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[8-D-01] Analysis of Laser-Supported Detonation Wave Expanding to the Outside of a Laser Beam

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Keywords: Detonation, Shock Wave, Bow Shock, Axisymmetric Euler Equation, SLAU

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Analysis of Laser-Supported Detonation Wave Expanding to the Outside of a Laser Beam

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Abstract: Laser-Supported Detonation (LSD) is induced by high-power laser and propagates converting laser energy into the fluid enthalpy. In CFD, it is replicated as a propagating heating region, but the mechanism determining its propagation velocity remains unclear, often relying on experimental values. Since LSD propagates slower than the Chapman-Jouguet (C-J) velocity assumed in 1-D propagation, radial outflow effects are anticipated. In this study, the effect by simulating LSD using 2-D axisymmetric CFD is evaluated. It is found that the mass advection outward laser channel due to wavefront curvature is approximately 70%. Considering 2-D effects, it is found that LSD reaches the C-J state, suggesting that propagation velocity can be predicted using CFD.

Keywords: Detonation, Shock wave, Bow shock, Axisymmetric Euler equation, SLAU.

1 Introduction

In the Repetitive Pulse laser propulsion system, Laser-Supported Detonation (Fig. 1) plays a role in converting the energy of the laser into the enthalpy of the working fluid. Propagation model of LSD wave is required for estimating the performance of future RP laser propulsion systems and for its optimal design. The mechanism determining the propagation velocity of LSD is not fully understood. Assuming 1-D propagation as chemical detonation, the Chapman-Jouguet (C-J) velocity of LSD $V_{\mathrm{CJ}}\,[\mathrm{km/s}]$ is calculated as $V_{\mathrm{CJ}} = 0.92 \times S^{0.33}$ [2, 3], whereas the propagation velocity V_{exp}, measured in the experiment [1] is written as $V_{\mathrm{exp}} = 0.22 \times S^{0.46}, (S \geq 500\ \mathrm{GW/m^2})$ which is approximately 60% of V_{CJ} around $S = 500\ \mathrm{GW/m^2}$ (Fig. 2). Therefore, to account for the existence of detonation solution, mechanism of 2-D outflow has been considered [4, 5], suggesting that the deceleration of shock waves can be attributed to outward advection.

Due to its high-pressure, high-temperature, and high-velocity, observing LSD poses challenges. Obtaining some physical quantities behind the wavefront is difficult, so that using numerical simulations is effective. Efforts has been made to reproduce this phenomenon solely using CFD by inputting some experimental values. the moving heated regions predicted from the captured images for simplicity, because LSD involves complex interactions of lasers, plasma, and shockwaves.

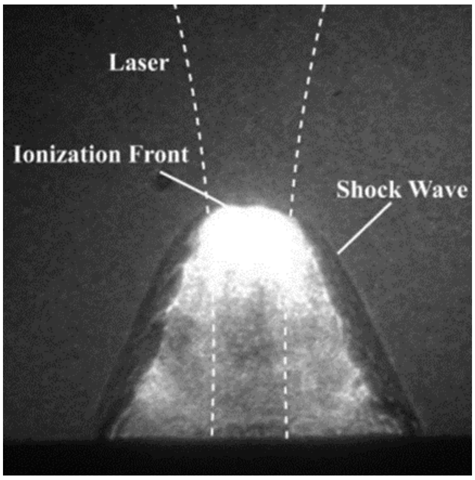

Figure 1: Structure of Laser-Supported Detonation (LSD) propagating from the bottom of the image to the laser source above. Ionization front and shock wave propagates sticking together [1].

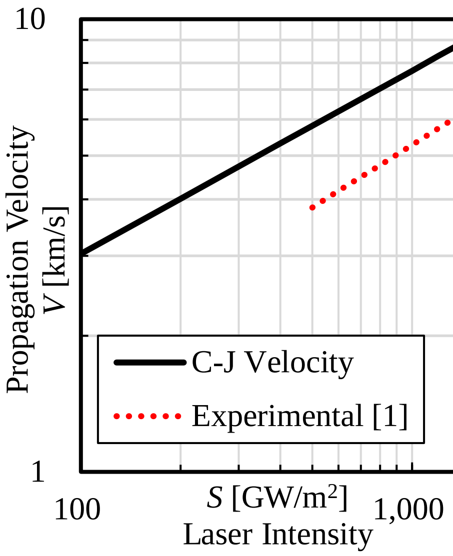

Figure 2: Laser intensity vs. LSD propagation velocity. Experimental value is slower than Chapman-Jouguet velocity [1].

2 LSD Simulation by axisymmetric CFD

Axisymmetric CFD is performed to simulate LSD propagation along the axis. The axisymmetric 2-D Euler equations were solved using the MUSCL extended to 3rd order spatial accuracy, with the SLAU for flux calculations to resolve Carbuncle phenomenon on the axis. The equation is written as:

$$\frac{\partial \boldsymbol{Q}}{\partial t}+\frac{\partial \boldsymbol{E}}{\partial z}+\frac{\partial \boldsymbol{F}}{\partial r}+\frac{\boldsymbol{H}}{r}=\boldsymbol{S}, \qquad \boldsymbol{Q}=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ e\end{pmatrix}, \boldsymbol{E}=\begin{pmatrix}\rho u\\ p+\rho u^2\\ \rho u v\\ (e+p)u\end{pmatrix}, \boldsymbol{F}=\begin{pmatrix}\rho v\\ \rho u v\\ p+\rho v^2\\ (e+p)v\end{pmatrix}, \boldsymbol{H}=\begin{pmatrix}\rho v\\ \rho u v\\ \rho v^2\\ (e+p)v\end{pmatrix}, \boldsymbol{S}=\begin{pmatrix}0\\ 0\\ 0\\ w\end{pmatrix}$$

The computational grid settings are shown as Table 1. The left boundary is the axis of symmetry, and LSD propagates along the central axis from bottom to top. To capture the shock wave in detail, the grid spacing is smaller in the axial direction.

To replicate LSD in CFD, the heating induced by LSD is set as a heating region propagating with velocity. The radial heating distribution was determined from a laser peak intensity and the laser specific intensity distribution measured under the same conditions. The time delay of heating due to the non-equilibrium of vibrational and translational temperatures is assumed, and it is obtained from the intensity distribution of plasma self-emission along the central axis as Fig. 3.

Table 1: Computational grid settings.

Laser power	Constant (Experimental)
Laser profile	Gaussian
Left boundary	Axisymmetric
Right boundary	Non-slip wall
Upper boundary	Free boundary
Lower boundary	Non-slip wall
Calculation area	10 mm × 20 mm
Number of grids	201 × 401
Radial grid width	50 µm
Axial grid width	50 µm
Courant number	0.5

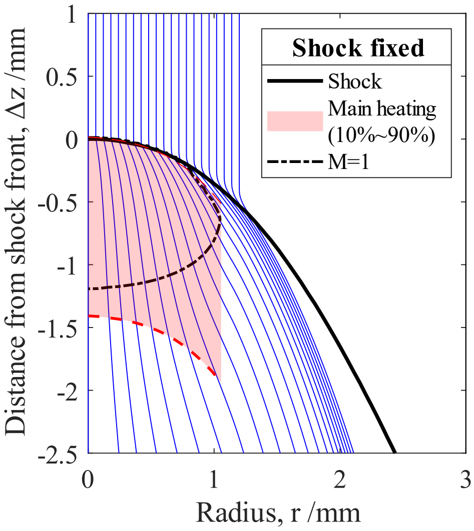

Figure 3: Streamlines of the result. Heating region is given in proportional to distribution of plasma self-emission intensity. Ionization front and shock wave propagates sticking together.

3 Result and Discussion

3.1 Evaluation of 2-D effect

The shock wave and the heated region are sticking (Fig. 3) as observed on experiments. Drawing streamlines from the obtained velocity distribution reveals that there is a gradual outflow from the entire heated region in case without the gap between the shock wave and the heating region. Estimating mass outflow fraction η_{m} by following mass preservation equation, η_{m} was approximately 70%. Subscript 1 represents the initial state and subscript 2 represents the sonic surface behind LSD wave in a coordinate fixed to the wavefront.

$$\rho_1 u_1 (1 - \eta_{\mathrm{m}}) = \rho_2 u_2$$

In the case of LSD where the propagation is slower than C-J velocity, it is found that the propagation of the detonation wave is maintained by 2-D outflow. However, even the wall is set to block the sonic surface in CFD (Fig. 4), LSD can still propagate. It implies that 2-D effect is mainly caused by the mass outflow due to curvature of wavefront.

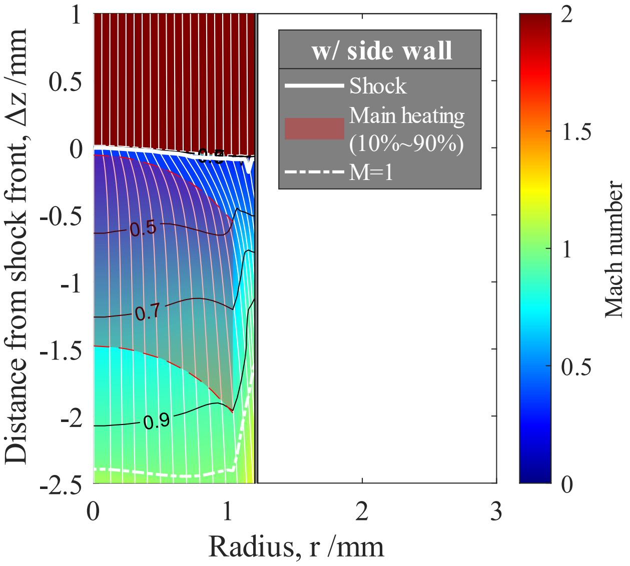

Figure 4: Streamlines of the result with wall blocking outflow. LSD wave still can propagate.

3.2 Hugoniot analysis of LSD

Hugoniot analysis is conducted on the axisymmetric axis of LSD from the initial state 1 to the sonic surface behind LSD wave in a coordinate fixed to the wavefront 2. In Fig.5, LSD cannot get solution by 1-D analysis. However, Rayleigh line and Hugoniot curve get a graph contact and it is different from C-J state by 0.8% in terms of input laser energy.

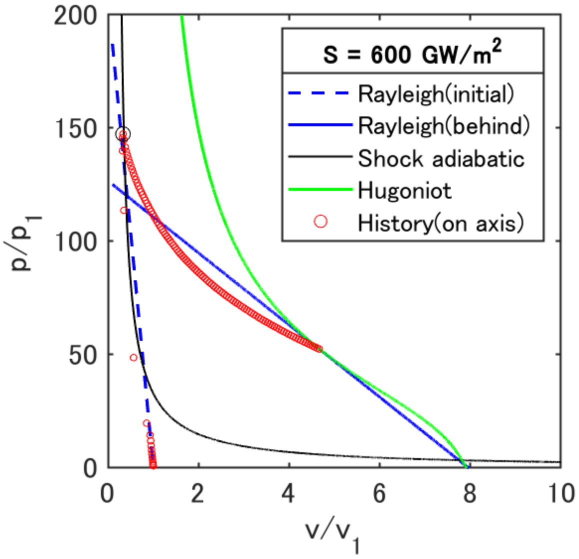

Figure 5: Hugoniot analysis on the axis from initial state 1 to the sonic surface behind LSD wave in a coordinate fixed to the wavefront 2 of the CFD result.

4 Conclusion and Future Work

In CFD, LSD is replicated as a propagating heating region, but the mechanism determining its propagation velocity remains unclear, often relying on experimental values. Since LSD propagates slower than the Chapman-Jouguet (C-J) velocity assumed in 1-D propagation, radial outflow effects are anticipated. In this study, the effect by simulating LSD using 2-D axisymmetric CFD is evaluated. It is found that the mass advection outward laser channel due to wavefront curvature is approximately 70%. Considering 2-D effects, it is found that LSD reaches the C-J state, suggesting that propagation velocity can be predicted using CFD.

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