Numerical Analysis of Laser Supported Detonation Waves in Air

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1. Introduction

There is a strong demand to frequently deliver payloads to space at a low cost. A pulse laser powered vehicle will be able to satisfy this demand: The payload ratio would be improved drastically because energy is provided from a laser base on the ground to the vehicle and atmospheric air can be used as a propellant. In addition, once a laser base is constructed, the cost is only electricity charges.

The pulse laser powered vehicle is shown in Fig.1. A gas-breakdown occurs by focusing a transmitted laser beam. The front of produced plasma absorbs the following part of laser beam and expands in the form of Laser Supported Detonation (LSD) wave.[1] After laser intensity decays to a LSD threshold, the shock wave in front of the LSD wave separates from the plasma front and the plasma expands in the form of Laser Supported Combustion (LSC) wave. In LSD process, laser energy is converted to thrust work by the LSD wave directly striking the nozzle wall. In LSC process, the energy-conversion is by the LSC wave expansion in the nozzle and the shock wave sweeping on the nozzle. In this work, the propagation processes of LSD and LSC waves in a parabolic nozzle are solved by the axisymmetric 2-D CFD code with laser-plasma interactions, and then the mechanisms of the conversion from laser energy to thrust work in LSD and LSC processes are discussed.

2. Momentum Coupling Coefficient and Blast Wave Efficiency

In pulse laser propulsion, a momentum coupling coefficient C_{m} is commonly used as a performance indicator. C_{m} is the ratio of cumulative impulse to pulsed laser energy and defined as,

$$C_{\mathrm{m}} = \frac{\int_0^t F dt}{E_{\mathrm{L}}}. \tag{1}$$

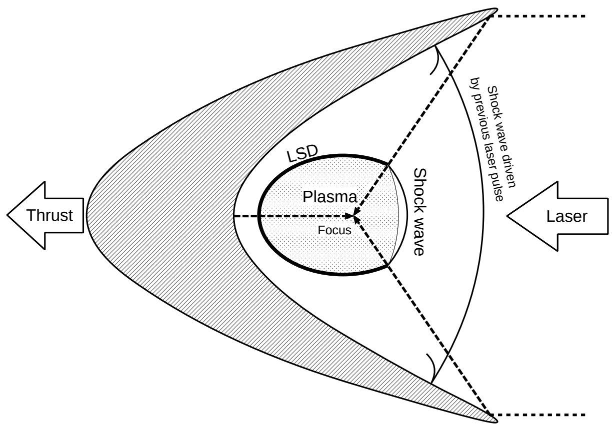

Fig. 1. Pulse laser powered vehicle.

where F, $E_{\rm L}$ are thrust and laser energy, respectively.

Laser energy absorbed in a gas is distributed into blast wave energy $E_{\rm B}$, chemical potential energy and radiation energy. $E_{\rm B}$ is defined as

$$E_{\rm B} = \int \left[h^{\rm t+r}(T) + h^{\rm t+r}(T_0) + \frac{\rho\left(u^2+v^2\right) - \rho_0\left(u_0^2+v_0^2\right)}{2} \right] dV, \tag{2}$$

where

$$h^{\rm t+r} = \int C_{\rm p}(T)\, dT - \int C_{\rm p,v}(T)\, dT - \Delta h^{\rm f}. \tag{3}$$

The subscript 0 indicates the properties before laser incidence, $h^{\rm t+r}$ is the sum of translational and rotational enthalpy, and $\Delta h^{\rm f}$ is the sum of enthalpy of formation of species. $C_{\rm m}$ would be a function of $E_{\rm B}/E_{\rm L}$ because only $E_{\rm B}$ contributes to thrust. Therefore, we introduce the blast wave efficiency $\eta_{\rm B}$ defined by

$$\eta_{\rm B} = \frac{E_{\rm B}}{E_{\rm L}}. \tag{4}$$

$\eta_{\rm B}$ depends on the heating process: Since the LSD process is an isometric heating and the LSC process is an isobaric one, $\eta_{\rm B}$ in LSD process is high since peak pressure is high compared with LSC process.

In this work, the time-variation of $\eta_{\rm B}$ will be investigated to clarify the mechanism of energy-conversion in LSD and LSC processes. In addition, the energy loss by chemically frozen flow and plasma radition will be estimated.

3. CFD Analysis Method

Flow field with thermo-chemical non-equilibrium, laser-plasma interaction, and plasma radiation are solved to clarify the LSD and LSC wave propagation processes in a parabolic nozzle such as Fig.1. To capture correctly laser supported waves, unstructured solution adaptive meshes are used.

4. Preliminary Analysis of Plain LSD Wave Propagation

Before CFD analysis, the plain LSD wave propagation in air was analytically calculated. Figure 2 shows the calculation model: The LSD wave is the plane wave which propagates in the laser channel, and the physical properties on the LSD front is uniform. Total E_{B} is calculated by accumulating the blast wave energy behind the LSD front at each time step. Physical properties behind the LSD front are calculated from one dimensional LSD relations,[2)]

$$
\begin{aligned}
p_2 &= \frac{p_1 + \rho_1 D_{\mathrm{CJ}}^2}{\gamma_2 + 1}, && (5)\\
\rho_2 &= \frac{(\gamma_2 + 1)\,\rho_1 D_{\mathrm{CJ}}^2}{\gamma_2\,(p_1 + \rho_1 D_{\mathrm{CJ}}^2)}, && (6)\\
T_2 &= p_2/R_2/\rho_2, && (7)\\
v_2 &= c_2 = \sqrt{\frac{\gamma_2 p_2}{\rho_2}}, && (8)\\
v_1 &= D_{\mathrm{CJ}}, && (9)\\
h_2 &= h_1 + \frac{1}{2}\left(D_{\mathrm{CJ}}^2 - v_2^2\right) + \frac{P_{\mathrm{L}}/A_{\mathrm{L}}}{\rho_1 D_{\mathrm{CJ}}}, && (10)
\end{aligned}
$$

where the subscripts 1 and 2 denote the states in front of and behind the LSD, respectively. The velocities refer the coordinate relative to the LSD wave. The cross section area of laser beam at the LSD front is

$$A_{\mathrm{L}} = \pi \left(\frac{z_d}{2f}\right)^2. \tag{11}$$

Here, z_{d} is the location of the LSD front. The f number(focal length/beam diameter) is 3.6. The history of laser power, P_{L}, was taken from Ref. (3). h_2 and γ_2 is calculated by solving iteratively Eqs. (5) $\sim$ (10) with a chemically equilibrium calculation. Then, the location of LSD wave is calculated by

$$\frac{dz_{\mathrm{d}}}{dt} = D_{\mathrm{CJ}}. \tag{12}$$

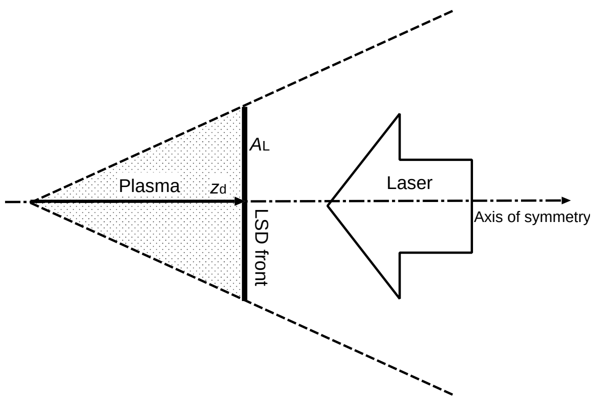

Fig. 2. Model of LSD propagation.

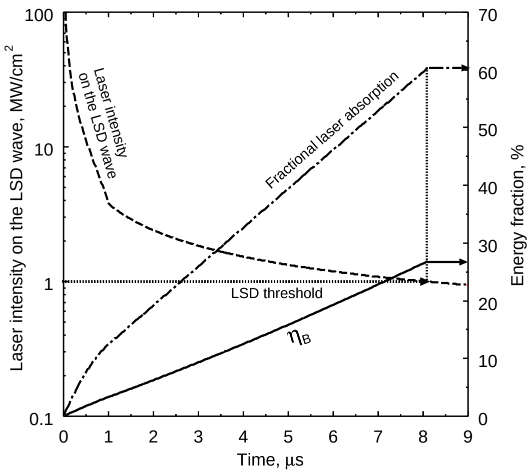

Fig. 3. Histories of E_{B} and laser intensity in atmospheric air.

Table 1. η_{B} in reduced air

$\rho_0, \mathrm{kg/m^3}$	$\eta_{\mathrm{B}}\,(t_0)$
1	26.8
0.5	17.2
0.1	12.8

Since the LSD wave is not sustained at the laser intensity below about $1\mathrm{MW/cm^2}$ at $p = 1\mathrm{atm}$,[4)] the calculation is terminated when laser intensity on the LSD wave decays to this threshold. Figure 3 shows the histories of laser intensity, fractional laser absorption and η_{B}. Resulting fractional absorption and η_{B} were 60 % and 27 %, respectively. Table 1 shows the η_{B} in reduced air. η_{B} decreases with the decrease of density. Thereby, the performance of the laser powered vehicle may degrade in high altitude.

In order to validate this result, the LSD threshold in several atmospheric densities will be investigated by solving the transition of LSD-LSC.

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