V_f which is an order of magnitude higher than the rate of evaporation of the liquid. We consider a sample volume around the evaporation front in a moving coordinate system attached to the evaporation front (Fig. 2). In this coordinate system, the superheated liquid approaches the evaporation front from the right and the vapor 4 (see Fig. 1)

moves from the evaporation surface to the left.

The liquid velocity at infinity is equal to the velocity of propagation of the evaporation front V_f . The pressure P_∞ and temperature T_l of the liquid at infinity are equal to the pressure and temperature of the liquid drop prior to boiling. In the vapor region at infinity, the pressure is assumed to be P_∞ . The saturation temperature corresponding to this pressure is denoted by T_s . At the critical point at the evaporation front, the liquid velocity is equal to the rate of evaporation V_0 . Here the pressure from the liquid reaches maximum value P_0 . The liquid temperature at the evaporation front is denoted by T_0 . In the vapor region on the outside of the Knudsen layer, the vapor velocity, pressure, temperature, and density are denoted by V_1 , P_1 , T_1 , and ρ_1'' , respectively, and the main curvature radii of the interface at the evaporation front are denoted by r_1 and r_2 .

The surface of the liquid being evaporated is a discontinuity surface [16], passing through which, the normal velocity, pressure, density, and enthalpy undergo a discontinuity. For the evaporation front, the laws of conservation of mass, momentum, and energy fluxes are the same as those for shock waves:

$$j = \rho_0' V_0 = \rho_1'' V_1; \quad (2)$$

$$P_0 + \rho_0' V_0^2 = P_1 + \rho_1'' V_1^2 - \sigma_0(1/r_1 + 1/r_2); \quad (3)$$

$$j(i_1 - i_0) + j(V_1^2 - V_0^2)/2 - \lambda_0' \nabla T_0 + \lambda_1'' \nabla T_1 = 0. \quad (4)$$

Here j is the mass flux, σ is the surface tension, i is the enthalpy, and λ is the thermal conductivity; the properties of the liquid and the vapor are denoted by one and two primes, respectively, and the subscripts 0 and 1 denote, respectively, the quantities on the discontinuity surface from the side of the liquid and on the discontinuity surface (outside of the Knudsen layer) from the side of the vapor. Equation (3) was obtained with allowance for the curvature of the evaporation front.

In a nonviscous approximation, the equation for steady liquid motion is reduced to the Bernoulli equation. For the central streamline, the latter has the form

$$P_\infty + \rho_l' V_f^2/2 = P_0 + \rho_0' V_0^2/2, \quad (5)$$

where ρ_l' is the liquid density at temperature T_l .

Accurate determination of the main curvature radii of the evaporation front is a rather complex problem. The temperature distribution over the front part of the interface is nonuniform. The surface temperature varies from the maximum value T_0 at the critical point to T_s . This is responsible for the nonuniform distribution of the forces exerted by the liquid and the vapor on each other. At present, we have no information on the temperature distribution at the interface in the vicinity of the critical point. An analysis of the photographs of explosive boiling of drops given in [1, 3, 4, 6, 17] shows that the shape of the frontal part of the interface is nearly spherical. Assuming that the surface of the evaporation front is spherical, we determine the main curvature radius from the following relation between the capillary forces and the vapor pressure at the discontinuity surface:

$$r = r_1 = r_2 = 2\sigma_0/(P_1 - P_\infty). \quad (6)$$

From Eqs. (2), (3), (5), and (6), for the velocity of the evaporation front, we obtain $V_f = j \sqrt{2[1/\rho_l' - 1/(2\rho_0')]/\rho_l'}$. For $\rho_1'' \ll \rho_0'$, we have $V_f = \sqrt{2j^2/(\rho_1''\rho_l')}$. This formula is similar to the Rayleigh formula (1). Instead of the difference in pressure, it contains the vapor recoil momentum j^2/ρ_1'' . According to the Rayleigh model, the vapor bubble growth is due to the difference in pressure between the vapor and the liquid, whereas in explosive boiling, the growth of disturbances occurring at the interface as a result of instability is determined by the action of the reactive force.

In the equation of conservation of energy flux through the evaporation front (4), the dissipation of energy due to viscosity is ignored. Heat transfer to the vapor region [the fourth term on the left side of Eqs. (4)] can also be neglected since account of it has little effect on calculation results. The difference in

TABLE 1

T_s , K	P_∞ , kPa	T_l , K	V_f , m/sec	P_1 , kPa	T_1 , K	T_0 , K	Re	P_1/P_{s1}	M_1
272.65	101.3	370.65	20.43	212.5	312.7	323.5	27.8	0.57	0.64
272.65	101.3	372.65	23.02	226.8	316.8	328.6	26.9	0.54	0.69
272.65	101.3	374.65	26.30	245.0	321.9	334.8	25.6	0.51	0.76
272.65	101.3	375.55	28.24	255.8	324.8	338.3	24.9	0.49	0.79
272.65	101.3	377.75	35.58	297.7	335.5	351.3	21.8	0.44	0.92
272.65	101.3	377.95	36.48	302.9	336.8	352.8	21.4	0.43	0.94
272.65	101.3	378.15	37.34	307.9	338.0	354.3	21.0	0.43	0.95

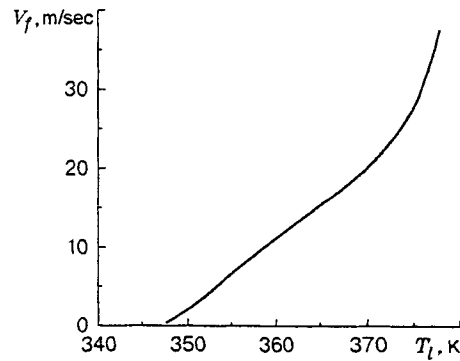


Fig. 3

enthalpies in Eq. (4) is equal to the heat of evaporation. It should be determined with allowance for the metastability of the liquid at the discontinuity surface:

$$i_1 - i_0 = H, \quad H = H_{s1} - (c'_{p0}T_0 - c'_{ps1}T_{s1}).$$

Here H_{s1} and c'_{ps1} are the heat of evaporation and the heat capacity of the liquid at the saturation temperature T_{s1} corresponding to the vapor pressure P_1 on the outside of the Knudsen layer.

The temperature gradient at the discontinuity surface from the side of the liquid phase is determined with allowance for evaporation in the vicinity of the frontal critical point for liquid flow past a sphere whose radius is equal to the main curvature radius of the evaporation front. The equation of convective heat transfer in the boundary-layer approximation has the form

$$u \frac{\partial T}{\partial x} + V \frac{\partial T}{\partial y} = a' \frac{\partial^2 T}{\partial y^2}, \quad T = T_0 \text{ for } y = 0, \quad T = T_l \text{ for } y \rightarrow \infty. \quad (7)$$

Here a' is the thermal diffusivity of the liquid.

In the vicinity of the critical point, the surface is equiaccessible [18], i.e., the solution is independent of x , and, hence, the first term in Eq. (7) can be ignored. Writing the longitudinal and transverse components of the liquid velocity for this region in the form $u = Ux/r$ and $V = -Uy/r - V_0$, respectively, substituting their values into Eq. (7), and integrating the latter, we obtain the following expression for the temperature gradient at the surface of the evaporation front from the side of the liquid:

$$\nabla T_0 = \sqrt{U/(2a'_0r)} (T_1 - T_0) \exp(-b) / \int_{\sqrt{b}}^{\infty} \exp(-\eta^2) d\eta.$$

Here $b = V_0^2 r / (2a'_0 U)$ and U is the liquid velocity at the interface. In the case of potential liquid flow past the sphere ($\text{Re} \gg 1$), $U = 1.5V_f$ and for viscous liquid flow [18], $U = V_f \mu'_0 / [2(\mu'_0 + \mu'_0)]$, where $\text{Re} = 2V_f r \rho'_0 / \mu'_0$ is the Reynolds number and μ is the dynamic viscosity.

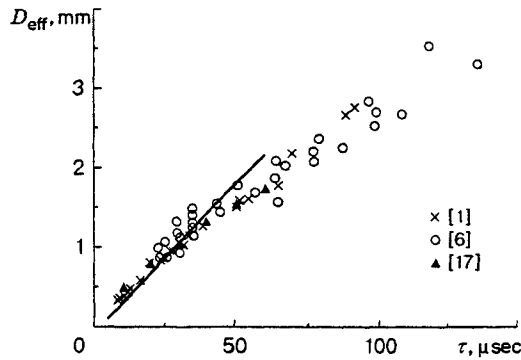


Fig. 4

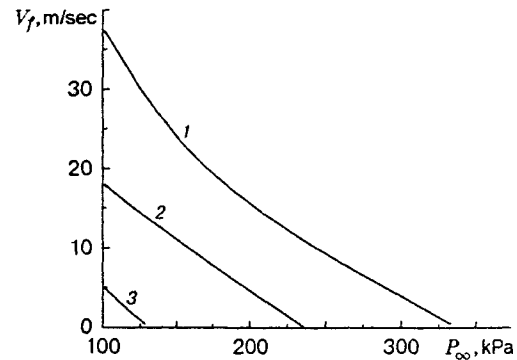


Fig. 5

Thus, for the process considered, the equation of conservation of energy takes the form

$$jH = \sqrt{V_f \lambda'_0 c'_{p0} \rho'_0 \mu'_0 / [2r(\mu'_0 + \mu''_0)]} (T_l - T_0) \exp(-b) / \int_{\sqrt{b}}^{\infty} \exp(-\eta^2) d\eta, \quad (8)$$

$$b = V_0^2 r(\mu'_0 + \mu''_0) / (V_f a'_0 \mu'_0).$$

In calculations, Eq. (8) was used to determine the liquid temperature at the evaporation front.

The vapor parameters on the outside of the Knudsen layer were calculated using the theory of nonequilibrium evaporation given in [19]:

$$\sqrt{\frac{T_1}{T_0}} = \frac{\sqrt{\pi M_*^2 + 4(m+4)^2} - \sqrt{\pi} M_*}{2m+8}, \quad \frac{P_0}{P_1} = \frac{2 \exp(-M_*^2)}{E + G \sqrt{T_1/T_0}}, \quad M_* = \frac{V_1}{\sqrt{2RT_1/W}} = M_1 \sqrt{\frac{m+5}{2m+6}},$$

$$E = \exp(-M_*^2) - \sqrt{\pi} M_* \operatorname{erfc}(M_*), \quad G = (2M_*^2 + 1) \operatorname{erfc}(M_*) - \frac{2M_* \exp(-M_*^2)}{\sqrt{\pi}}, \quad m = \frac{5 - 3\gamma_1}{\gamma_1 - 1},$$

where W is the molecular weight and γ is the adiabatic exponent.

To determine the vapor density on the outside of the Knudsen layer, we used the equation of state for a real gas given in [20]. This equation was also employed to obtain the local speed of sound on the outside of the Knudsen layer by the formula $u_1 = \sqrt{\gamma_1 (\partial P / \partial \rho'')_{T_1}}$.

The vapor velocity on the outside of the Knudsen layer is equal to the local speed of sound if the pressure P_1 far exceeds the ambient pressure P_∞ . When the counterpressure is high, the vapor velocity is lower than the speed of sound and is related to the pressure jump at the shock-wave front by the equation [16, 21]

$$F = (P_1 - P_\infty) \sqrt{2 / \{\rho''_\infty [P_1(\gamma_\infty + 1) + P_\infty(\gamma_\infty - 1)]\}}.$$

Thus, the required relationship between the parameters V_1 , ρ''_1 , and T_1 was given by the relations [22] $V_1 = u_1$ for $u_1 \leq F$ and $V_1 = F$ for $u_1 > F$.

The results of calculations for butane at atmospheric pressure using the model described above are given in Table 1 and Figs. 3-5. One can see that at the superheat limit, the explosive boiling of the liquid is an extremely nonequilibrium process. The liquid temperature at the evaporation front far exceeds the saturation temperature in the vapor region T_s . On the outside of the Knudsen layer, the vapor is superheated ($P_1/P_{s1} < 1$, where P_{s1} is the pressure on the saturation curve at temperature T_1). At the limiting temperature of 105°C, the calculated velocity of the evaporation front for butane was 37.3 m/sec. Under these conditions, the regime of vapor removal from the evaporation front is close to the critical ($\text{Max} \sim 1$).

From the model given above, it is clear that in studies of the dynamics of explosive boiling of drops, one should determine the time variation in the distance between the site of formation of the initial bubble and the evaporation front l rather than the effective radius of the vapor formation as was done in [1] and

the subsequent studies. The quantity closest to V_f is the growth rate of the effective diameter of the vapor formation D_{eff} . The difference of the calculated value of V_f from $dD_{\text{eff}}/d\tau$ ($dD_{\text{eff}}/d\tau = 28.6$ m/sec [1]) was about 30%, whereas the difference between the experimental values of the evaporation front velocity for heterogeneous explosive boiling of organic liquids and calculations using the model did not exceed 20%. In our opinion, the greater difference between the calculated and experimental data can be due to the following factors.

1. Difference of the effective diameters of the vapor formation from l .
2. Effect of fine drops in the vapor region on the vapor dynamics. (Our model does not allow for this factor.)
3. Difference between the pressure in the vapor region and atmospheric pressure. (In [1, 3, 4, 6, 17], measurements were carried out in a background liquid (ethylene glycol) with explosive boiling of drops. Calculations using the above model give the evaporation front velocity equal to the experimental value provided the pressure in the vapor region P_∞ is equal to 128 kPa.)
4. Nonuniformity of the temperature field in the drop prior to boiling.

Figure 3 shows calculated values of the evaporation front velocity versus the liquid temperature before boiling for butane at a pressure of 102 kPa. It follows from Table 1 and Fig. 3 that the evaporation front velocity depends strongly on the liquid temperature prior to boiling. Since a bubble always arose at the boundary of the drop, where the temperature is maximum, the growth rate of the vapor formation at the initial stage is also maximal. Figure 4 shows the experimental time dependences of [1, 6, 17] for the effective diameter of the vapor formation. Results of calculations using the model are also shown here (solid curve). The calculations are in agreement with the experimental data at the initial stage of growth of the vapor formation, where propagation of the evaporation fronts occurred in the liquid with a temperature of 105°C.

Figure 5 shows calculated evaporation front velocity versus pressure for the following butane temperatures prior to boiling: $T_l = 378.15$, 368.15, and 363.15 K (curves 1–3). The evaporation front velocity decreases with increase in pressure. For butane at pressures higher than 280 kPa, instability of the interface was not observed experimentally during the entire stage of bubble growth until complete evaporation of the drop [6].

In heterogeneous boiling, the lower the degree of liquid metastability, the later the stage of bubble growth at which interfacial instability arises with subsequent formation of evaporation fronts. Since all experiments were carried out with drops of small sizes (approximately 1–2 mm), explosive boiling did not occur at pressures over 280 kPa, because of the deficit of the superheated liquid. The drops were entirely evaporated but the bubble did not reach the size at which its surface becomes unstable. Increasing the volume of a metastable liquid will probably extend the range of the regime parameters in which homogeneous explosive boiling occurs.

As is shown by calculations (see Table 1), the liquid temperature at the evaporation front is much higher than the saturation temperature. The nonuniform temperature distribution on the interface gives rise to a tangential force directed from regions with lower surface tension to regions with higher surface tension. This leads to the liquid moving from the evaporation front to the base of the disturbance growing in the metastable liquid (see Fig. 2). In the vapor region, the small liquid jets that arose under the action of the thermocapillary force break up into drops 5 (see Fig. 1) due to Helmholtz instability. The distance between the two-phase region “vapor–liquid drops” and the evaporation front is not less than the amplitude of the disturbance growing in the metastable liquid. The absence of liquid drops in the vapor region in the vicinity of the evaporation front apparently gives grounds to ignore the effect of the liquid drops on the vapor dynamics in our model.

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