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DESTRUCTION OF COARSE AND FINE WATER DROPS BY MONOPULSES OF A RUBY LASER

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UDC 535.21

In addition to the known method of evaporating water drops in the intensive radiation field of a CO_2 laser, papers have recently appeared wherein the destruction of water drops without the conversion of the light energy they absorbed into heat is investigated (surveys [1, 2], for example). Papers devoted to nonthermal methods of destroying a water aerosol, although still few in number, indicate the proposal of three methods of destroying the drops: optical breakdown in water, excitation of mechanical vibrations of the drops, and photochemical destruction of the water molecules [1, 2]. The optical breakdown phenomenon, when intense destructive shocks occur in a water drop subjected to a laser monopulse, has been investigated more fully than the other methods but also clearly insufficiently. Experiments on destroying millimeter- and micron-sized drops by ruby laser monopulses are described in this paper, values of the parameters characterizing this process are determined, and an approximate estimate of the energy and power of the laser pulses required to destroy a water aerosol in a track of definite length is also given.

1. Experimental Investigation of the Destruction of Coarse Water Drops. The effect of monopulse laser radiation on a suspended water drop of ~2 mm radius was observed in the experiments. The diagram of the apparatus is presented in Fig. 1. The gigantic pulse from a OGM-20 ruby laser 2 was focused at the center of the drop 4 suspended from the capillary 1 by using a lens with a 5-cm focal length 3. By using a plane-parallel divider plate 5 and the collector lens 6, a part of the radiation is sent off to the IKT-1M calorimeter 7 to measure the pulse energy. The pulse duration of the ruby laser was ~20 nsec at the half-power level, the maximum energy per pulse was ~0.5 J, and the area of the focal spot in air, determined by the hole pierced in foil, was about $2.8 \cdot 10^{-3}$ cm^2.

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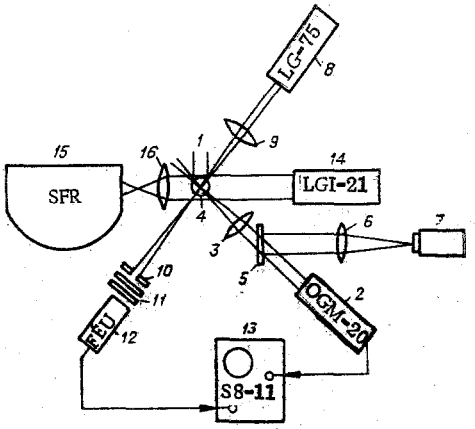

Fig. 1

The following scheme was used to record the process of drop destruction in time. The beam from an LG-75 laser 8 was focused on the drop somewhat below its center by using the lens 9, so that the red beam refracted by the drop would not be incident in the window of the diaphragm 10. In the absence of a drop the light will pass through the diaphragm window and yield constant illumination on the photomultiplier 12. The signal from the photomultiplier was recorded by using an S8-11 storage oscilloscope 13, whose sweep was triggered by the ignition pulse from the ruby laser pumping lamp. Two $\lambda = 0.63$ μm interference light filters 11 were used to suppress the parasitic illumination of the photomultiplier from the ruby laser light pulse scattered by the drop. A number of photographs of the process of drop destruction can be obtained by using the LGI-24 laser 14, the objective 16, and the high-speed SFR movie camera 15.

It is seen from a series of photographs of the destruction process that the drop swells before the explosion, then water spots splash out from it, and then scattering into fragments occurs. Photographs of individual fragments of the drop explosion processes, taken at different times after illumination [a) before the effect, b) after 200 μsec, c) after 300 μsec, d) after 1 msec, e) after 3.8 msec from the laser pulse], are presented in Fig. 2. The suspended drop appears black in Fig. 2a. The light spot in the middle and the illumination in the upper part of the drop are due to beam refraction in the area of drop contiguity to the capillary. The dark swollen drop is seen in a gray background in the next two photographs, where a bright flash is seen at the center. The effect of the blue glow at the center of the drop was also observed visually. This glow is apparently associated with the presence of dielectric breakdown in water and the formation of a plasma within the drop. The swollen drop fills the whole field of view of the SFR lens in the next frames and individual fine drops, "fragments" blasted from the coarse drop, start to appear in the frame.

A time study of the drop dissipation process was conducted by means of the transient characteristics obtained on the oscilloscope screen, examples of which are shown in Fig. 3. Two characteristic times are seen clearly on the transients. The time t_1 from the time of the light pulse to the time of the first minimum on the transient can be considered the characteristic time of drop destruction. The time t_2 from the time of the light pulse to the end of the transient characterizes the time of total drop destruction. The oscillograms are quasivibrational in nature for radiation power densities exceeding the breakdown threshold insignificantly, which is apparently associated with either pulsations of the drop during dissipation, or with some "periodicity" in the destruction of the drop (e.g., with the successive cleavage of layers of liquid) (Fig. 3b, obtained for $W = 4.6$ GW/cm^2). For power densities greater than 8 GW/cm^2 in the area of the focal spot, the quasivibrational nature of the transient vanishes because of the rapid dissipation of the explosion products (Fig. 3a). The dependence of a reciprocal quantity of the total drop dissipation time t_2^{-1} on the power density W in the focal spot of the lens is represented in Fig. 4 for the case of distilled (solid line and dark points) and tap water (dashed line and open circles). The experimental points were approximated by a parabolic dependence. It is seen from Fig. 4 that the pulse power density threshold needed to destroy a coarse water drop is ~ 2.1 GW/cm^2.

With regard to the characteristic time of drop dissipation t, and its dependence on the power density in the laser pulse, this characteristic time is 145 ± 35 μsec with 95% confidence, in the range investigated.

The deduction can be made from the experiments conducted that the effects of the destruction of a coarse water drop under the effect of a ruby laser monopulse are due to the high-intensity light field in the pulse and not to thermal effects [2]. To verify this deduction, the ruby laser was transferred to the free generation mode with the same energy per pulse but with a pulse duration of about 1 msec so that the energy density at the center

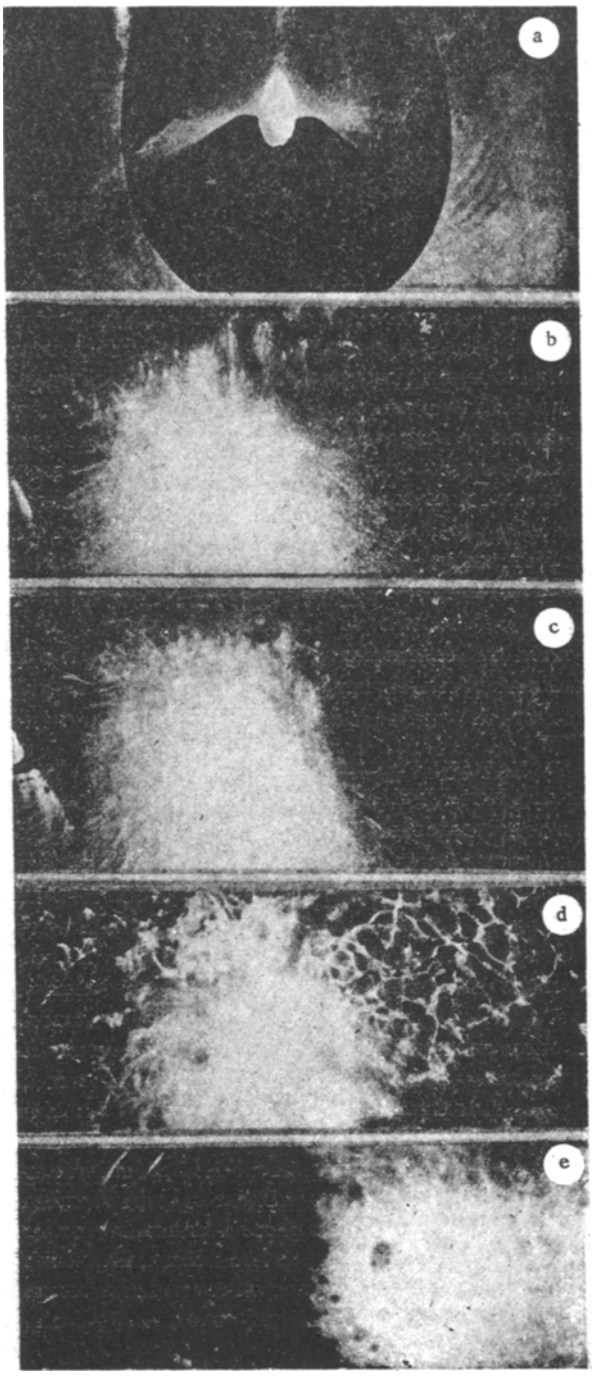

Fig. 2

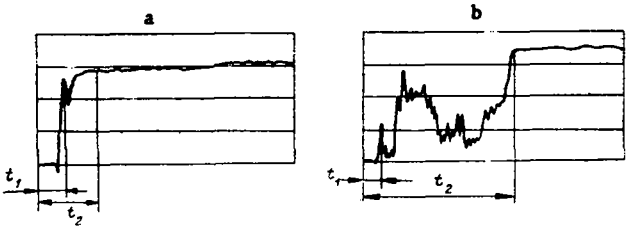

Fig. 3

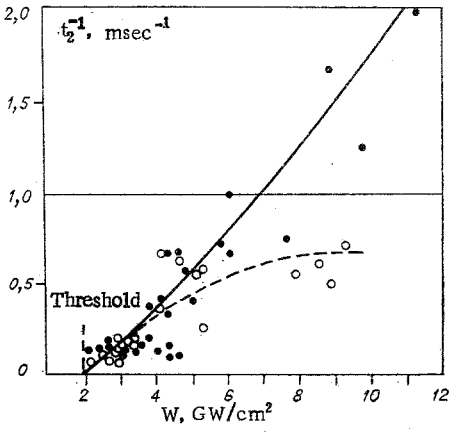

Fig. 4

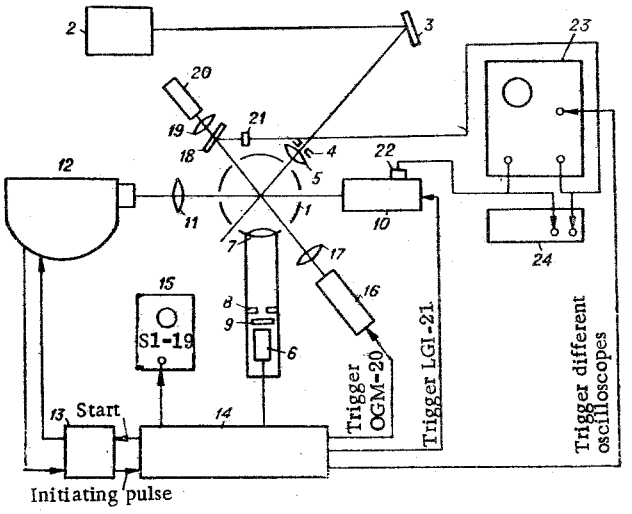

Fig. 5

of the drop remained the very same but the power was decreased by more than four orders of magnitude. In this case no drop destruction effects were observed.

2. Experimental Investigation of the Destruction of Micron-Sized Water Drops. An experimental setup, whose diagram is shown in Fig. 5, was produced for the visual investigation of the behavior of 1-10 μm radius water drops subjected to the monopulse radiation of a ruby laser. The apparatus permits recording the behavior of only those drops which are incident in the working volume formed at the focus of the three laser beams.

An ultrasonic atomizing system described in [3] was used as the micron-size drop generator. Water drops from the atomizing cuvette are delivered by compressed air to the working volume. If the drop were to be incident at the focus of the three optical systems, then it will scatter the light of the He–Ne laser 2, focused at the center of the measuring cuvette 1 by using the mirror 3, the diaphragm 4, and the lens 5. An image of the drop is constructed by means of the objective 7 in the plane of the diaphragm 8 in the light of the red laser beam. If the drop is at a given point of space (the focus of the three optical systems), then the light it scatters is incident on the photomultiplier 6 through the diaphragm window and the interference light filter 9 at the 0.63-μm wavelength. Ultraviolet radiation ($\lambda = 0.337$ μm) of the LGI-21 laser 10 is used for a photographic recording of the drop destruction process by the high-speed SFR camera 12 in transmitted light. The image on the SFR film is constructed by using the quartz glass objective 11. The optical system magnification is 60. To obtain a high power density in the zone of action on the water drop by a light pulse from the OGM-20 ruby laser 16, its radiation was focused by the lens 17 at a spot of radius ~ 0.4 mm. To measure the energy in the ruby laser pulse an IKT-1M calorimeter 20 was used. Radiation was collected in the calorimeter by the lens 19 after the light dividing plate 18. Control of the recording process was automatic by using a special automation module 14. After the drop was incident at the focus of the three optical systems, the signal from the pho-

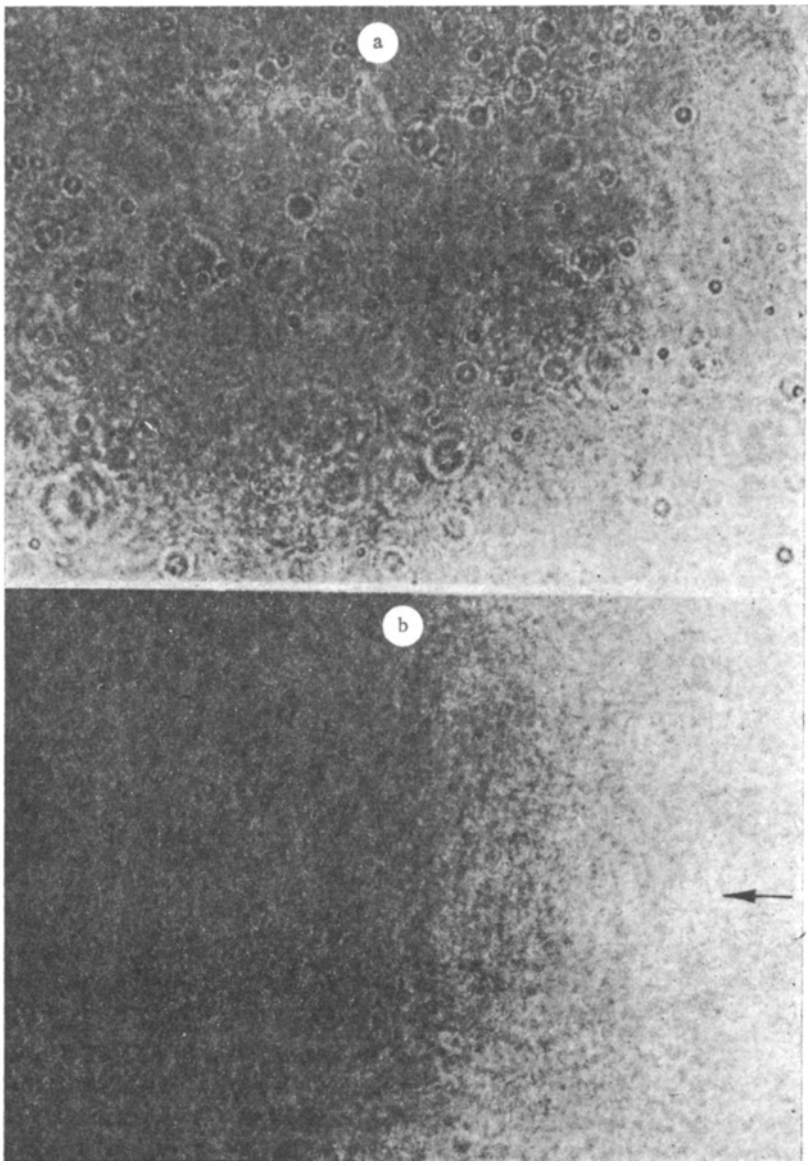

Fig. 6

tomultiplier (FÉU) closes the contact of the "Start" button on the SFR control panel 13 through the automation module, after which the signal is sent to open the mechanical shutter of the SFR camera. When the mechanical shutter of the SFR camera is open, an initiating pulse is taken off from the SFR transducer and goes to the delay unit in the automation module. Two pulses from the day unit go to trigger the UV lasers separated in time by 4.5 msec (the minimum time to prepare the supply module for this laser). Moreover, pulses to trigger the OGM-20 ruby laser and the sweep of the oscillograph 23 emerge from the delay unit. The automation system permitted the SFR to record three frames on the photographic film: before the action of the radiation, in the light of the acting ruby laser radiation, and after the action of the radiation.

The time between the first and third frames is ~4.5 msec, while the time between the second and third frames can vary within the limits of several microseconds to 3.8 msec. To check the aerosol density in the area of the focus, an oscilloscope 15 was used, to which a signal was delivered from the photomultiplier. To check the passage of the light pulses and for a rough measurement of the intervening time intervals, the two-channel storage oscilloscope 23 was used. Light pulses from the ruby and ultraviolet lasers were recorded by the FSK-2 photoresistors 21 and 22 and a digital meter of time intervals ChZ-35-A 24 was used for an accurate measurement of the time intervals between the second and third frames.

The diameter of the focal spot of the ruby laser was 0.8 mm, and the size of the field of view of the SFR objective (the working volume) was 0.3 mm, so that the effect of the laser radiation is realized on all drops present in the working volume.

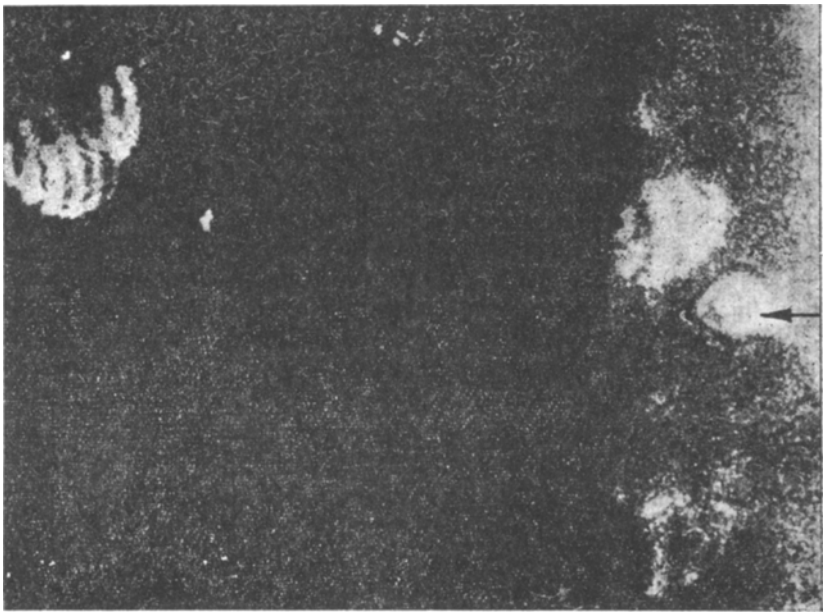

Fig. 7

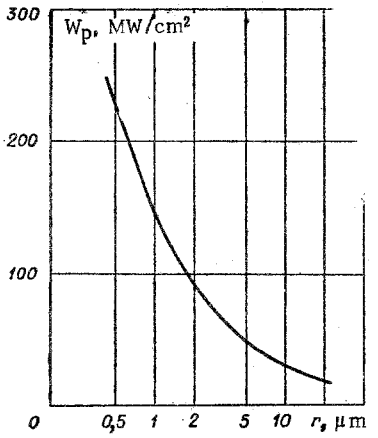

Fig. 8

Let us present some experimental results. A photograph of an aerosol drop in the working volume prior to action is represented in Fig. 6a, and a photograph of the working volume 300 μsec after the action of the ruby laser pulse in Fig. 6b. The power density per pulse was ~330 MV/cm² (the pulse duration is ~20 nsec). The scale of the image in the frames is 250:1. The direction of laser pulse incidence is indicated by the arrow. An ensemble of drops of different size (dark circles, sometimes with a white spot in the center) at both the focus of the SFR objective and outside it (these latter are surrounded by aureoles) is seen in the first frame. The field of view of the objective was cleared completely in the second frame.

Some drops not subjected to destruction remained in the working space when the power density in the laser pulse was reduced.

An investigation of the time characteristics of the drop destruction process showed the following. In 200 μsec after the effect of the laser pulse, the drops were destroyed completely. It was not possible to obtain photographs less than 200 μsec after because the second and third frames became superposed on the SFR film in this case. In this connection, it is difficult to estimate the characteristic times of destruction of the fine drops. However, the photographs of the working space in the scattered light of the ruby laser exhibit an interesting fact. A photograph obtained in the scattered ruby laser light is represented in Fig. 7 in the same scale as in Fig. 6. Light aureoles intersected by a number of dark bands are seen in the photograph in place of the aerosol drops. The size of these aureoles is about 60 μm (the initial drop size is 4-6 μm along the radius). If it is assumed that these aureoles are either the swollen drop prior to explosion or the explosion

products, then the characteristic time of the process of fine drop destruction is on the order of the duration of the laser pulse, i.e., ~20 nsec.

3. Possibility of Nonthermal Destruction of an Atmospheric Aerosol. On the basis of the experiments conducted and [4], where analogous experiments had been performed, the following characteristics could be determined for the phenomenon of coarse water drop destruction under the effect of a laser monopulse: The destruction of water drops occurs at the threshold value of the ruby laser pulse power density: ~2.1 GW/cm^2; the drop starts to explode in a time less than 16 μsec, and the characteristic time of drop disappearance is ~150 μsec; the pressure on the shock front destroying the drop will drop rapidly with distance from the focal point, after having reached thousands of bar in direct proximity to it. The higher the pulse energy, the greater the pressure on the shock front, and the higher the velocity and the greater the distance at which the explosion products dissipate; as the energy increases in the laser pulse, all the more energy goes into "accelerating the fragments" of the drops and their scattering velocity and range grow.

By knowing the breakdown threshold in coarse drops, the magnitude of the breakdown can be estimated even for drops of micron size. As was indicated in a number of papers ([2], for example), diffraction effects result in the formation of intensity maximums in the light field distribution over the volume of the drop. An approximate dependence of the relative magnitude of the highest maximums (as compared with the intensity incident on the drop) on the drop radius is also presented in [2]:

$$\gamma = 11.63(r/\lambda)^{0.65},$$

where r is the drop radius, μm; λ is the incident radiation wavelength, μm. The dependence is valid for the range of values of r/λ between 0.6 and 40, and the breakdown threshold of micron drops subjected to a ruby laser pulse can be determined by using it:

$$W_p(r) \simeq 180(r/0.694)^{-0.65}$$

(W_p, MW/cm^2; r, μm).

The dependence $W_p(r)$ is presented in Fig. 8, from which it is seen that a 300 MW/cm^2 monopulse power density was adequate for the breakdown to occur in aerosols of all sizes in experiments on the destruction of fine drops. In experiments in [5] in which the power density in a parallel neodymium laser monopulse beam was just about 30 MW/cm^2, an increase in the optical thickness of the artificial mist by 12-14% was observed after the passage of the power pulse. This indicated the presence of drop explosion products in the action zone, from which it could be assumed that a 30 MW/cm^2 power exceeds the threshold just slightly and, therefore, the kinetic energy of fragment dissipation is low. This indeed follows from Fig. 8, where it is seen that the power of this order could only destroy drops with $r > 10$ μm, which were not many under the conditions of the experiment in [5] (the drop-size distribution was described by a γ distribution with the parameters $r_0 = 3$ μm and $\mu = 3$).

In conclusion, let us execute an approximate estimate of the monopulse energy required to destroy drops in an aerosol column of length L. Let us assume that the aerosol is monodispersed with the drop size along the radius r_0 μm and the concentration N_0. Then its attenuation factor is $\alpha_0 \simeq 2\pi r_0^2 N_0$. If the laser pulse possesses the power W_0 exceeding the threshold power for a drop of this size $W_p(r_0)$, then the first laser pulse destroys all the drops on a track of length $\Delta l_1 = (1/\alpha_0) \ln [W_0/W_p(r_0)]$. The characteristic time of destruction is not greater than 10^{-4} sec, and if a second laser pulse of the same power acts after 10^{-4} sec, then it will pass through the drop explosion products after the first pulse and destroy the aerosol on a track of length

$$\Delta l_2 = \frac{1}{\alpha_0}\left\{\ln \frac{W_0}{W_p(r_0)} - \alpha_1 \Delta l_1\right\},$$

where α_0 is the attenuation factor of powerful laser radiation in the explosion products, and $\alpha_1 < \alpha_0$. Therefore, a channel of length

$$L = \sum_{i=1}^{N} \Delta l_i = \frac{1}{\alpha_0} \ln \frac{W_0}{W_p(r_0)} \sum_{i=1}^{N} \left(1 - \frac{\alpha_1}{\alpha_0}\right)^{i-1}$$

is formed in the aerosol after the passage of N pulses. Let us present a numerical example. The values of the parameters are: $r_0 = 5$ μm, $N_0 = 60$ cm^{-3}, $\alpha_0 \simeq 19$ km^{-1}, $\alpha_1/\alpha_0 = 0.5$, L = 0.5 km, $W_p = 48$ MW/cm^2. Then after four pulses a track of length 0.5 km is bleached under a pulse with the power

$$W_0 = W_p \exp\left\{\frac{L\alpha_0}{\sum_{i=1}^{N}\left(1 - \frac{\alpha_1}{\alpha_0}\right)^{i-1}}\right\} \simeq 7.6 \text{ GW/cm}^2.$$

Taking into account that $\tau = 2 \cdot 10^{-8}$ sec, we obtain the energy density required: ~ 150 J/cm^2.

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ROLE OF BUBBLE BOILING IN THE INTERACTION OF INTENSE RADIATION WITH MATTER

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UDC 533.7

The model of stable evaporation [1-4] is widely used to study the interaction of intense radiation with matter. In this model the radiation flux normally incident on a planar surface of the body is constant in magnitude, which also guarantees stationarity of parameter distributions in a coordinate system related to the surface. An assumption of the model is that evaporation occurs at the surface only. As noted in [1, 2], however, in establishing metal evaporation the surface is found to be in a liquid overheated state. Consequently, the evaporation mechanism can be complicated by bubble boiling. This process is usually neglected due to the fact that the surface tension coefficient of metals is large (if the temperature is not too close to the critical temperature), and, consequently, the probability of bubble formation is low [2]. Quantitative estimates are needed to justify this statement. Such estimates were carried out in [5, 6], where it has been shown that there exists a certain intensity flux q_*, above which surface evaporation is modified by bulk boiling. A number of inaccuracies, however, were admitted in [5, 6], which, as shown below, strongly distort the boundaries of the evaporation mechanisms in several cases. The purpose of the present study is to remove these inaccuracies and calculate the quantity q_* more correctly.

1. Vapor bubbles occur in a liquid either as a result of thermal fluctuations (fluctuating bubbles) or due to extraneous impurities (stationary bubbles) [6].

Only bubbles whose radius exceeds a critical r_*, determined from the equation [7]

$$p_0(T)\exp\left(-\frac{2v\sigma}{r_* kT}\right) = p + \frac{2\sigma}{r_*}, \tag{1.1}$$

participate in boiling. In this expression p_0 is the saturated vapor pressure over a planar surface; σ, surface tension coefficient; p, pressure in the liquid; and v, mean volume of the liquid (calculated per molecule).

At temperatures not too close to the critical temperature, where the liquid can be separated into gas-like phases, i.e., the vapor density is much lower than the liquid density ($\rho_{vap} \ll \rho_{liq}$), Eq. (1.1) has the approximate solution

$$r_* = \frac{2\sigma}{p_0(T) - p} = \frac{2\sigma}{\Delta p}. \tag{1.2}$$

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