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RECENT PUBLICATIONS, SUBMITTALS FOR PUBLICATION AND PRESENTATIONS:

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ABSTRACT

We analyse the interactions of atmospheric aerosols with a high-energy laser beam. The energy balance equation allows us to compute the conversion of the pulse energy into temperature increase, vaporisation, conduction, and convection. We also include the shrinkage term whose significance has recently been discussed by Davies and Brock.

INTRODUCTION

The propagation of a high-flux beam of electromagnetic radiation through the atmosphere results in a variety of interactions between the beam and atmospheric aerosols present along the propagation path. At low irradiances,[1] linear absorption and scattering processes comprise the dominant aerosol-beam interactions. Aerosol heating and vaporisation become important as the irradiance increases;[2-6] for even higher irradiances hydrodynamic, plasma, and nonlinear optical phenomena may occur.[7] For example, for micron-size water droplets irradiated by 10.6μm light, heating and vaporization become significant at an irradiance ~ 10^3

W/cm^2, whereas for irradiance levels $\geq 10^6$ W/cm^2 hydrodynamic, plasma, and nonlinear optical effects become significant.

In this paper, we emphasize the intermediate irradiance regime, where aerosol heating and vaporization are important. In this case, the diffusive mass transport and conductive energy transport dominate the aerosol-beam interactions. A numerical analysis of the coupled aerosol-beam equations allows us to compute the energy conversion of the incident laser pulse. This will be given in the form of plots showing the fractional energy conversion. We include the droplet radius shrinking with time similar in form to that recently analysed by Davies and Brock.[8]

AEROSOL HEATING AND VAPORIZATION

For an incompressilble droplet of density ρ and constant specific heat C, the general energy conservation equation has the form

$$\rho\frac{\partial}{\partial t}(CT_L + \frac{1}{2}v^2) + \rho\nabla\cdot\left[(CT_L + \frac{P}{\rho} + \frac{1}{2}v^2)\mathbf{v}\right] + \nabla\cdot(-\kappa\nabla T_L) = W, \tag{1}$$

where T_L and $\mathbf{v}$ are the droplet temperature and velocity at any point of the droplet, κ is the thermal conductivity, and W is the rate at which the energy is absorbed by the beam. For moderate fluxes considered here the kinetic energy term in the first term of Eq. (1) can be neglected as compared to the internal energy of the drop. If a denotes the instantaneous droplet radius, we obtain after integrating over the sphere with the radius $a + \epsilon$, where ϵ is an infinitesimally small number:

$$\frac{4\pi a^3}{3}\rho C\frac{dT}{dt} + 4\pi a^2 m[L + C(T - T_0)] - 4\pi a^2 K\left(\frac{\partial T}{\partial r}\right)_{r=a} + 4\pi a^2\frac{m^3}{2\rho'^2} = \pi a^2 Q_a F. \tag{2}$$

Here we have defined the mass flux $m = \rho v$; L is the heat of vaporization, and T_0 and T_g refer to the ambient temperature and the temperature of the gas. The other symbols in Eq. (2), K, ρ', Q_a, and F denote the thermal conductivity and density of the surrounding medium, Mie absorption efficiency factor, and the incident flux, respectively. Finally, the volume-averaged droplet temperature,[8] is identified with the temperature T at the drop's surface. We note that the term $4\pi a^2 C(T - T_0)$ accounts for the droplet radius shrinking with time. If T_{boil} denotes the boiling temperature, the relative significance of this term can be expressed by the ratio $C(T_{boil} - T_0)/L$. For water droplets this does not exceed 15%; we retain, however, the shrinkage term for completeness.

Energy and mass conservation in the surrounding medium allow us to compute the mass and heat fluxes. If the explicit time dependence in the conservation equations is ignored, the desired relations are

$$m = \frac{D}{a} ln \left[\frac{1 - Y_0}{1 - Y_0 exp(\frac{LM}{RT_0} - \frac{LM}{RT})} \right], \tag{3}$$

$$K(\frac{\partial T}{\partial r})_{r=a} = - \frac{mC_p(T - T_0)}{exp(mC_p a/K) - 1}, \tag{4}$$

where D, M, and C_p are the vapor-diffusion coefficient. molecular weight, and specific heat, respectively; R is the ideal gas constant, and Y_0 is the ambient-vapor mass fraction in the surrounding medium.

Inserting Eq. (4) into Eq. (2), and using the relation $m = -\rho \partial a/\partial t$, results in two coupled eqautions for the droplet temperature and radius. These equations have the form

$$\frac{\partial T}{\partial t} = \frac{3Q_a F}{4a\rho C} - \frac{3m}{4a\rho C} \{ L + \frac{C(T - T_0)}{m} + \frac{C_p(T - T_0)}{exp(mC_p a/K) - 1} + \frac{m^2}{2\rho'^2} \}, \tag{5}$$

$$\frac{\partial a}{\partial t} = - \frac{m}{\rho}. \tag{6}$$

The beam irradiance F is given by the solution to transport equation, which—due to the dependence of the scattering and absorption coefficients on F—defines a nonlinear transport problem

ENERGY DEPOSITION IN IRRADIATED DROPLETS

Equation (2) may be integrated term-by-term over the duration of the pulse and the volume of a single droplet to determine the distribution of incident beam energy into different dissipative modes. This yields:

$$E_H^{(0)} + E_V^{(0)} + E_C^{(0)} + E_S^{(0)} = E_P^{(0)}, \tag{7}$$

where $E_i^{(0)} (i = H, V, C, S)$ gives the energy deposited in heating, vaporisation, conduction, and drop shrinking, respectively, and where $E_P(0)$ is the energy of the pulse deposited in a single drop. In Eq. (7), we have neglected the small contribution arising from the convection term. Integrating Eq. (10) over the volume swept by the beam, when the beam traverses a distance s, we get the energy balance equation for the laser beam. In fractional form, it reads

$$Q_H + Q_V + Q_C + Q_S = 1. \tag{8}$$

Here $Q_i = E_i/E_T (i = H, V, C, S)$ gives the fraction of the deposited beam energy. At a distance s from the input plane, E_T can be computed from the equation

$$E_T = E_0 - \int F(r, t) dt d^2 r, \tag{9}$$

where E_0 is the initial energy of the pulse.

In Fig. 1, we show the contributions of the energy terms in Eq. (8) for the low flux case in which the maximum value of the irradiance of a Gaussian pulse is 10^3 W/cm^2. For the sake of completeness, we also show in Fig. 2 the pulse irradiance as a function of the propagation distance z and the time t. In Figs. 3 and 4, we present similar results for a higher flux case corresponding to $F_{MAX} = 10^5$ W/cm^2.

CONCLUSIONS

In this paper, we have obtained solutions to the coupled system of droplet-beam equations, which are valid for beams of moderate irradiance. The results of these calculations illustrate features of interest such as punch-through and the significance of droplet vaporisation. For the low flux case, as shown in Fig. 1, the beam energy is depleted primarily by the droplet vaporisation process. For the high flux case, Fig. 3, the beam energy essentially remains constant although droplet vaporisation continues to be the dominant process.

In future work, we will extend these results into the regime where convective vaporisation and hydrodynamic effects must be included.

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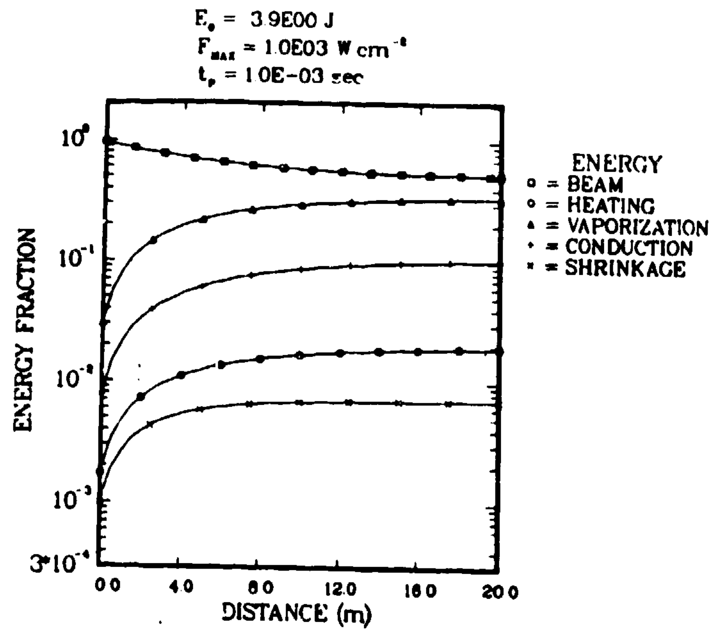

FIGURE 1. Energy balance for 5μm water droplets irradiated by 10.6 μm laser radiation; $F_{MAX} = 1 \times 10^3$ W/cm^2.

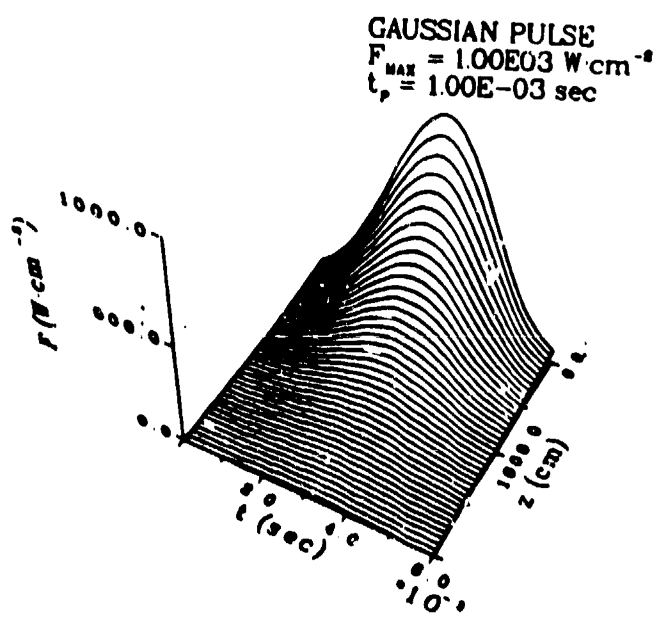

FIGURE 2. Spatio-temporal behavior of laser beam irradiance; $F_{MAX} = 1 \times 10^3$ W/cm^2.

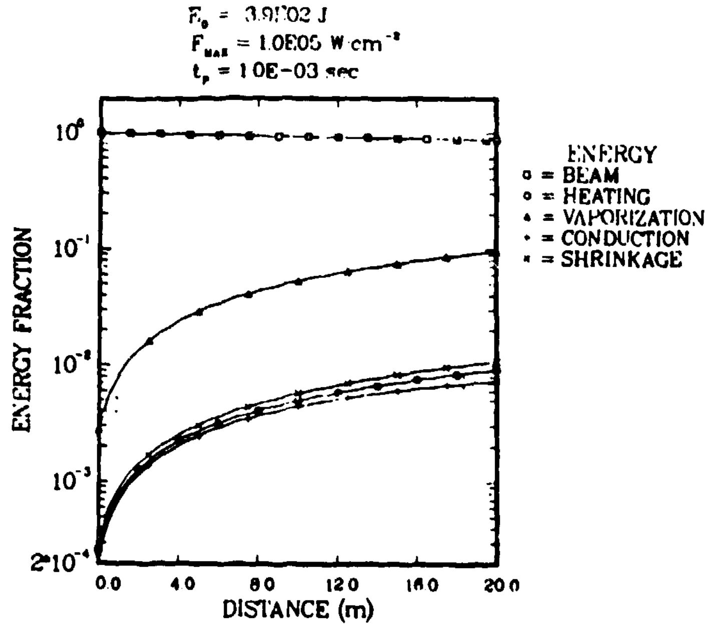

FIGURE 3. Same as Fig. 1, but $F_{MAX} = 1 \times 10^5$ W/cm^2.

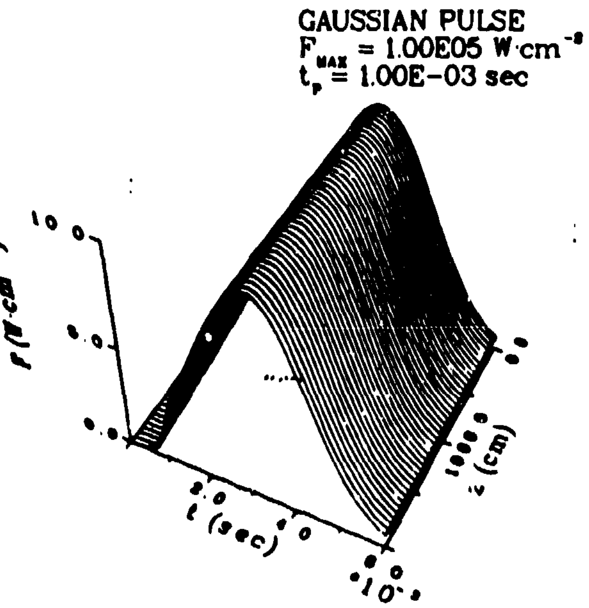

FIGURE 4. Same as Fig. 2, but $F_{MAX} = 1 \times 10^5$ W/cm^2.