Generation of Quasi-Planar Laser-Driven Detonations

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1 Introduction

A detonation wave is a supersonic wave where a leading shock wave and the subsequent heating zone propagate as one. Figure 1 shows the one-dimensional model of a detonation wave. The role of the leading shock wave is to trigger the heating. The heating occurs after some delay in general. The heated fluid expands and pushes surrounding fluids, and maintains the leading shock wave. The propagation speed of the self-sustained detonation wave is obtained by the mass, momentum, and energy conservation laws (control-volume analysis) together with the Chapman-Jouguet (CJ) condition (fluid flows out the detonation rear surface at the local sound speed). When the propagation Mach number is very large, the propagation speed of the self-sustained detonation wave (D_{CJ}) is given by

$$D_{CJ} = \sqrt{2\left(\gamma_2^{\ 2} - 1\right)\left(q_{react} + q_{ext}\right)} \qquad (1)$$

where γ_2, q_{react}, and q_{ext} are the specific-heat ratio at the detonation rear surface, the specific released heat of chemical reactions occurring in the detonation wave, which is positive for exothermic reactions, and added heat per unit mass in the detonation wave from external energy sources, respectively.

Detonation waves driven by exothermic chemical reactions (combustion) have been extensively investigated for decades. In this case, chemical reactions are triggered by the leading-shock heating because reaction rates steeply rise with temperature. Initially, decomposition reactions prevail. After some delay, recombination reactions become dominant, and fluid is rapidly heated. In the case of chemical-reaction-driven detonation waves, $q_{react}>0$ and $q_{ext}=0$. It is well known that the measured propagation speed of a self-sustained detonation wave in a tube is in good agreement with calculated D_{CJ} where q_{react} is determined in consistent with the chemical equilibrium and the conservation laws. Although the propagation speed is well predicted by the one-dimensional model and the wave front looks macroscopically planar, it is also well known that a one-dimensional self-sustained detonation wave is unstable and

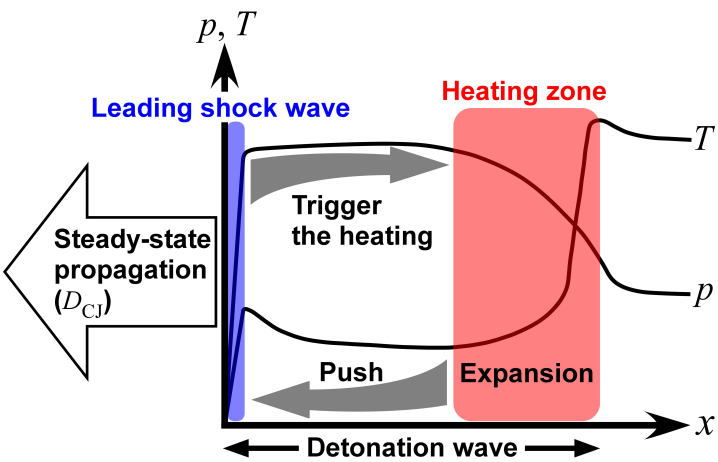

Fig. 1 One-dimensional model of a detonation wave.

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the real wave front is microscopically highly multi-dimensional.

As another type of detonation waves, laser-driven detonation waves have been known since the 1960s [1]. A laser-driven detonation wave is maintained by the absorption of laser energy. In the situation shown in Fig. 1, a laser beam is coming from the left, where the gas ahead of the leading shock wave is not ionized and the incident laser energy flux is below the breakdown threshold. In this case, the incident laser energy is not absorbed by the gas ahead of the leading shock wave in the context of classical physics. When the leading shock wave is so strong that the shock-heated gas becomes ionized, the incident laser starts to be absorbed in the shock-heated gas by the inverse bremsstrahlung. Thus, the shock-heated gas is further heated by the absorption of the laser energy, and therefore, the degree of ionization becomes higher in the downstream of the leading shock wave. Because the laser-absorption coefficient (κ) is given by the formula [2] :

$$\kappa = \frac{7.8\times10^{-9}\, Z n_e^{\,2} \ln \Lambda}{\nu^2 \left(k_B T_e\right)^{\frac{3}{2}} \sqrt{1-\left(n_e / n_{cr}\right)}} \tag{2}$$

where κ is in cm^{-1}, Z is the ionic charge state, n_e is the number density of free electrons in cm^{-3}, lnΛ is the Coulomb logarithm, ν is the laser frequency in s^{-1}, k_B is the Boltzmann constant, T_e is the electron temperature, where $k_B T_e$ is in eV, and n_{cr} is the critical electron number density for the incident laser in cm^{-3}, the heating of the gas (plasma) by laser absorption becomes strong nonlinearly from left to right in Fig. 1. As a result, the structure as shown in Fig. 1 is formed, and a detonation wave is driven by the absorption of laser energy. In the case of laser-driven detonation waves, $q_{ext}>0$ and $q_{react}<0$ because the reactions in laser-driven detonation waves are dissociation and ionization.

Although laser-driven detonation waves have been known since the 1960s, the stability of planar laser-driven detonation waves has hardly been investigated as far as we know. Because a laser-driven detonation wave propagates along the incident laser beam oppositely in a gaseous medium, the laser-driven detonation wave is gradually eaten away from its sides by rarefaction waves. That is, in order to study the stability of planar laser-driven detonation waves, the diameter of the incident laser beam should be so large that a quasi-planar portion remains in the wave front. However, in the past experiments on laser-driven detonation waves, the diameter of the incident laser beam was smaller than the detonation-propagation distance. This may be the principal reason for that the stability of planar laser-driven detonation waves has hardly been investigated.

In this paper, we describe experiments on laser-driven detonation waves, where the diameter of the incident laser beam was so large that a quasi-planar portion remained in the wave front. Although this work is in progress, the objective of this research is to investigate the stability of planar laser-driven detonation waves. Comparing with detonation waves driven by combustion, laser-driven detonation waves include high-energy electrons and photons, whose mean free paths are so long that diffusive effects (preheating of the gas ahead of the leading shock wave and heat transport in the detonation wave) are not negligible. Therefore, it is not clear whether planar laser-driven detonation waves are unstable like those driven by combustion or not.

2 Experimental arrangement

The experiments were carried out by using the GEKKO XII-HIPER (High Intensity Plasma Experimental Research) laser system [3,4] at the Institute of Laser Engineering, Osaka University. Figure 2 schematically shows the experimental arrangement. A planar aluminum (Al) target was irradiated by laser in nitrogen (N_2) or helium (He) gas. The aluminum, whose ionization potential was lower than that of nitrogen (N_2) or helium

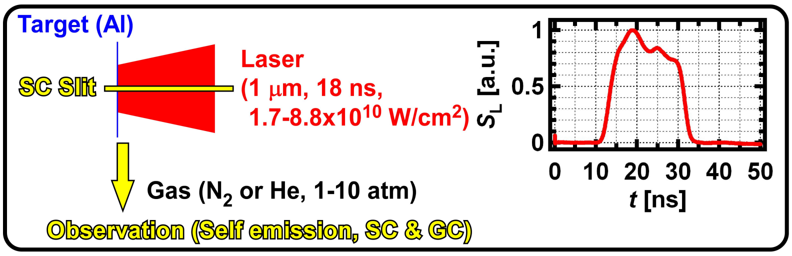

Fig. 2 Schematic of the experimental arrangement.

(He), target was used as the source of seed electrons, from which a laser-driven detonation wave was initiated. The laser wavelength was 1.05 μm. The pulse shape of the laser was shown in Fig. 2, where its FWHM was about 18 ns. The diameter of the laser irradiation was 2.5 mm, which was the standard condition, or 0.9 mm, which was for comparison. The thickness of the planar aluminum targets was 10 μm, which was the standard condition, or 0.8 μm, which was for comparison. Also 0.5-μm-thick parylene (CH) foils coated with 0.1-μm-thick aluminum were used as targets for comparison, where the aluminum-coated side was irradiated by laser. The gas used in the experiments was nitrogen (N_2) or helium (He) at room temperature, whose initial pressure was varied in the range of 1-10 atm. For diagnostics, self-emitted visible radiation was observed from the orthogonal direction to the center axis of the incident laser by using a streak camera (SC) and a gated CCD camera (GC). The center axis of the incident laser was imaged on the slit of the streak camera.

3 Results and discussions

Figure 3 shows typical data obtained in the experiments. The conditions for the data shown in Fig. 3 are the following. The target was a 10-μm-thick planar aluminum foil. The gas surrounding the target was nitrogen (N_2) whose initial pressure was 403 kPa. Three laser beams, whose total energy was 20 J, came from the right and irradiated the same spot, whose diameter was 2.5 mm, of the target. The incident laser energy flux was 2.2x10^{10} W/cm^2, which was about a half of the breakdown threshold. The exposure timing and duration of the gated CCD camera were around 27 ns in the pulse shape shown in Fig. 2 and 200 ps, respectively. As shown in the streak-camera data in Fig. 3, the region emitting radiation moved from left to right, that is, in the opposite direction to the incident laser. This moving region emitting radiation is interpreted as the laser-heated region corresponding to the laser-driven detonation wave. The gate-camera data in Fig. 3 shows that a quasi-planar portion remained in the wave front though it was somewhat inclined.

Figure 4 shows the propagation speed of the moving region emitting radiation measured from the streak-camera data. In laser-driven detonation waves, the added heat per unit mass by the incident laser is expressed as $q_{\mathrm{ext}} = S_{\mathrm{L}}/(\rho_1 D_{\mathrm{CJ}})$, where S_{L} and ρ_1 are the incident laser energy flux and the initial mass density of the gas, respectively. Therefore, if $|q_{\mathrm{react}}| \ll q_{\mathrm{ext}}$, the propagation speed of the self-sustained laser-driven detonation wave is given by

$$D_{\mathrm{CJ}} = \left[2\left(\gamma_2^{\,2}-1\right)\left(S_{\mathrm{L}}/\rho_1\right)\right]^{\frac{1}{3}} \qquad (3).$$

The above formula is reflected in the horizontal axis of Fig. 4. Also the calculated speed by eq. (3) is shown in Fig. 4. The data shown by closed circles and squares in Fig. 4 correspond to the cases where the incident laser energy flux was beyond the breakdown threshold. In these cases, two propagation speeds, which were higher and lower than the speed calculated by eq. (3), were recognized as the data of #30325 in Fig. 4. The data corresponding to the cases where the incident laser energy flux was below the breakdown threshold showed almost the same scaling as the theory. Therefore, it is concluded that the moving region emitting radiation corresponded to the laser-driven detonation wave, although the origin of the quantitative disagreement between the experimental results and the theory has not yet been understood well.

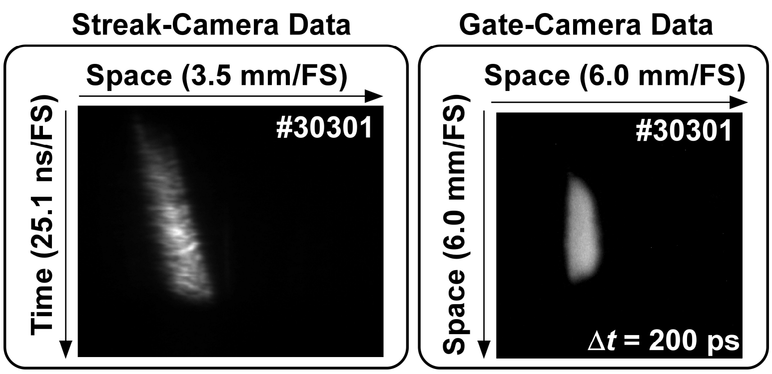

Fig. 3 Typical data obtained in the experiments.

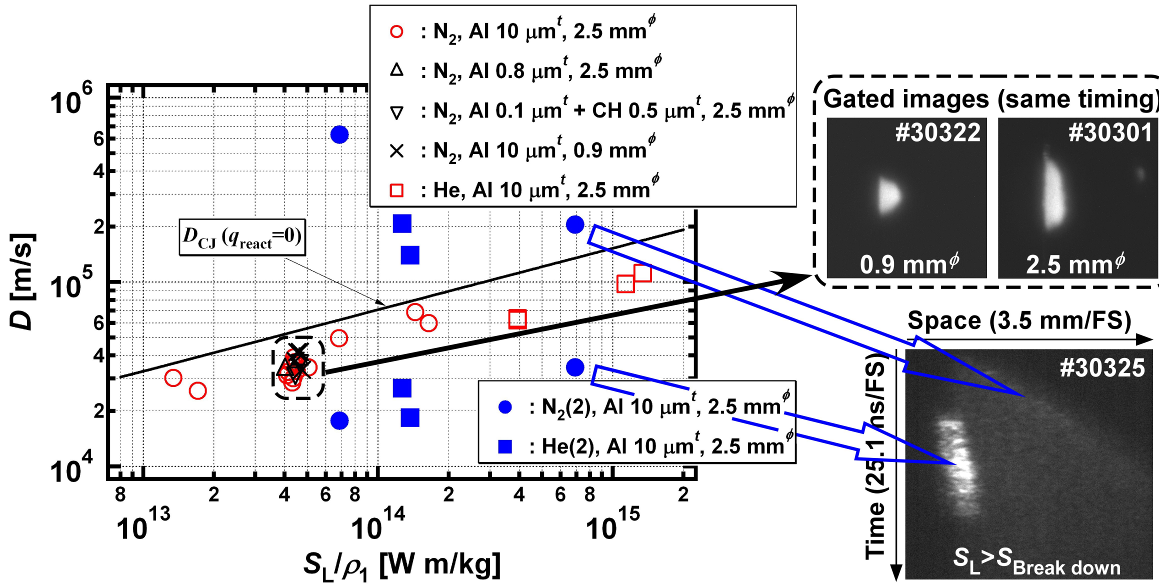

Fig. 4 Measured propagation speed of the moving region emitting radiation.

4 Summary and future works

We carried out experiments on laser-driven detonation waves, where the diameter of the incident laser beam was so large that a quasi-planar portion remained in the wave front, although the experimental data have not been analyzed enough yet. We think that these experiments opend up a new field of detonation physics. In future, we will analyze the experimental data more, and conduct experiments where the critical electron density exits in the detonation wave.

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