Numerical study of laser-induced blast wave coupled with unsteady ionization processes

Y Ogino¹, N Ohnishi¹² and K Sawada¹
¹ Department of Aerospace Engineering, Tohoku University, 6-6-01 Aramaki-Aza-Aoba, Aoba-ku, Sendai, 980-8579, Japan
² Center for Research Strategy and Support, Tohoku University, 6-6-01 Aramaki-Aza-Aoba, Aoba-ku, Sendai, 980-8579, Japan
E-mail: yogi@rhd.mech.tohoku.ac.jp

Abstract. We present the results of the numerical simulation of laser-induced blast wave coupled with rate equations to clarify the unsteady property of ionization processes during pulse heating. From comparison with quasi-steady computations, the plasma region expands more widely, which is sustained by the inverse-bremsstrahlung since an ionization equilibrium does not establish at the front of the plasma region. The delayed relaxation leads to the rapid expansion of the driving plasma and enhances the energy conversion efficiency from a pulse heating laser to the blast wave.

1. Introduction
Propulsion systems using laser energy from a distant place have been expected to the future transportation technology in space and the other applications. In the gas-driven laser propulsion system, the thrust power is obtained as a result of the interaction with a propellant gas heated by laser irradiation. After the focused laser induces a breakdown in the propellant gas, a blast wave is formed by the laser-produced plasma and propagates to the projectile through the surrounding gas. The performance of the gas-driven laser propulsion highly depends on the blast wave dynamics and the plasma states sustaining it. In our previous works [1, 2], the computational method was developed to find the dynamics of the blast wave sustained by the laser-produced nonequilibrium plasma in which we employed quasi-steady state (QSS) model, so called collisional radiative equilibrium (CRE) model for the population probability calculation. Although basic features of the blast wave were successfully reproduced as observed in the experiments [3], the computed pressure value at the acceleration tube wall was found to be substantially higher than the measured one. A possible cause of this discrepancy was discussed in the comparison of emission spectra from the plasma core region given by the numerical simulation with the experimental result [2]. Typical line spectra of singly ionized argon were obtained from the experiment, while these spectra were not found in the computed spectra in the corresponding region. One may attribute the cause of the discrepancy seen in the pressure profile to an inadequate modeling of ionization nonequilibrium plasma.

The objective is to clarify the physical phenomena of the laser-driven blast wave in order to improve the energy conversion efficiency from laser to blast wave. For this purpose, we develop the numerical code in which the flow equations and the rate equations are simultaneously solved.
The properties of the blast wave driven by nonequilibrium plasma are analyzed with this code. In particular, we estimate the unsteady nature of ionization processes during pulse heating and claim on the importance of it for the prediction of energy conversion efficiency.

2. Numerical procedure
In the present study, since the temperature and density of the propellant gas can become several eV and $10^{18}$ cm$^{-3}$, it is likely that the plasma core region is optically thin, partially ionized and in thermally nonequilibrium state. Therefore, a two-temperature model is employed to account for thermal nonequilibrium. We solve the rate equations of the population density consisting of collisional radiative processes in plasmas for including effects of ionization nonequilibrium.

2.1. Flow equations
The governing equations for the flowfield are spherically symmetric conservation equations written in Lagrangean form [2],

\[
\frac{dP}{dt} + \frac{\partial (r^2 P u)}{\partial \xi} - r^2 u \frac{\partial P^2}{\partial \xi} = 0, \tag{1}
\]

\[
\frac{du}{dt} + \frac{\partial (r^2 P)}{\partial \xi} - \frac{2P}{\rho r} = 0, \tag{2}
\]

\[
\frac{dE}{dt} + \frac{\partial (r^2 P u)}{\partial \xi} = S = S_i + S_e, \tag{3}
\]

\[
\frac{dz_i}{dt} + \frac{\partial (r^2 P u)}{\partial \xi} - r^2 u \frac{\partial P_i}{\partial \xi} = S_i = -\nabla \cdot q_i + Q_{ei}, \tag{4}
\]

\[
\frac{dz_e}{dt} + \frac{\partial (r^2 P u)}{\partial \xi} - r^2 u \frac{\partial P_e}{\partial \xi} = S_e = -\nabla \cdot q_e - Q_{ei} - S_{rad} + S_{lsr}, \tag{5}
\]

where $\xi$ is the mass coordinate defined using density $\rho$ and radius $r$ as $\xi \equiv \int_0^r \rho r^2 d\hat{r}$, and $u$ is flow velocity. The variables $\varepsilon_i$ and $\varepsilon_e$ are ion and electron internal energy, respectively. Hereafter, the subscript $i$ is used for ion and $e$ for electron. The total energy $E$ and the total pressure $P$ are defined by $E = \varepsilon_i + \varepsilon_e + 1/2 |u|^2$ and $P = P_i + P_e$, respectively. The term $-\nabla \cdot q$ is the divergence of thermal conduction flux [4, 5], and $Q_{ei}$ is the relaxation rate due to electron-ion collision. The electron-ion collision time ($\approx 10^{-7}$s) is relatively long respect to the characteristic time of the fluid motion ($\approx 10^{-8}$s). $S_{rad}$ is the radiative cooling due to self-emission of the propellant gas whose typical cooling time is about $10^{-7}$s and $S_{lsr}$ is the absorbed laser energy by inverse-bremsstrahlung of free electrons. It is assumed that the gas does not absorb the radiation except for laser. The numerical flux is given by the second-order Godunov scheme employing MUSCL approach [6]. The equations are integrated in time using a first-order explicit method except for thermal conduction and relaxation terms which are implicitly treated.

2.2. Time-dependent rate equations
The population density $N_{\zeta,m}$ which has a charge $\zeta$ and a quantum number $m$ is determined by solving a system of rate equations consisting of collisional radiative processes in the plasmas [2],

\[
\frac{dN_{\zeta,m}}{dt} = - \sum_{\text{depopulating processes}} n_e k N_{\zeta,m} \mathcal{R} (\zeta, m \rightarrow \zeta', m') + \sum_{\text{populating processes}} n_e k N_{\zeta',m'} \mathcal{R} (\zeta', m' \rightarrow \zeta, m), \tag{6}
\]

where $\mathcal{R} (\zeta, m \rightarrow \zeta', m')$ denotes a rate coefficient from $(\zeta, m)$ state to $(\zeta', m')$ state. The variable $Z$ is atomic number, and $M_{\zeta}$ is an available quantum number of $\zeta$th ionized species.
which is included up to 45. The variable $n_e$ is the electron number density and $k$ is a number of electron required for each transition process. The corresponding averaged charge $\bar{Z}$ in the flow equation can be written as $\bar{Z} = \sum_{\zeta,m} \zeta N_{\zeta,m}/n_i$ where $n_i$ is ion number density. The quantum mechanical quantities (energy levels, statistical weight, oscillator strength, etc.) for estimating the rate coefficient are provided from the atomic structure code developed by Yamada [7].

2.3. Definition of electron internal energy
Electron internal energy $\varepsilon_e$ is defined as the sum of the translational energy of free electron and all excitation energies,

$$\varepsilon_e = \frac{3}{2m_i} \bar{Z} T_e + \frac{1}{m_i} \sum_{\zeta,m} N_{\zeta,m} E_{\zeta,m}. \quad (7)$$

Where $E_{\zeta,m}$ is the energy level of ($\zeta, m$) state measured with respect to the ground state energy.

2.4. Simulation condition
We use 601 grid points to cover $0 \leq r \leq 0.6$cm. The ambient temperature and density of surrounding argon gas are assumed to be in 300K and $1.6 \times 10^{-3}$ g/cm$^3$. At the beginning of the simulation, we make a central spot which has a higher electron temperature because of the lack of the breakdown processes in our code. The electron temperature of the spot is distributed in a Gaussian form with FWHM of 10μm and the peak value of $\approx$ 1eV. As a result this region is slightly ionized at the first time step and heated by inverse-bremsstrahlung of pulse beam at the subsequent steps. Our pulse profile imitates a typical profile of CO$_2$ RP laser as shown in Fig. 1. The pulse is consisted of two parts, a Gaussian distribution part whose FWHM is 50ns and an exponential decay part. The time integrated laser energy is set to be 2.5J. This pulse condition corresponds to the experimental one of Ref. [3].

3. Results

![Figure 1. Pulse laser profile.](image)

At first, we show the spatial distributions of density and electron temperature (Fig. 2(a)) and absorbed laser energy and radiative cooling rate (Fig. 2(b)) after 2μs from the laser incidence. One can see that the shock front with solving unsteady rate equations is faster than that with QSS because laser-induced plasma region behind the shell of blast wave less re-radiates the absorbed laser energy while the temperature is higher in this region. And also radiative cooling rate from a nearby the origin is two order of magnitude less than the QSS case.
Figure 3 shows the comparison of x-t diagram of $\bar{Z}$ between unsteady and QSS. In the early stage of pulse heating, ionization relaxation of the unsteady case delays about a few 100ns than the QSS case. Note that the front of the contours does not correspond to the shock front but to the plasma region sustaining the shock. The initial rapid expansion of the blast wave is sustained up to $\approx 0.5\mu s$ because of the unsteady ionization-recombination processes. After that, an isolated plasma region is formed just behind the shock wave. In this region, the averaged charge is not so different with that of the QSS case while the front is accelerated faster. Actually the absorption of the laser energy is almost same between the unsteady and QSS case, but the emission is significantly different (See Fig. 2(b)). The delayed relaxation is most responsible for the rapid shock propagation of the unsteady case.

We estimate the amount of the blast wave energy by means of comparing to the Sedov-Taylor solution of spherically symmetric blast wave [8]. By the 2$\mu$s the blast wave energy results in about 1.3J which becomes 1.7 times as the QSS case, though the time integrated absorbed energy becomes almost same value in either case.

Figure 4 shows the Boltzmann plot at 1.5$\mu$s: $T_e = 1.1[eV]$ and $n_i = 2.8 \times 10^{19}/cm^3$ in front of the plasma surface (the point of $\star$ in Fig. 3). In the figure, red plots are results of the unsteady case and dashed lines with blue plots indicate results of QSS solution obtained from the same temperature and number density. Here, the excitation energy of outermost shells are truncated by continuum lowering effect. One can find that relatively high energy levels of neutral argon are still in the ionizing phase, that is, the front of the plasma surface sustaining blast wave evolves with an unsteady population density.

**4. Conclusion**

We performed the numerical simulation of laser-induced blast wave coupled with rate equations to study the unsteady property of excitation and ionization processes during pulse heating. From comparison with the QSS simulation, the laser-induced plasma driving the blast wave is still in the recombination relaxation processes without achieving ionization equilibrium over the pulse duration except that the front of the plasma surface is dominated by the ionization processes. The results suggest importance of ionization nonequilibrium for the prediction of energy conversion efficiency.

**References**

[1] Ohnishi N et al. 2005 AIAA paper 2005-749
[2] Ogino Y et al. 2006 AIAA paper 2006-1358
[3] Sasoh A et al. 2005 Transaction of the Japan Society for Aeronautical and Space Sciences 48 63
[4] Spitzer L and Harm R 1953 Physical Review 89 977
[5] Braginskii S I 1965 Reviews of Plasma Physics Consultants Bureau Inc.
[6] Leer B V 1979 Journal of Computational Physics 32 101
[7] Yamada S 2002 Journal of Plasma Fusion Research 78 10 in Japanese
[8] Sedov L I 1993 Similarity and Dimensional Methods in Mechanics CRC Press