WATER DROPLET EVAPORATION IN A CONTINUOUS CO_2 LASER RADIATION FIELD

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Experimental data are presented on the evaporation of small water droplets in the powerful radiation beam of a CO_2 laser. Possible reasons for divergence between experimentally measured and calculated evaporation rates are considered.

A complete theoretical study has been performed of droplet evaporation with internal heat sources [1-7]. In the case where heat liberation within the droplet is produced by dissipation of continuous CO_2 laser radiation there are available experimental data on droplet evaporation rate for radiation intensities $I \leqslant 10^3$ W/cm^2 and droplet diameters $d \geqslant 50$ μm [8-11].

The purpose of the present study is to complement the existing experimental data with a study of the evaporation rate of small water droplets with $d \leqslant 70$ μm at high ($I \geqslant 10^3$ W/cm^2) continuous radiation intensities at a wavelength $\lambda = 10.6$ μm and to evaluate the data obtained.

In contrast to previous studies, the present experiments were performed with droplets in free fall. This eliminated the distorting influence of the suspension filament.

In the experiments, droplet size was determined as a function of time from the commencement of irradiation (with a high-speed camera) and the radiation intensity was measured. A detailed description of the measurement equipment is presented in [12]. Droplet size was measured to an accuracy of ±1 μm, radiation intensity to ±15%, and the commencement of irradiation and time intervals to $\pm 10^{-5}$ sec. The parameters varied were initial droplet diameter and intensity of the radiation.

Table 1 presents typical experimental data on the time dependence of water droplet diameter in the CO_2 laser radiation field.

Table 2 presents averaged values of evaporation rate $|\dot{d}|$ for eight ranges of CO_2 laser radiation intensity I and six ranges of current droplet diameter d. Data of 70 experiments were used in the averaging. The evaporation rate $|\dot{d}|$ corresponding to a certain value of current droplet diameter was determined from the slope of the straight line drawn through the experimental points of the time dependence of droplet diameter located in the vicinity of the diameter value under consideration. The straight line was extended through not less than four points. The initial portion of the evaporation curve corresponding to droplet heating was eliminated from consideration. The error in $|\dot{d}|$ determination was estimated from the scattering in evaporation rates for several droplets located in the same range of current droplet diameters at an identical radiation intensity. The equation describing droplet evaporation with which the experimental data will be compared follows from the energy balance equation:

$$\dot{d} = -\frac{IK_a}{2\rho L}. \tag{1}$$

This formula is obtained with the assumption that all the radiation power absorbed by the droplet is expended in evaporation only. It is obviously invalid in the case where it is necessary to consider heat losses produced by thermal conductivity of the vapor–air medium (for $dIK_a \leqslant 1.4$ W/cm [9]), and also in the initial stage of radiation interaction with the droplet, where the droplet is heated.

In all radiation intensity and droplet size intervals examined in the present study heat loss due to thermal conductivity may be neglected, and the initial stage of evaporation must be eliminated from consideration, since the error in droplet size measurement referred to above prohibits quantitative analysis of this stage.

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TABLE 1. Water Droplet Diameter versus Time for Various Laser Radiation Intensities, λ = 10.6 μm

I=930±140 W/cm²	$t\cdot10^3$ sec	0	1,15	2,30	3,45	4,60	5,75	6,90	8,05	9,20	10,35	11,50
	d, μm	70	70	69	66,5	64,5	61,5	59				
		50	50	48	45,5	42,5	39,5	37	35	32,5	30	
		30	29,5	27,5	25	23	21	18,5	16,5	15	13,5	12,5
I=(1.3±±0,1)·10⁴ W/cm²	$t\cdot10^4$	0	1	2	3	4	5	6	7	8	9	10
	d	58	58	57	54	51,4	48,5	45	43,5	40	38	36
	$t\cdot10^4$	0	0,5	1,5	2,5	3,5	4,5	5,5	6,5	7,5	8,5	
	d	26	26	25	23	21	18	16	14	12	10,5	
	$t\cdot10^4$	0	0,7	1,7	2,7	3,7	4,7	5,7	6,7	7,7		
	d	12	12	10,5	9	8	7	5,5	5	4,5		
I=(2.2±±0.2)·10⁴ W/cm²	$t\cdot10^4$	0	0,8	1,8	2,8	3,8	4,8	5,8	6,8			
	d	32	31,5	27,5	23,5	20	16,5	14	12			
	$t\cdot10^4$	0	0,8	1,8	2,8	3,8	4,8	5,8				
	d	24	23,5	20,5	17	14	11,5	9,5				
	$t\cdot10^4$	0	0,6	1,6	2,6	3,6	4,6	5,6				
	d	14	13,5	11,5	9	6,5	5	4				

TABLE 2. Droplet Evaporation Rate, cm/sec, for Various Droplet Diameters and Radiation Intensities

$I\cdot10^{-4}$ W/cm²	Diameter, μm					
	5–10	10–15	15–20	20–30	30–40	40–55
1,1±0,1		1,5±0,1	1,8±0,1	2,0±0,2	2,3±0,2	2,3±0,2
1,3±0,1	1,3±0,1	1,8±0,1	2,1±0,2	2,3±0,2	2,7±0,2	2,7±0,2
1,5±0,1		2,0±0,1	2,4±0,2	2,6±0,2	3,1±0,2	3,2±0,2
1,9±0,2	1,8±0,1	2,5±0,1	3,0±0,2	3,3±0,2	3,9±0,2	
2,2±0,2	2,0±0,1	2,6±0,1	3,5±0,2	4,0±0,2		
2,5±0,4	2,4±0,2	3,2±0,2	4,5±0,3			
2,7±0,4	2,5±0,2	3,6±0,2	4,2±0,2			
3,0±0,4	3,0±0,2	3,6±0,2	4,6±0,3			

Thus, in the present case Eq. (1) should be sufficiently accurate.

In fact, the experimental data (Table 1) and calculations with Eq. (1) for radiation intensities of the order of 10^3 W/cm² do coincide within the limits of experimental error.

At high radiation intensities ($I \geqslant 10^4$ W/cm²) up to threshold values for droplet destruction [13] one can also divide the droplet interaction with radiation into a heating stage and a quasistationary evaporation stage and not consider the former. However, as was demonstrated in [14], at such radiation intensities the thermal energy lost by the drop in the heating stage must be considered. Consideration of this factor leads to an increase in evaporation rate at $I \geqslant 10^4$ W/cm² by approximately 20-30% as compared to the value calculated with Eq. (1).

However, the experimental data (Table 1) show a decrease in evaporation rate as compared to Eq. (1). This decrease exceeds the limits of experimental error.

It is thus necessary to explain why the experimental evaporation rate values in this range of radiation intensity and droplet size are lower than expected.

Two reasons which could reduce the evaporation rate appear most probable: change in the optical constants of water at significant superheatings and an increase in loss of energy absorbed by the droplet to kinetic energy of the vapor flow from the surface of the intensely evaporating droplet.

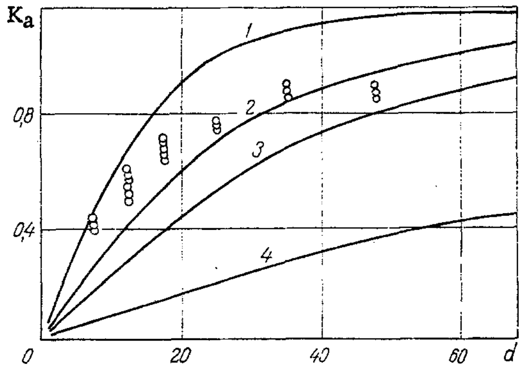

Fig. 1

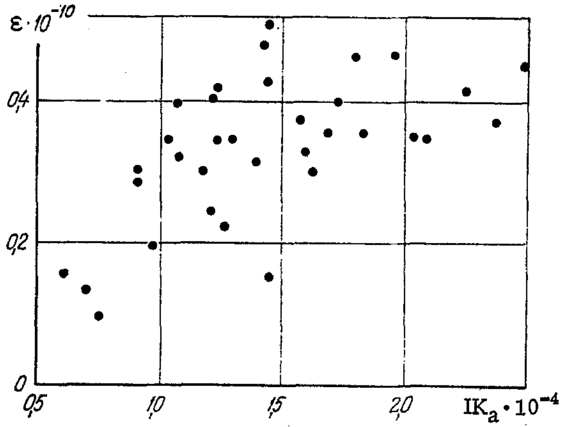

Fig. 2

Fig. 1. Radiation absorption effectiveness factor K_a for $\lambda = 10.6$ µm for water droplets of various size. Points show K_a values calculated from experimental data. Solid curves are K_a values calculated with the Mie theory for various values of the imaginary component of the complex index of refraction: 1) $m = 1.175 - i \cdot 0.0790$; 2) $1.175 - i \cdot 0.0395$; 3) $1.175 - i \cdot 0.0263$; 4) $1.175 - i \cdot 0.0079$. K_a, dimensionless; d, µm.

Fig. 2. The effect of IK_a on specific kinetic energy of a vapor flow calculated by the experimental data. IK_a, W/cm²; ε, cm²/sec².

We will now consider these two possible mechanisms. The behavior of the imaginary component of the index of refraction of water $\varkappa_{10.6}$ at a temperature $T > 90°C$ is unknown, and we can only assume from general considerations that $\varkappa_{10.6}$ decreases with increase in water temperature. According to the data of [15], in the temperature range 5-90°C, $\varkappa_{10.6}$ decreases not more than 30%.

The solid lines of Fig. 1 show values of the radiation absorption effectiveness factor, calculated by numerical methods with the use of the Mie theory, as a function of droplet radius for various values of the imaginary component of the complex index of refraction $m = n - i\varkappa$. The points on the figure show K_a values calculated from experimental data (Table 2) using Eq. (1), with the assumption that the experimentally observed reduction in evaporation rate is related exclusively to temperature change of $\varkappa_{10.6}$. For each radius value the set of points in Fig. 1 corresponds to the entire range of radiation intensities realized in the experiments (from $1 \cdot 10^4$ to $3.4 \cdot 10^4$ W/cm²).

From Fig. 1, considering data on the temperature dependence $\varkappa_{10.6}(T)$ [15] and the fact that in our case the mean water temperature in the evaporating droplets is significantly above 100°C [5, 7], we can conclude that the temperature dependence $\varkappa_{10.6}(T)$ may be the cause of the observed reduction in droplet evaporation rate.

However, in such an interpretation of the data it is difficult to explain why K_a depends quite strongly on droplet radius while its dependence on radiation intensity is unexpectedly weak.

We will consider another possibility. In Eq. (1), in the denominator there appears the specific heat of evaporation L. While the total pressure of the vapor–air medium near the evaporating droplet is equal to atmospheric, the evaporation process is isobaric and L is equal to the difference between the enthalpies of water and its vapor [16]. For higher radiation intensities, where the droplet surface temperature exceeds 100°C, the process is no longer isobaric. In this case the effective specific heat of evaporation L* is equal to the enthalpy difference plus the specific kinetic energy of the vapor flow $L^* = L + \varepsilon$, where $\varepsilon = v_v^2/2$.

Figure 2 shows the dependence of the quantity ε on IK_a calculated with the experimental data of Table 2 and Eq. (1) with L replaced by L*. It was assumed that the observed reduction in evaporation rate is produced exclusively by this effect.

The quantity ε can be determined from the experimental data only with great uncertainty, but the basic tendencies of the function $\varepsilon(IK_a)$ are completely determined from the location of the points: For $IK_a \sim 0.5 \cdot 10^4$ W/cm^2, ε is close to zero, and with increase in IK_a to $2.5 \cdot 10^4$ W/cm^2 it reaches values comparable to the square of the speed of sound in water vapor.

It should be noted that the form of the function $\varepsilon(IK_a)$ and the numerical values of ε are close to those expected, which indicates indirectly that it is this mechanism which produces the basic contribution to the reduction in droplet evaporation rate in the radiation field as compared to calculated values.

Evaluations made show that all other mechanisms (for example, temperature dependence of specific heat, density, or heat of evaporation; consideration of effects related to inhomogeneity in the distribution of heat sources over droplet volume; etc.) cannot explain the observed divergence in the data on evaporation rate.

It must be noted that if at $I \geqslant 10^4$ W/cm^2 the addition to L, ε (see Fig. 2) begins to play a significant role, then this means that even at $IK_a \sim 0.5 \cdot 10^4$ W/cm^2 a gasdynamic regime of droplet evaporation is realized [9], and hence the water condensation coefficient value of 0.03 [7] would be more correct than unity.

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NOTATION

I, intensity of laser radiation; λ, wavelength of laser radiation; d, water droplet diameter; $\dot{d}$, droplet evaporation rate; K_a, radiation absorption effectiveness factor for a droplet; $m = n - i\varkappa$, complex index of refraction; n, real component of index of refraction; $\varkappa_{10.6}$, imaginary component of index of refraction at wavelength of 10.6 μm; ρ, water density; L, specific heat of evaporation of water; $L^* = L + \varepsilon$, effective specific heat of evaporation; ε, specific energy of vapor flow; v_v, vapor flow rate at droplet surface; α, water condensation coefficient.

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