# DYNAMICS OF THE RADIUS AND TEMPERATURE OF A PARTICLE OF A WET CARBON AEROSOL IN THE COURSE OF ITS COMBUSTION IN A POWERFUL OPTICAL FIELD

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*The results of calculations of the time-dependences of the radius and temperature of a carbon aerosol particle during its combustion in the radiation field of a powerful laser in wet air are presented. The combustion is shown to take place more rapidly than in dry air. The process of particle combustion was also observed experimentally. Qualitative agreement with the calculations was obtained. A distinct thermal halo around the particle due to the combustion of hydrogen formed in the reaction of carbon with water vapor was detected.*

Propagation of powerful laser radiation in a carbon particle-containing atmosphere has been studied in many papers without consideration of the problem of the effect of atmospheric humidity upon the process. However, as our calculations show,[1,2] the rate of combustion of a particle in a radiation field in the presence of water vapor is greater than in dry air, which has a direct effect on the rate of clearing of the medium. In the indicated papers, the combustion rate is calculated as a value which characterizes the loss of carbon mass from a unit area of the particle surface per unit time. Based on those results,[1,2] in this paper we determine the time-dependences of the radius $a(t)$ and the surface temperature of the particle $T_s(t)$ during the process of combustion in a radiation field of known intensity $I$ applying the laws of mass and energy conservation.

The law of conservation of the total carbon mass leads to in the equation

$$\frac{da}{dt} = -\frac{K(a,\ T_s)}{\rho}\ , \tag{1}$$

while the law of energy conservation leads to the equation

$$\frac{dT_s}{dt} = \frac{3}{4a\rho C_p}\left[k_a(a)I + 4Q(a,\ T_s) - \frac{4}{a}\int_{T_0}^{T_s}\mu(\xi)\,d\xi - 4\sigma\left(T_s^4 - T_0^4\right)\right]\ . \tag{2}$$

here ρ and $C_p$ are the density and the specific heat of the particle substance, respectively, $K(a, T_s)$ is the rate of combustion of the particle in kg/m$^2$s, $k_a(a)$ is the absorption efficiency factor, $I$ is the radiation intensity, $Q(a, T_s)$ is the specific heat effect of the complex of combustion reactions, $T_0$ is the air temperature far from the particle, $\mu(T)$ is the thermal conductivity coefficient of air, and σ is the Stefan-Boltzmann constant. The initial conditions of the problem are $a(0) = a_0$ and $T_s(0) = T_0$. The combustion rate $K(a, T_s)$ is found both for small particles, for which it is possible to neglect the homogeneous burndown reaction of CO in the vicinity of the particle, and for large ones, for which CO burndown begins to appear. At the same time, the influence of the homogeneous reaction on the combustion rate is not great, although the partial pressures of the reactants can vary considerably. Therefore, it is possible to use the formula for $K(a, T_s)$ obtained in the heterogeneous combustion approximation[1] in the calculations. Note that it is necessary to meet the conditions which ensure the burndown regime of the hydrogen produced in the reaction of carbon with water vapor in a thin spherical layer around the particle. This condition is discussed in Ref. 2 and has the form

$$a\,\frac{\alpha(T_s)}{D(T_s)}\,\frac{p_{H_2O}}{p_{O_2}} < 1, \tag{3}$$

where $D(T_s)$ is the effective diffusion coefficient in the vicinity of the particle,[2] $a(T_s)$ is the reaction constant of the gas-exchange reaction $C + H_2O \rightarrow CO + H_2$, and $p_{H_2O}$ and $p_{O_2}$ are the partial pressures of $H_2O$ and $O_2$ far from the particle.

The heat effect $Q(a, T_s)$ is expressed in terms of the specific heat effects of the heterogeneous reactions $2C + O_2 \rightarrow 2CO$ and $C + O_2 \rightarrow CO_2$, and the CO and $CO_2$ fluxes, the formulas for which were obtained in Ref. 1.

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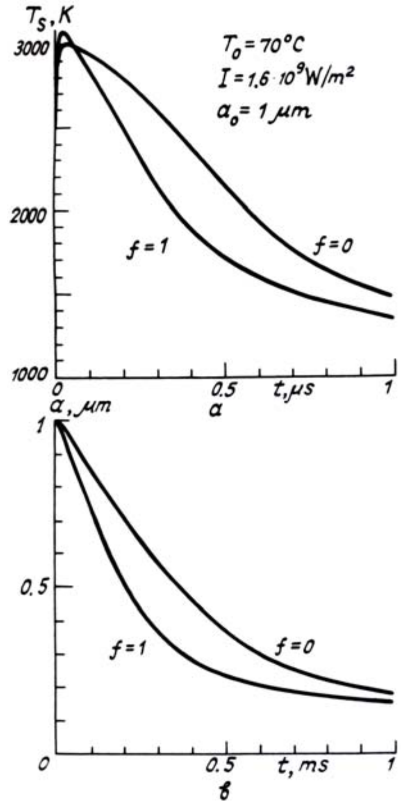


*FIG. 1. Calculations of $T_s(t)$ (a); and $a(t)$ (b) for* $T_0 = 70°C$ $I = 1.6 \cdot 10^9$ W/m$^2$, *and* $a_0 = 1$ μm

The results of the numerical calculations are displayed in Figs. 1–3. The process parameters are so selected as to make it possible to change the relative air humidity $f$ from 0 to 1 for particles of different dimensions while still maintaining condition (3). The greater the absolute air humidity, the more distinct the difference between the curves $a(t)$ and $T_s(t)$ in the "dry" and "humid" cases is. The presence of humidity results in an acceleration of the combustion. The maximum temperature increases slightly in the case of small particles, while decreasing for larger ones. We used the dependence $k_a(a)$ for the radiation wavelength $\lambda = 1.06$ μm, calculated beforehand according to the model described in Ref. 3, in our calculations, the complex refraction index of carbon being taken equal to $1.95–i0.66$.[4]

To verify our calculated results, measurements of the process of particle combustion by means of a high-speed photography were carried out. Soot particles were placed at the butt-end of a quartz fiber in a special cell, in which a heater and an evaporator had been installed. Continuous radiation from an LTN-102 laser with wavelength 1.06 μm, which was focused onto the particle by a lens, was introduced into the cell through a window. Prior to the experiment, the air in the cell was heated to 60–80°C, and the evaporator was then turned in. When a high air humidity (close to $f = 1$) had been reached, an electromagnetic gate was opened and powerful radiation impinged upon the particle. The radiation intensity $I$ was of the order of $10^7$ W/m$^2$. The combustion process was recorded by an SKS-1M high-speed motion picture camera.

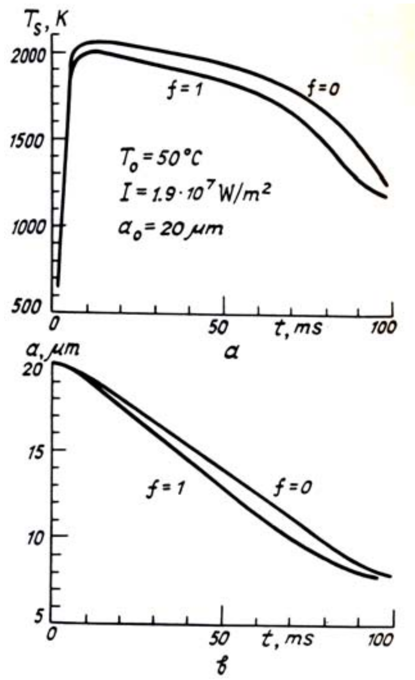


*FIG. 2. Calculations of $T_s(t)$ (a); and $a(t)$ (b) for* $T_0 = 50°C$ $I = 1.0 \cdot 10^7$ W/m$^2$, *and* $a_0 = 20$ μm

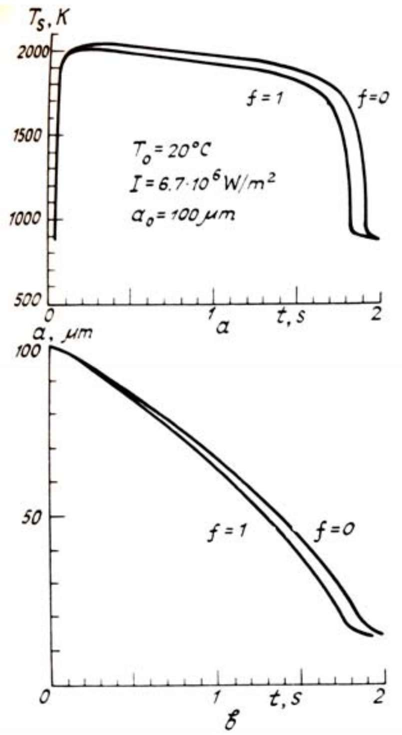


*FIG. 3.* Calculations *of $T_s(t)$ (a); and $a(t)$ (b) for* $T_0 = 20°C$ $I = 6.7 \cdot 10^6$ W/m$^2$, *and* $a_0 = 100$ μm

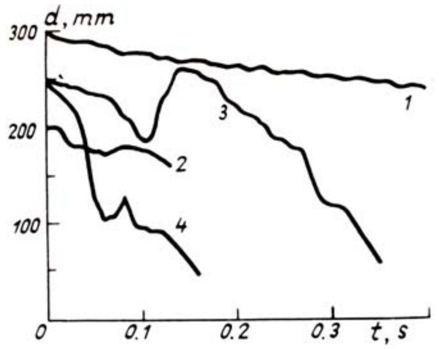


*FIG. 4. Processing results of. the cinegrams of particle combustion: 1 and 2 — in a dry atmosphere, 3 — in a wet atmosphere,* $T_0 = 67°C$*; 4 — in a wet atmosphere,* $T_0 = 75°C$.

The results of processing several cinegrams are presented in Fig. 4. Curves 1 and 2 correspond to combustion of particles in dry air at room temperature, while curves 3 and 4 correspond to combustion in wet air at an increased temperature. Measurement of the diameter of the particles was carried out up until the moment of particle breakaway from the fiber and its disappearance from the field of view. In the experiments in wet air, their partial fragmentation was observed, whereupon the apparent diameter of a luminous particle increased owing to the formation of an optically noticeable heat halo (Curve 3). A possible cause of fragmentation is the rapid evaporation of the humidity adsorbed in the outer particle layers. The halo concealed the true dimensions of the particle and decreased in size as the particle burned. As the process comes to an end, the temperature of the particle decreases, the halo becomes weaker, and the outline of the particle becomes visible again (see curve 3, $t > 0.3$ s). For combustion in dry air the halo becomes less distinct. The presence of a more distinct halo in wet air is apparently explained by the combustion of hydrogen formed in the vicinity of the particle's surface. This process, as estimates show, occurs around the particle in a layer comparable in its thickness with the particle's dimensions (i.e., condition (3) is not met). A great quantity of heat is produced in this layer, which strongly effects the refraction index profile of the gas medium. The rate of decrease of the particle radius, as can be seen from our experimental results, is greater in wet air than in dry air, which is in qualitative agreement with the results of our calculations.

## REFERENCES

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