LITERATURE CITED

1. V. I. Alferov, A. S. Biryukov, E. A. Bozhkova, et al., "Study of interaction of a hypersonic excess air stream and CO_2 aerosol," Inst. Fiz. Akad. Nauk SSSR Preprint No. 275 (1975).
2. B. G. Efimov and L. A. Zaklyaz'minskii, "Experimental study of the effect of mixing conditions in a de Lavalnozzle on the amplification in a supersonic stream," Fiz. Goreniya Vzryva, No. 1, 97-102 (1979).
3. N. A. Fomin and R. I. Soloukhin, "Gasdynamic problems in optically inverse media," Appl. Phys. Rev., 14, No. 2, 421-437 (1979).
4. P. Cassady, J. Newton, and P. Rose, "A new mixing gasdynamic laser," AIAA Paper No. 343 (1976).
5. P. V. Avizonic, D. R. Dean and R. Grotbeck, "Determination of vibrational and translational temperatures in gasdynamic lasers," Appl. Phys. Lett., 23, No. 7, 375-378 (1973).
6. O. V. Achasov, R. I. Soloukhin, and N. A. Fomin, "Numerical analysis of the characteristics of a gasdynamic laser with selective thermal excitation and mixing in a supersonic stream," Kvantovaya Elektron., 5, No. 11, 2337-2341 (1978).
7. A. I. Anan'kin and V. A. Zhevnerov, "Design of gas lasers with mixing streams," Vopr. Radioelektron., Ser. Obshchetekh., No. 3, 84-88 (1976).

DEPENDENCE OF THE BREAKDOWN OF WATER DROPS ON THE PARAMETERS OF A CO_2 LASER PULSE

A. P. Prishivalko

UDC 536.423.1:535.21

Results of a theoretical study are presented pertaining to vaporization and explosion of water drops by a pulsed CO_2 laser, with the nonuniformity of internal heat generation taken into account.

It has been demonstrated in earlier studies [1-4] that a strongly nonuniform internal heat generation enhances appreciably the effect of radiation from high-intensity sources on water drops. Inasmuch as most experimental equipment used for exposing water drops to radiation operates in the pulse mode, the method used in those studies [1-4] is also applicable to studies concerning the vaporization of water drops by pulsed radiation at the $\lambda = 10.6$ μm wavelength and intensities corresponding to the gas-kinetic mode or the explosion mode [5,6].

As a basis for specific calculations, we will proceed by analogy to another study [7] and express the intensity of pulsed radiation being a function of time as the sum of two exponential terms. In order to account for the effect of a usually finite rise time of a pulse, we introduce into the analytical expression for the latter a linear relation between intensity and time during the initial buildup period.

We consider two pulse variants. The first variant will be described by the expressions

$$I(t) = \begin{cases} I_0 [A \exp(-\alpha_1 t_1) + B \exp(-\alpha_2 t_1)]\, t/t_1 & \text{at } 0 \leqslant t < t_1, \quad (1) \\ I_0 [A \exp(-\alpha_1 t) + B \exp(-\alpha_2 t)] & \text{at } t_1 \leqslant t \leqslant t_2, \quad (1a) \end{cases}$$

with the constant coefficient I_0 determined by the source power.

The second variant will be described by the expressions

$$I(t) = \begin{cases} I_0 [(A+B)\, t/t_1] & \text{at } 0 \leqslant t < t_1, \quad (2) \\ I_0 [A \exp(-\alpha_1 (t - t_1)) + B \exp(-\alpha_2 (t - t_1))] & \text{at } t_1 \leqslant t \leqslant t_2. \quad (2a) \end{cases}$$

Letting the variable pulse parameters assume values approximately corresponding to the experimental conditions [7-9], we obtain A = 2, B = 1, $\alpha_2 = 0.5 \cdot 10^6$ sec^{-1}, and $t_2 = 2$ μsec. At time $t_1 = 0$ the half-width of a pulse depends on α_1 and decreases by a factor of 8 as α_1

Institute of Physics, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 38, No. 6, pp. 994-998, June, 1980. Original article submitted May 7, 1979.

 0022-0841/80/3806-0610$07.50

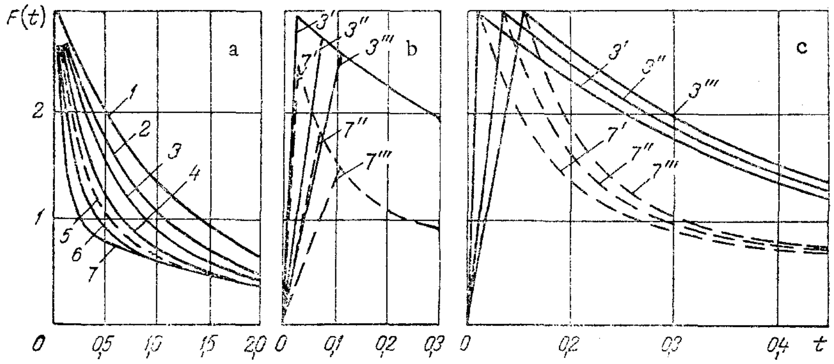

Fig. 1. Pulse form at various values of parameter α_1 (sec^{-1}): 10^6 (1); $1.5\cdot10^6$ (2); $2\cdot10^6$ (3); $3\cdot10^6$ (4); $4\cdot10^6$ (5); $6\cdot10^6$ (6); $12\cdot10^6$ (7) and of t_1 (μsec): $t_1 = 0$ (a); $t_1 = 0.024$ (3', 7'); 0.073 (3", 7"); 0.109 (3''', 7''') (b, c); $F(t) = I(t)/I_0$.

increases from 10^6 to $1.2\cdot10^7$ sec^{-1} (Fig. 1a). In the first pulse variant introducing and then increasing time t_1 results in a lower maximum intensity and a longer half-width of such a pulse, these changes being more appreciable as α_1 increases (Fig. 1b). In the second pulse variant there only occurs a shift of a pulse along the t_1 time scale, without a change in the form of its leading edge (Fig. 1c).

We will now consider vaporization and explosion of water drops with initial radii $R_0 = 10$ and 15 μm by powerful pulsed radiation.

For the purpose of determining the dependence of the time to reach the explosive evaporation mode and of the energy absorbed in this time on the pulse rise time and half-width, at α_1 values within the said 10^6–$1.2\cdot10^7$ sec^{-1} range, calculations have been made of the temperature fields inside such drops for four values of t_1 (0, 0.024, 0.073, and 0.109 μsec) at a fixed $I_0 = 2\cdot10^6$ W/cm^2. In this case varying the parameters α_1 and t_1 corresponds to varying, within a certain range, the energy passing through a unit area of the light beam section over the duration of a pulse.

The results of calculations for drops with radius $R_0 = 15$ μm irradiated by pulses of forms (1) and (2) are given in Table 1, where it appears that the time to reach explosion of a drop is minimum when α_1 is smallest within the given range and $t_1 = 0$. With α_1 fixed, increasing the rise time of a pulse (1) results in a longer time to reach the explosive evaporation mode, 25-30% longer as t_1 changes from 0 to 0.109 μsec (50-60% longer in the case of drops with $R_0 = 10$ μm). As α_1 and t_1 increase simultaneously, the time to reach the explosive evaporation mode can become 2-3 times longer. In the case of a pulse of form (2) increasing its rise time affects the time to reach the explosive evaporation mode to a lesser degree (making t_{expl} not more than 20% longer at a fixed α_1).

It is characteristic that the amount of energy absorbed prior to explosion almost does not depend on the pulse form. The difference in energy E_{abs} does not exceed 4-5% for drops with $R_0 = 15$ μm and 10-13% for drops with $R_0 = 10$ μm.

The case where the amount of energy E passing through a unit area over the pulse duration remains the same regardless of the pulse form has been considered analogously. This condition can be attained by an appropriate regulation of I_0 during the variation of parameters α_1 and t_1. In the simplest case of $t_1 = 0$, I_0 was varied from $1.18\cdot10^6$ to $2.46\cdot10^6$ W/cm^2 to correspond to an increase of α_1 from 10^6 to $12\cdot10^6$ sec^{-1}. With a light beam diameter of 0.425 cm, this corresponded to a pulse energy of 0.5 J. Here calculations for drops with $R_0 = 10$ μm have revealed that, as the half-width of a pulse is decreased, the time to reach the explosive evaporation mode first decreases by a factor of approximately 1.5 and then again increases. The minimum time to explosion, approximately 0.24 μsec, corresponds to $\alpha_1 \simeq 5\cdot10^6$ sec^{-1} and $I_0 \simeq 2.1\cdot10^6$ W/cm^2. The amount of energy absorbed by drops with radius $R_0 = 10$ μm prior to explosion varied within 10%. For drops with $R_0 = 15$ μm the minimum time to reach the explosive evaporation mode is 0.36 μsec with $\alpha_1 = 4\cdot10^6$ sec^{-1} and $I_0 = 2\cdot10^6$ W/cm^2, i.e., with the pulse parameters corresponding to the experimental conditions [7]. The effect of possible variations of I_0 has been considered by the author in the case of pulses of exactly this form.

TABLE 1. Time to Reach the Explosive Evaporation Mode (μsec) and Energy Absorbed in this Time (μJ) for Drops with R_0 = 15 μm, at Various Values of α_1 (sec^{-1}) and t_1 (μsec), with I_0 = $2 \cdot 10^6$ W/cm²

α_1, sec^{-1}	t_1, μsec	Pulse (1)		Pulse (2)	
		t_{expl}	E_{abs}	t_{expl}	E_{abs}
$2 \cdot 10^6$	0	0,292	10,4	0,292	10,4
	0,0243	0,304	10,2	0,292	10,2
	0,0729	0,340	10,2	0,304	10,2
	0,109	0,365	10,1	0,316	10,2
$4 \cdot 10^6$	0	0,363	10,4	0,363	10,4
	0,0243	0,377	10,2	0,340	10,1
	0,0729	0,440	10,2	0,340	10,1
	0,109	0,486	10,2	0,346	10,1
$8 \cdot 10^6$	0	0,535	10,4	0,535	10,4
	0,0243	0,559	10,2	0,486	10,1
	0,0729	0,653	10,2	0,450	10,1
	0,109	0,717	10,2	0,426	10,0
$12 \cdot 10^6$	0	0,644	10,5	0,644	10,5
	0,0243	0,669	10,2	0,596	10,2
	0,0729	0,766	10,2	0,547	10,2
	0,109	0,839	10,3	0,511	10,1

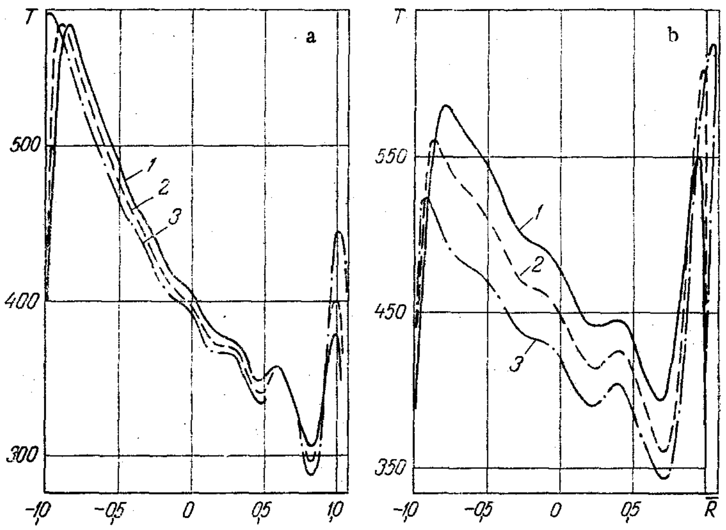

Fig. 2. Temperature distribution at the instant of explosion, along the diameter of drops in the direction of incident radiation, in (a) drops with R_0 = 15 μm and (b) drops with R_0 = 10 μm; t_1 = 0, $\alpha_1 = 4 \cdot 10^6$ sec^{-1}; I_0: 1) $0.75 \cdot 10^6$ W/cm²; 2) 10^6 W/cm²; 3) $2.5 \cdot 10^6$ W/cm².

For the purpose of extending the range of radiation intensity in this study, the pulse duration was increased to t_2 = 10 μsec. Then I_0 could vary from $0.7 \cdot 10^6$ to $2.5 \cdot 10^6$ W/cm². At lower levels of intensity I_0 the pulse energy was insufficient for explosion of a drop. At higher intensity levels the mechanism of explosion was already not a thermal one and our method of analysis would cease to be valid.

As the intensity I_0 decreases from $2.5 \cdot 10^6$ to 10^6 W/cm² in the case of drops with R_0 = 15 μm, the time to reach the explosive evaporation mode becomes 5 times longer and the energy absorbed in this time increases by only 5-6%. As the intensity I_0 decreases to $0.75 \cdot 10^6$ W/cm², however, the time to reach the explosive evaporation mode becomes already 12.5 times longer and the absorbed energy increases by 14%. An explanation for this is that a drop receives a large part of the energy necessary for its explosion at the "tail" end of a pulse, governed by the second term in expression (1a). Meanwhile, all energy losses increase only slightly.

TABLE 2. Coefficients in Expressions (3) and (4)

R_0, μm	a, cm²/MW·μsec	b, μsec⁻¹	c, μJ⁻¹	d, MW/cm²·μJ
10	3,072	2,107	0,37	0,090
15	2,126	1,310	0,107	0,0142

The graphs in Fig. 2 indicate that, as I_0 increases, the temperature distribution in drops with R_0 = 15 μm as well as in drops with R_0 = 10 μm changes most substantially within the extremum ranges of the $T(\bar{R})$ relation. This contributes to an appreciable shortening of the time from the beginning of irradiation to the instant of explosion, with a small change in the total absorbed energy.

As the intensity I_0 decreases from $2.5 \cdot 10^6$ to 10^6 W/cm² in the case of drops with R_0 = 10 μm, the time to reach the explosive evaporation mode also becomes 5 times longer but the absorbed energy increases somewhat more — by 18%. As I_0 decreases further, the temperature peak shifts into the irradiated hemisphere and becomes much more blurry there. As a consequence of this "blurring" of the temperature peak, at $I_0 = 0.75 \cdot 10^6$ W/cm² the time to reach the explosive evaporation mode becomes 16 times longer and the absorbed energy becomes 42% higher than in the case of a pulse with $I_0 = 2.5 \cdot 10^6$ W/cm².

For pulses with $\alpha_1 = 4 \cdot 10^6$ sec⁻¹ and $t_1 = 0$ the expression

$$t_{\mathrm{expl}} = (aI_0 - b)^{-1} \tag{3}$$

approximates, with an error smaller than 15%, the dependence of the time to explosion of a drop on the intensity of radiation I_0 and the approximate expression

$$E_{\mathrm{abs}} = I_0 (cI_0 - d)^{-1} \tag{4}$$

yields, with an error smaller than 5%, the energy absorbed in this time. In both expressions the unit of I_0 is MW/cm². The coefficients in expressions (3) and (4) are given in Table 2.

For drops with R_0 = 10 μm expression (4) overestimates the absorbed energy E_{abs} by 6-10% at $I_0 = (0.7\text{–}0.75) \cdot 10^6$ W/cm², while expression (3) is valid only when $I_0 \geqslant 10^6$ W/cm².

It follows from the preceding analysis that with the main parameters of powerful pulsed radiation varying over the given ranges, the time to reach the explosive evaporation mode can change very appreciably (by a factor of 20). Meanwhile, the energy absorbed by a drop in this time does not change by more than 45% even under the most unfavorable conditions (shift of the temperature peak from the shaded to the irradiated hemisphere of drops with $R_0 \approx 10$ μm). Without such a shift of the temperature peak, moreover, the energy absorbed prior to explosion changes little: not more than by 20%.

NOTATION

A, B, α_1, α_2, parameters characterizing the pulse form; t_1, time to reach the maximum intensity; t_2, time corresponding to the pulse "tail"; I_0, radiation intensity, dependent on the source power; R_0, radius of drops (μm); t_{expl}, time to reach the explosive evaporation mode; E_{abs}, energy absorbed in time t_{expl}; and T, temperature.

LITERATURE CITED

1. A. P. Prishivalko and N. G. Kondrashov, "Analysis of the temperature field inside a drop with nonuniform heat generation," in: First All-Union Conference on Atmospheric Optics [in Russian], Part 2, Inst. Optiki Atmosf. Akad. Nauk SSSR, Tomsk (1976), pp. 168-174.
2. N. G. Kondrashov and A. P. Prishivalko, "Temperature field inside a drop and evaporation in the case of nonuniform heat generation," in: Atmospheric Optics, Trans. Inst. Exper. Meteorology [in Russian], No. 18(71), Gidrometeoizdat, Moscow (1978), pp. 12-22.
3. A. P. Prishivalko, "Evaporation and explosion of water drops due to irradiation with nonuniform internal heat generation," Kvantovaya Elektron., 6, No. 7, 1452-1458 (1978).
4. A. P. Prishivalko, "Effect of changes in the imaginary part of the refractive index of water during heating of water drops on the energy and the time they require to explode due to action of a CO_2 laser," Izv. Akad. Nauk Bel. SSR, Ser. Fiz.-Mat. Nauk, No. 6, 84-89 (1979).

5. A. P. Semenov and P. N. Svirkunov, "Evaporation of a drop in the case of intensive internal heat generation," in: Physics of Aerodispersion Systems, Trans. Inst. Exper. Meteorology [in Russian], No. 23, Gidrometeoizdat, Moscow (1971), pp. 91-107.
6. A. P. Semenov, "Evaporation of a water drop in a radiation field," in: Atmospheric Optics, Trans. Inst. Exper. Meteorology [in Russian], No. 18(71), Gidrometeoizdat, Moscow (1978), pp. 3-11.
7. R. W. Weeks and W. W. Duley, "Interaction of radiation from a TEA CO_2 laser with aerosol particles," Appl. Opt., 15, No. 11, 2917-2921 (1976).
8. P. Kafalas and A. P. Ferdinand, "Fog droplet vaporization and fragmentation by a λ = 10.6 μm laser pulse," Appl. Opt., 12, No. 1, 29-33 (1973).
9. P. Kafalas and J. Herrmann, "Dynamics and energetics of explosive vaporization of fog droplets by a λ = 10.6 μm laser pulse," Appl. Opt., 12, No. 4, 772-775 (1973).

QUENCHING OF AN AIR PLASMA BY SOLID PARTICLES

L. N. Korovin and V. A. Shchelchkov UDC 533.932

An analytical expression which describes the quenching of a relatively cold plasma by cold solid particles is used for designing the length of the quenching reactor. The cooling law thus obtained agrees with experimental data.

Quenching of the products of plasmochemical reactions is one of the governing stages, especially of processes yielding bound nitrogen or acetylene [1-3]. Among the most effective methods of quenching is injection of the plasma into a fluidized bed or, conversely, injection into the plasma jet of cold solid particles acting as the intermediate heat carrier [4-6]. Results of calculations of the heat transfer from plasma to solid particles have been presented in other reports [7-9] in either numerical or criterial form. No simple expressions are given there, however, which would be convenient to use for practical calculations. In order to obtain such expressions, we will here find an analytical solution to the problem of heat transfer from a gas (originally plasma) stream to solid particles.

We consider a cylindrical channel of length l and diameter d. The channel axis coincides with the X axis of coordinates. At the X = 0 section of the channel a gas stream enters carrying spherical solid particles of the same diameter D. The gas velocity is $W_0 \gg W_s$ (soaring velocity). We assume that all motion is steady and the gas flow is one-dimensional. The latter assumption implies that the gas velocity and temperature at any X do not vary along Y and Z. When the solid particles in the gas stream are uniformly distributed over the cross section of the latter, then to each solid particle corresponds a definite mass of gas (gaseous "particle").

The equations of heat transfer according to Newton's law and the equation of heat balance are

$$-mc_p dT = m_s c_{ps} dT_s = \alpha F (T - T_s)\, dt, \tag{1}$$

$$-\frac{d}{dt}(T - T_s) = \alpha F \left(\frac{1}{mc_p} - \frac{1}{m_s c_{ps}}\right)(T - T_s), \tag{2}$$

$$\int_{T_0}^{T_f} mc_p dT = \int_{T_{sf}}^{T_{s0}} m_s c_{ps} dT_s. \tag{3}$$

The energy balance (3) yields

$$\frac{m_s}{m} = \frac{G_s}{G} = \frac{\int_{T_0}^{T_f} c_p dT}{\int_{T_{sf}}^{T_{s0}} c_{ps} dT} \tag{4}$$

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 38, No. 6, pp. 999-1004, June, 1980. Original article submitted May 24, 1979.

 0022-0841/80/3806-0614$07.50