the centerline, Eq. (6), approach those obtained using Eq. (7). Also, since the latter formulation does not contain the unrealistic uncoupling of the centerline from the remainder of the flow, the "true" solution can be approximated with fewer grid points when the integrated approach is used.

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Laser-Induced Impulse to a Phenolic Surface

Peter K. Wu* and Peter E. Nebolsine†
Physical Sciences Inc., Woburn, Mass.

Introduction

THE phenomenology of laser-induced impulse to a surface has been studied both in vacuum and under atmospheric conditions.[1,2] This Note examines the transient momentum transfer in vacuum to graphite and carbon phenolic surfaces for laser intensities below the threshold for plasma formation. In vacuum, experimental measurements[3] indicate that the laser-induced breakdown above the carbon phenolic and ATJ graphite surfaces for 10.6μ laser beam is of the order of 10^7 W/cm^2. Here we consider intensities below this level.

Analysis

A one-dimensional transient heat conduction problem has been formulated and applied to carbon phenolic.[2] Here we apply the same analysis to ATJ graphite as well as a carbon phenolic with different characteristics from that of Ref. 2. The nominal resin content in the present carbon phenolic is about 34% by weight while the previous carbon phenolic has a resin content of about 11%. Here we consider the absorption coefficient for 10.6μ to be 0.62 (Ref. 4), instead of 0.81 (Ref. 2) and use a more recent reaction rate for the pyrolysis.[5] Finally, in Ref. 2, the molecular species coming off the surface in the process of vaporization is assumed to be carbon (C). However, recent experiments[6] indicate that C_3 is the predominant specie in the saturated vapor. In these calculations, the thermodynamic properties of both ATJ graphite and carbon phenolic are taken from Ref. 7.

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*Principal Scientist. Member AIAA.

†Principal Scientist.

The laser energy is assumed to be instantaneously absorbed at the surface. This implies that the absorption length in the solid is small compared with the characteristic thermal depth. For the carbon phenolic, which is made with a carbon fiber content of about 66% by weight and ATJ graphite, the surface absorption assumption is justified because of short absorption depth of 10.6μ radiation in carbon ($\sim 1\mu$).[3] For the carbon phenolic, which is made with a nominal resin content of 34% by weight, the phenolic resin decomposes at an elevated temperature that is below the sublimation temperature of carbon and the phenolic gas is assumed to be able to escape through the porous carbon char.

The calculation of impulse delivered per unit of incident energy, i.e., the "coupling coefficient," requires some knowledge of the conditions above the solid surface. Assuming that the vapor temperature immediately above the surface is the same as the surface temperature, $T_v = T_s$; that the rate of graphite evaporation equals the rate of condensation under equilibrium conditions; and that the accommodation coefficient is unity; one then has the Knudsen-Langmuir expression for vacuum environment

$$P_v = \dot{m}\sqrt{2\pi R T_s}$$

The mass flux $\dot{m}$ and the surface temperature T_s are obtained from the energy balance at the solid surface. For the vapor gas constant, one needs to know the molecular species in the vapor when vaporization is generated from a surface with a high-power laser. In studying the characteristics of freejet vapor expansions created by the pulse-laser vaporization of graphite materials, Covington et al.[6] have observed that the equilibrium conditions (C_3 is the predominant specie) prevail in the saturated vapor phase at high temperatures. Now that the vapor pressure is known, one can readily calculate the integrated coupling coefficient

$$C = \int_0^t P_v \mathrm{d}t \Big/ \int_0^t I \mathrm{d}t$$

Results and Discussion

The calculations have been carried out for ATJ graphite and carbon phenolic. The coupling coefficients for ATJ graphite and carbon phenolic are given in Fig. 1 as a function of time with laser intensity varying from 10^3 to 10^7 W/cm^2. We first consider the results for ATJ graphite. Before the surface temperature reaches the sublimation temperature of graphite, the coupling coefficient is negligibly small. As the surface temperature passes the sublimation temperature of graphite, the coupling coefficient rises rapidly and approaches the asympotic value of approximately 6 dyn-s/J. In order to present the preceding results in a format that can be readily compared with some actual measurements in the future, we plot the coupling coefficients as function of fluence for laser pulse times of 1, 3, and 20 μs (Fig. 2). Again, the coupling coefficients are observed to rise rapidly to the steady-state value after the appropriate levels of fluence, which correspond to the sublimation temperature, have been reached.

After the laser intensity reaches the breakdown threshold ($\sim 10^7$ W/cm^2), a plasma is ignited and a steady-state situation may eventually be attained. Basov et al.[8] have modeled the two-dimensional steady-state plasma by assuming that the plasma is a completely singly ionized gas. For the steady-state coupling coefficient with the plasma, one gets $C \approx \rho u^2/I$, where u is the velocity at the surface. From the results of Basov et al.[8] one gets

$$C \approx 3.5 \times 10^3 \, (M^{7/2}/I^2 r \lambda^2)^{1/9}$$

where I is the laser intensity, r is the radius of the beam, λ is the laser wavelength, and M is the atomic weight. The coupling coefficients for the plasma with $r = 1$ cm are presented in Fig. 2.

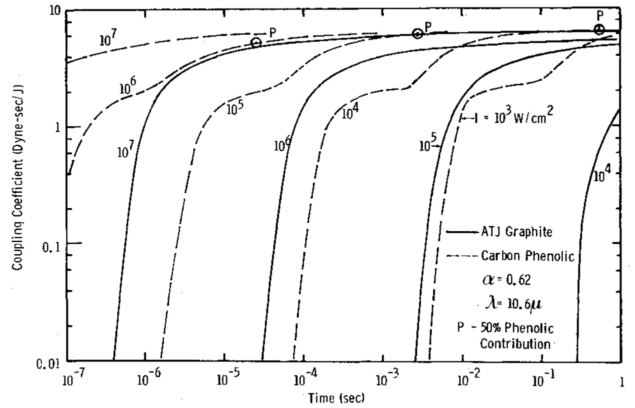

Fig. 1 Time history of coupling coefficients for ATJ graphite and carbon phenolic.

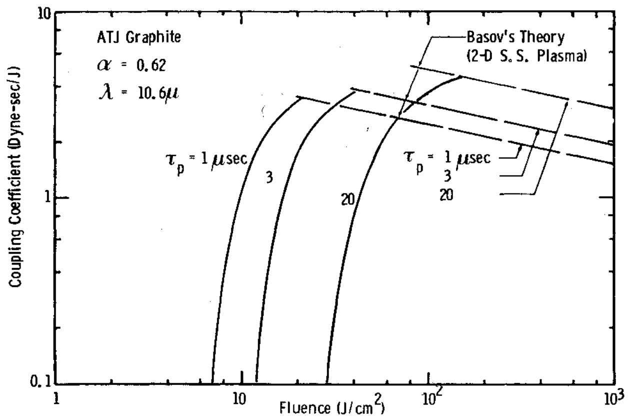

Fig. 2 The coupling coefficient of ATJ graphite as a function of fluence for given pulse times.

For carbon phenolic, the coupling coefficients as a function of time are presented in Fig. 1. For a given laser intensity, the coupling coefficients for carbon phenolic are observed to rise at an earlier time than that of the graphite because the vaporization of phenolic begins to take place at a few hundred degrees Celsius. As shown in Fig. 1, the coupling coefficients rise after the vaporization temperature of phenolic has been reached and eventually approach the asymptotic steady-state value of approximately 6 dyn-s/J. The change in curvature on the curve is due to the characteristic pyrolysis reaction at low temperature. In addition, along the coupling coefficient curves for 10^4-10^6 W/cm^2 the locations *P* where the phenolic contributes 50% of the coupling coefficient values have been indicated. The corresponding locations on the 10^3 W/cm^2 curve are to the right of the plot (or at times greater than 1 s). Hence, for the carbon phenolic considered here, the contributions to the coupling coefficient from the phenolic are significant.

As shown in Fig. 3, the coupling coefficients for carbon phenolic are presented as a function of fluence for pulse times of 1, 3, and 20 μs. Again, the coupling coefficients for the two-dimensional steady-state plasma are also given as reference, and the locations A and B indicate the fluence levels where the phenolic contributions are 90% and 20%, respectively. For the pulse time considered here, the coupling coefficient rises rapidly to 1-2 dyn-s/J then gradually increases to about 4 dyn-s/J over a wide range of fluence (approximately 1-10 J/cm^2) and finally approaches the steady-state value at higher fluence. In terms of the coupling coefficient, the present (single pulse) results show that for low intensity (10^3-10^5 W/cm^2) and long pulses the effect of phenolic is important in providing the laser-induced impulse to a carbon phenolic surface. Now consider a multiple pulse train where the interpulse time is long compared with the characteristic thermal diffusion time. For these multiple pulse

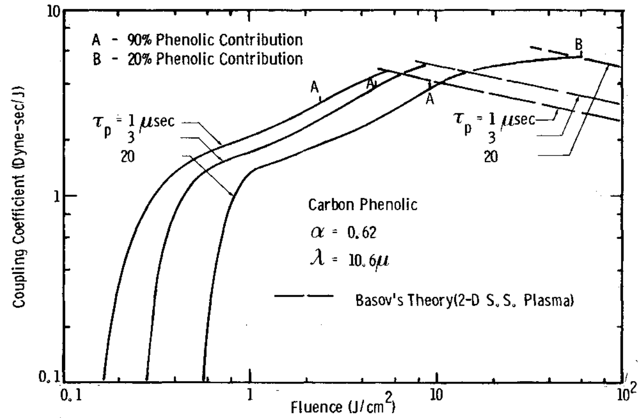

Fig. 3 The coupling coefficient of carbon phenolic as a function of fluence for given pulse times.

trains, one expects that the coupling coefficient, which is dominated by phenolic contribution, would decrease after the first pulse, because a portion of the phenolic near the surface has been depleted while the carbon char surface is intact.

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Improvements in the Combustion Driving Technique for Shock Tubes

F. Anthony Hewitt* and David E. Fussey†

University of Nottingham, Nottingham, England

RECENT work at this university, involving measurement of the rates of formation of nitric oxide from combustion mixtures led to the need for a shock tube producing post-

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*Research Fellow, Dept. of Mechanical Engineering. Presently at Advanced Research Laboratory, Rolls Royce Ltd. Derby, United Kingdom.

†Lecturer, Dept. of Mechanical Engineering. Presently at Papua New Guinea University of Technology.