EVAPORATION OF A DROP OF WATER UNDER THE INFLUENCE OF A PULSE OF LIGHT

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The dynamics of a drop of water in a pulsed optical field is investigated. The experimental results are compared with the obtained analytic formulas.

The evaporation regime of a drop of absorbing liquid heated by radiation depends strongly on the radiation density, the absorption coefficient of the drop material, and the drop dimensions. The least investigated regime is one in which the stationary model [1-3], which is valid in a weak field, does not hold. An elementary theory of evaporation of a drop in a pulsed field was proposed in [4], but the effects accompanying powerful radiation (nonstationarity of the temperate field of the drop, the Stefan flow, the vapor temperature and pressure discontinuities on the drop surface, and possible changes of the regimes) are taken most consistently into account in [5]. It is shown there that the rate of evaporation of the drop in an optical field whose power satisfies the inequality

$$W K_{abs} r \gg \frac{2Q\mu_1 P}{3R} \left(\frac{D}{T^e}\right)^*,$$

$$Q = L + c_p T_b \quad \left(\frac{D}{T^e}\right)^* \simeq \frac{D}{T_b},$$

is equal to

$$\frac{dr}{dt} = -\frac{3K_n a^2}{2Q\gamma r^2} \sum_{n=1}^{\infty} \int_0^t W(\tau) \exp\left[-\left(\frac{a\pi n}{r}\right)^2 (t-\tau)\right] d\tau. \tag{1}$$

Expression (1) was obtained assuming that the optical field inside the drop is isotropic.

If the inequality

$$-\frac{3K_{abs}}{2c\gamma r} \sum_{n=1}^{\infty} (-1)^n \int_0^t W(\tau) \exp\left[-\left(\frac{a\pi n}{r}\right)^2 (t-\tau)\right] d\tau + T_b \geqslant T_{kp} \tag{2}$$

is satisfied, then the regime of evaporation from the surface gives way to an explosion regime.

In the described experiment, the duration of the light pulse satisfies the condition

$$t_p \ll \frac{r_0^2}{a^2}, \tag{3}$$

so that we can use the approximation

$$W(\tau) = E\delta(\tau), \tag{4}$$

where $\delta(\tau)$ is a δ-function.

Integrating (1) with (4) taken into account, we have

$$\frac{dr}{dt} = -\frac{3EK_n(r_0)a^2}{2Q\gamma r^2} \sum_{n=1}^{\infty} \exp\left(-\frac{a^2\pi^2 n^2}{r^2} t\right), \tag{5}$$

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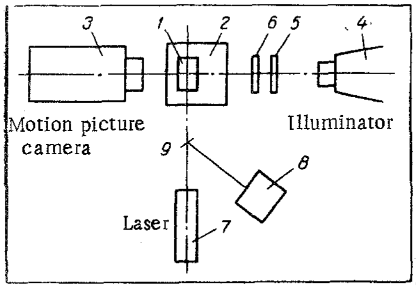

Fig. 1. Experimental setup.

which leads to an asymptotic character of the r(t) curve. The final radius of the particle is obtained from the formula

$$r_k = \left(r_0^3 - \frac{3EK_p r_0^2}{4Q\gamma} \right)^{1/3}. \tag{6}$$

The explosion threshold condition (2) takes in this case the form

$$EK_{abs}(r_0) \geqslant 2/3 c\gamma r_0 (T_{kp} - T_b). \tag{7}$$

In the experiment we observed the evaporation of drops of radius 140-190μ. The explosion condition for these drops takes the form $EK_{abs} \geq 2.56$-3.47 cal/cm^2.

If the strength of the drop is high enough, the explosion can occur without pulverization of the condensate. Boiling of the substance should be observed in this case, and the radius of the drop decreases jumpwise to the value determined by formula (6).

We present here the results of an experimental investigation of the evaporation of a water drop in the field of pulsed optical radiation and compare them with the conclusions that follow from [5].

The kinetics of a water drop in optical-radiation field was measured with a setup whose diagram is shown in Fig. 1. A water drop of diameter 380-280μ was suspended with the aid of a syringe on a filament placed in cell 1. The cell was mounted on a rotating stage 2 capable of microscopically fine motion in two horizontal directions and smooth motion in the vertical direction. We used glass filaments of 12μ diameter and tungsten wires of 11 and 6μ diameter.

The dynamics of drop evaporation was registered with SKS-1M and SFR-2L high-speed motion-picture cameras (3 in Fig. 1). The SKS-1M camera can take pictures at a rate from 100 to 4000 frames per second, while the speed of SFR-2L is up to $2.5 \cdot 10^6$ frames per second. Photography was in transmitted light by the light-field method, and the SFR-2L camera operated in the time magnification mode.

The influence of illuminator 4 on the rate of drop evaporation was excluded with the aid of a water filter 5 and a glass light filter SZS-10 (6 in Fig. 1), which cut off the thermal radiation of the illuminator.

The radiation source was a GOR-02 ruby laser 7 with light-pulse output energy 0.15 J. The radiation wavelength was 0.69μ and was focused on the drop with lenses having different focal lengths.

Monitoring of the laser operating stability and the determination of the radiation energy were carried out with the aid of a calorimetric receiver 8; the radiation for monitoring was diverted with the aid of semitransparent plate 9.

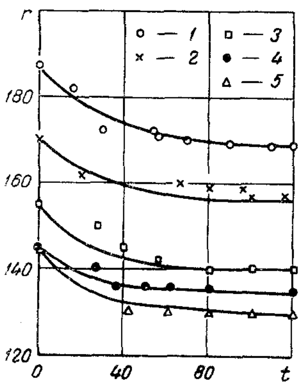

Fig. 2

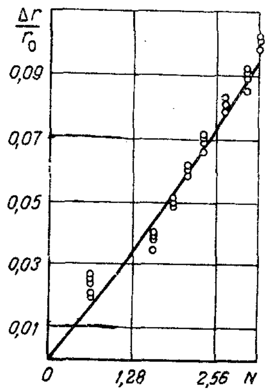

Fig. 3

Fig. 2. Dependence of the drop of the radius (r, μ) on the time (t, sec $\cdot 10^{-3}$) at subthreshold values of the effective radiation energy flux: 1) N = 4.31 cal/cm^2; 2) 3.01; 3) 3.42; 4) 2.35; 5) 3.4.

Fig. 3. Relative change of drop radius vs. the effective radiation energy flux (N, cal/cm^2).

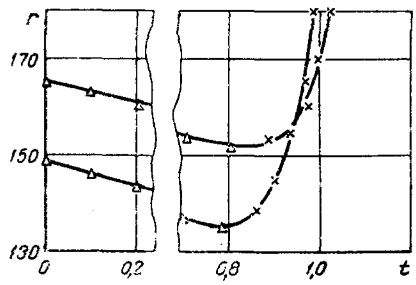

Fig. 4. Time dependence of drop radius at an effective radiation energy flux 15 cal/cm^2 (r, μ; t, sec $\cdot 10^{-3}$).

The following procedure was used for the microphotography of the laser-irradiated drop. The camera objective was replaced with a microscope objective. The laser radiation was used to burn a hole in a screen mounted in the focal plane of the objective, and the crosshair of the camera viewfinder was placed at the center of this hole. The screen was then removed and the drop, suspended on the filament, was introduced into the crosshair of the optical sight. Thus, the drop was introduced into the focal plane of the micro-objective and the laser radiation was focused on the drop. To determine the photography scale, we photographed the scale of an object-micrometer with distance 10μ between divisions. The temperature and humidity of the surrounding air were determined with an aspiration psychrometer before each picture-taking run.

Each series of measurements of the drop-dimension dynamics under laser irradiation was accompanied by determination of the rate of evaporation of the drop without the irradiation. The purpose of such measurements was to determine the influence of the conditions prevailing in the cell. The temperature and humidity of the surrounding air in the experiments were usually 20°C and 25-30%, respectively.

As seen from (2)-(7), the rate of evaporation depends on the product EK_{abs}. The absorption coefficients of pure water, for radiation with wavelength 0.69μ, is quite small, $\varkappa \sim 10^{-7}$. To obtain noticeable effects of the thermal action of the radiation we therefore used drops of aqueous solutions of a black dye, for which $\varkappa \sim 10^{-4}$. The irradiation conditions will henceforth be characterized by the quantity $N = EK_f$.

In the first measurement run, the results of which are shown in Fig. 2, the values of the introduced factor N range from 2.4 to 4.3 cal/cm^2, i.e., they were close to the explosion threshold. An asymptotic variation of the drop radius with time was observed, however. The points corresponding to the experimental data are in good agreement with calculations by formula (5) (continuous curves). The observed values of the explosion threshold were somewhat higher than those calculated by formula (7) in all cases, and amounted to ~ 5 cal/cm^2. This discrepancy between the experimental data and the theory of the presence of the suspension filament, which prevents the critical parameters from being reached at the center of the drop, as a result of which the explosion takes place when the critical state is reached at a certain distance from the center, at correspondingly higher values of the factor N.

Figure 2 shows plots of the rate of evaporation of drops suspended on glass filaments of 12μ diameter. To explain the character of the influence of the suspension filament material, a series of measurements was performed using tungsten wires of 11 and 6μ diameter. The results of this series, performed under the same conditions as the preceding series, show that the rate of drop evaporation decreases sharply. This effect can apparently be attributed to the appreciable thermal-conductivity coefficient of the tungsten filaments.

The points of Fig. 3 show the empirical dependence of the ratio $\Delta r/r_0$ on N, obtained on the basis of an extensive series of measurements at subthreshold values of N. The curve was calculated in accordance with (6). Satisfactory agreement between the experimental and calculated data is observed.

The dynamics of the explosion regime of drop evaporation was investigated with the aid of the SFR-2L motion-picture camera at $6 \cdot 10^3$ to $125 \cdot 10^3$ frames/sec. Figure 4 shows plots of the drop evaporation at $N \geqslant 15$ cal/cm^2. During the time necessary to reach the critical parameters (~ 1 msec), the r(t) plot is almost linear. This is followed by a sharp acceleration of the process, thus confirming the existence of an explosion regime. Complete evaporation of the drops occurs in this regime within 150-2000 msec. The points on the rising sections of the curves correspond to the radius of the volume of superheated stream – the explosion product, which is clearly seen as a result of the strong Rayleigh scattering.

When the factor N was varied in the range $5 \leqslant N \leq 15$ cal/cm^2, boiling of the drops without pulverization was observed. In this case the measured values of their final radius agree well with formula (6).

NOTATION

a^2 is the thermal diffusivity of liquid;
c, c_p is the specific heats of liquid and vapor–gas mixture at constant pressure;
D is the vapor diffusivity in gas;
E is the radiation energy flux;
K is the efficiency factor of radiation absorption by drop;
L is the specific heat of evaporation;
P is the vapor gas mixture pressure;
R is the universal gas constant;
r is the drop radius;
T_b is the liquid boiling point at pressure P;
T_{cr} is the critical temperature of liquid;
t is the time;
W is the radiation power flux;
γ is the density of liquid;
$\varkappa$ is the liquid absorption coefficient;
μ_1 is the molecular weight of vapor.

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