Laser-induced carbon plasma; modelling and experiment

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Laser ablated carbon plume is studied both theoretically and experimentally. Plasma temperature and electron density in the early phase of expansion into vacuum are determined as a function of distance from the target using optical emission spectroscopy. The expansion velocity of the plasma plume is determined using the time of flight method. The results are in fair agreement with the theoretical results of the hydrodynamic model.

The laser ablation is widely used to used to obtain a variety of carbon-related materials, such as diamond-like carbon, fullerenes, and carbon nanotubes. The evaporation of a material is strongly affected by plasma formation. The dense plasma absorbs energy from the laser beam and its temperature and pressure grow. The thickness of the plasma layer is small compared with its other dimensions; therefore the pressure gradient inside the major part of this layer is large and nearly perpendicular to the surface. Such a pressure gradient accelerates the plume to a high velocity perpendicular to the target.

The hydrodynamic model which describes the target heating, formation of the plasma and its expansion consists of equations of conservation of mass, momentum and energy and is solved with the use of the Fluent software package. It is assumed that the carbon plume expands to ambient air at a pressure of 10^{-3} Pa. It is also assumed that the electron temperature T_e at the end of the Knudsen layer equals the target surface temperature T_s contrary to the temperature of the heavy particles T_h which, according to the theory of the Knudsen layer, is 0.67 T_s. The estimation shows that there is no time for energy equilibration between the carbon atoms and the electrons in the Knudsen layer. Hence it is assumed that the vapour is in the Saha equilibrium at a temperature T_e=T_s and T_e/T_h =1.5. Since the energy of the laser beam is supplied to electrons the electron temperature will always exceed the temperature of heavy particles during the laser pulse. Therefore, the temperature ratio T_e/T_h =1.5 is kept for first 9 ns of calculations; then the temperature reaches 25 kK and the electron density $N_e \approx 1\times10^{26}$ m^{-3} and T_e/T_h tends to unity. After the cessation of the laser pulse the energy equilibration time between electrons and heavy particles is a few nanoseconds. The energy source term I_L was used in the form which fits the shape of the laser pulse and the plasma absorption coefficient included all possible absorption mechanisms: the electron -atom inverse bremsstrahlung, the electron-ion inverse bremsstrahlung, the photoionization and the Mie absorption. We used the same total absorption coefficient as in [1] supplemented with the Mie absorption. Radiative losses included total continuum and line radiation but were treated in a simplified way. It was assumed that at pressures higher than 0.5×10^5 Pa the line radiation with λ < 200 nm was trapped in the plasma and hence was not included in the energy loss function. At lower pressures this radiation was gradually included into energy losses.

The experimental setup was described in [2]. Graphite target irradiation was performed using a Nd:YAG laser operating at its fundamental wavelength of 1064 nm with pulse energy of ~400 mJ and 10 ns pulse duration. The laser fluence was 15 J·cm^{-2} (intensity, I=1.5 GW·cm^{-2}). The incident angle of the laser beam was 45° to the surface normal. The target was rotated to avoid crater formation. The ablated plume expanded in a chamber evacuated to a background pressure of 1×10^{-4} Pa. The emission spectra of the plasma plume was registered with the use of a spectrograph / monochromator and an ICCD camera. The camera was gated by a digital delay generator triggered by the signal from the laser. The exposure time (gate width) was 10 nanoseconds. The delay time changed from 15 ns to 180 ns. Plasma temperature and electron density in the early phase of expansion were determined using optical emission spectroscopy. The electron temperature and density was determined from the intensities and profiles of C IV, C III and C II lines. The expansion velocity of the plasma plume was determined using the time of flight method. Temporal evolution of the intensity of specific spectral lines were measured with a monochromator and photomultiplier at various distances from the target and registered on an oscilloscope. These measurements allowed us to determine the expansion velocity of the plasma plume using the time of flight method .

The results are shown in figures 1 - 2. Figure 1 shows the theoretical distributions of plasma temperature and electron density, 40 ns from the beginning of the laser pulse. The experimental and theoretical results are compared in Fig.2 where the axial temperatures and plasma front velocities are presented as a function of time delay from the laser pulse. The agreement between the theoretical model and the experiment is fairly good and validates the theoretical model of plasma expansion.

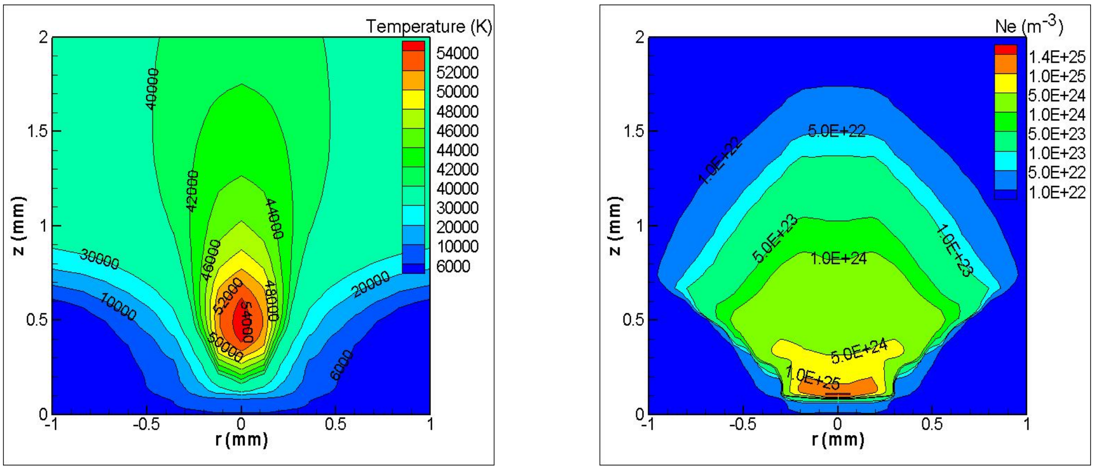

Fig.1: Distribution of the plasma temperature and electron density 40 ns from the beginning of the laser pulse

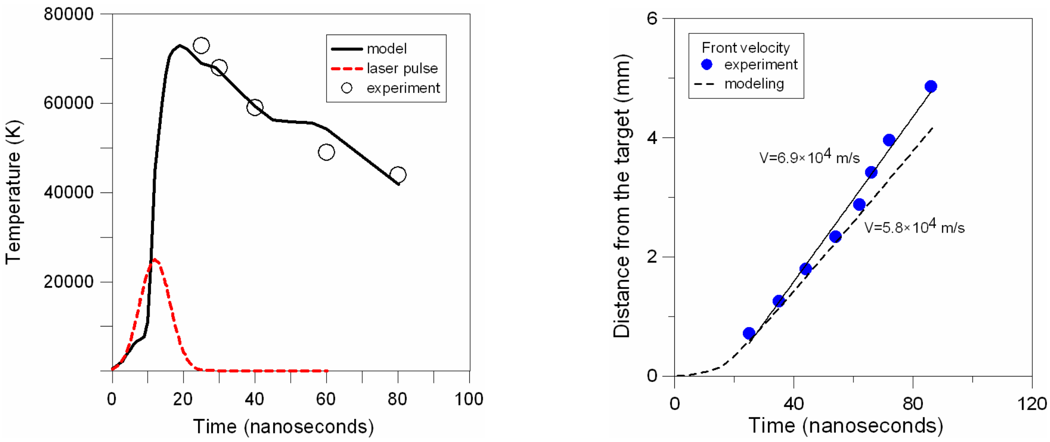

Fig. 2:. Axial electron temperature (a) and distance of the luminous plasma front from the target (b) vs. time from the beginning of the laser pulse

References

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