1. Introduction

Laser propulsion\(^1\) is one of the concepts of beamed energy propulsion that has a comparative advantage with respect to conventional chemical rocket systems. This includes high specific impulse and thrust, and low lift-off weight because of the capability of utilizing an off-board energy source. This concept has been demonstrated by the Lightcraft\(^2\): a laser-propelled launch vehicle. Impulse generation capabilities on the order of one-tenth Ns have also been stipulated for an ablative-type of laser propulsion.\(^3\) Other applications of laser-induced plasma discharge include, but are not limited to, laser-induced breakdown spectroscopic studies.\(^4\–6\)

Laser-supported detonation (LSD) is known as overdriven detonation in which laser-induced discharge (LID) drives a shock wave. With a decrease in laser intensity, \(S\), regime transition occurs from LSD to laser-supported combustion (LSC) due to reduction in the laser-induced discharge propagation velocity \(u_{\text{LID}}\). At the laser intensity near this transition threshold, \(u_{\text{LID}}\) approaches the Chapman-Jouguet (C-J) detonation velocity. The C-J detonation velocity, \(u_{\text{CJ}}\), is as shown in Eq. (1).

\[
u_{\text{CJ}} = \left[2\left(\gamma^2 - 1\right)S/\rho\right]^{1/2}.
\] (1)

Where \(\gamma\) is the specific heat ratio of the ambient gas, \(S\) is laser intensity and gas density, respectively. Raizer\(^7\) stipulated a power law exponential value, such that \(u_{\text{LSD}} \propto S^{1/3}\) and is based on hydrodynamic relations. Previous studies conducted in order to understand the LSD wave mechanism include the influences of the focusing \(f\) number,\(^8\) ambient pressure\(^9\) and laser power density.\(^10\) Moreover, Raizer’s lateral expansion\(^11\) effect on LSD termination has been investigated by Ushio et al.\(^12\). The regime transition was also predicted via Hugoniot analysis by Shimamura et al.\(^13\).

Supersonic expansion regimes of plasma due to laser-induced breakdown have been characterized by \(u_{\text{LID}}\) as a function of \(S\). These regimes, in an increasing order of discharge velocity for a given \(S\), include the LSD wave,\(^8,11,14–16\) laser-supported radiation wave (LSRW) and fast ionization wave (FIW).\(^17–20\) This study, however, focuses on the LSD wave regime at \(S < 10^3\) GWm\(^{-2}\) because FIW and LSRW regimes at \(S > 10^3\) GWm\(^{-2}\) do not possess sufficient pressure build-up for an efficient propulsive effect.

In a recent related study,\(^21\) a uniquely defined relation in atmospheric air with and without confinement of the induced discharge was obtained as: \(u_{\text{LID}} \propto S^{0.46}\). That study concluded that, for a laser beam with an effective diameter \(D\), such that \(D \geq 5.1\) mm, \(u_{\text{LID}}\) is uniquely defined as a function of \(S\). Figure 1 shows the velocity–intensity plots of studies in the LSD regime and compares induced discharges with \(D \geq 5.1\) and \(D < 5.1\) mm.

A one-dimensional LID photoionization model\(^22\) proposed by Shimamura et al. is described in Eq. (2).

\[
u_{\text{LID}} = \frac{v_i l}{\ln(n_e\text{peak}/n_{e1})}.
\] (2)

Where \(n_e\text{peak}\) and \(n_{e1}\) are the electron number density distribution, respectively, at the peak and precursor locations, and \(l\) is the distance between the peak and precursor positions. Here, the precursor position is defined as the point of non-zero \(n_e\) distribution at the wavefront. This discharge-based physics equation defines \(u_{\text{LID}}\) as a function of the ionization frequency \(v_i\), which is also a function of \(S\). Therefore, a study of the LID propagation velocity dependence on \(S\) is vital for understanding the sustenance of the LSD wave regime. The objective of this study is to investigate the influence of the ambient gas content (helium and argon) on the LID propagation velocity. These gases were used because of their possible rocket mode applicability to laser propulsion and also for the simplicity of ionization kinetics analysis due to their monoatomic nature.

2. Experimental Setup

A transversely excited atmospheric (TEA) CO\(_2\) pulse laser was used. The output energy was controlled within the range from 5 J to 12 J, avoiding the multiple breakdown phenomenon, especially in the case of using Ar gas. In order to ensure that the shot-to-shot pulse energy deviations were below ±5% throughout experimentation, a gentec-EO joule meter (model QE50LP-H-MB, max measurable energy (without attenuator) 15 J, effective aperture 50 mm × 50 mm) was used
to measure the pulse energy before and after the experiments. The laser beam was focused by two sets (each set is a pair) of off-axis gold-coated cylindrical mirrors and an anti-reflection (AR)-coated Zinc-Selenide (Zn-Se) convex lens in order to achieve effective diameters \(D\) of 9.1, 7.2 and 5.1 mm, respectively. The mirrors have an average reflection value of 98% due to the gold coating, whereas the Zn-Se lens has an average transmission in excess of 97% due to its AR coating. The chamber pressure was set at 1 atm and the experiments were carried out under room-temperature conditions.

A diode pumped solid-state (DPSS) laser (continuous wave (CW), 532 nm, 1.45 W) was used as the probe beam for the shadowgraph study of LID propagation. Images of the laser-induced plasma were taken using an Ultra 8 (DRS Tech., resolution 520 \times 520\ pixels, exposure time of 10 ns) ICCD camera. A spatial filter (with a 10\(\mu\)m pinhole) was used to remove unwanted multiple-order energy peaks and spatial noise from the probe beam before traversing the test section. The probe beam was collimated using a pair of N-BK7 plano-convex spherical lenses with focal lengths of 500 mm and 300 mm, respectively. The temporal and spatial resolutions were 30 ns and 36\(\mu\)m, respectively. The schematic diagram for the shadowgraph experiment setup is as shown in Fig. 2. The CO\(_2\) laser focusing apparatus for the respective effective diameters in this study was as shown in Fig. 3. The spatial intensity (Gaussian and Top-hat) profiles of the laser beam at the focal point for the case of \(D = 7.2\) mm is as shown in Fig. 4. \(D\) was derived from the diameters at the focal point of the Gaussian and Top-hat distributions, \(D_G\) and \(D_T\), respectively (i.e. \(D = 2\sqrt{(D_G D_T)/\pi}\)). Here, the diameters have the appropriate respective beam quality factors \(M^2\), included in their definitions and are as shown in Eq. (3):

\[
D_{G,T} = 2 \frac{M_{G,T}^2 f}{\pi R},
\]

where \(\lambda\) is the laser wavelength, \(f\) is the focal length of the lens/mirror, and \(R\) is the radius of the laser beam on the surface of the lens/mirror. The \(M^2\) of the CO\(_2\) pulse laser were respectively estimated to be 20 and 50. Approximately 86% of the laser beam power is confined within the area defined by \(D_G\) and \(D_T\).

Figures 5(a) and 5(b) show shadowgraph sample images (propagation history) of argon (Ar) gas with a laser beam \(D\) of 9.1 mm, and helium (He) gas with a laser beam \(D\) of 5.1 mm, respectively. An observation from these images is that, the plasma displacement in He gas is much greater than
that in Ar gas for a given $t$. The discharge velocity $u_{\text{LID}}$, was obtained analytically from the shadowgraph images using a displacement–time ($x$–$t$) plot obtained from the images. Figure 6 shows an $x$–$t$ plot and a corresponding $u_{\text{LID}}$–$t$ plot for a $D$ of 7.2 mm in both Ar and He gases. The elapsed time $t$ is defined with its origin set at the initial irradiance of the laser beam. The error bars for $x$ in Fig. 6 represent the standard error of the mean value. The error bars for $u_{\text{LID}}$ in Figs. 6–8 describe the propagated error due to deducing $u_{\text{LID}}$ from the $x$–$t$ plot. The $u_{\text{LID}}$ error bars were obtained by using the least squares method. Each data point is the mean of five data point sets.

3. Results

The LID propagation velocities for Ar gas using four different $D$s are shown in Fig. 7. This shows the essence of sufficiently large $D$ (7.2 mm) in order to uniquely define $u_{\text{LID}}$ as a function of $S$. Therefore, for a $D$ less than 7.2 mm, $u_{\text{LID}}$ is slower for a given $S$ and the dependence is not unique. Velocity plots were graphed as a function of peak $S$. This is because propagation velocity is a localized phenomenon. The influence of the gas species are as shown in Fig. 8. $D = 5.1$ mm was sufficiently large for He gas plasma. The exponential values $\alpha$ of the power law relation $u_{\text{LID}} \propto S^\alpha$, for He, air and Ar are respectively 1.18, 0.4621) and 0.23. Table 1 shows the comparison of $\alpha$ for this study to that of ambient air studies with laser beams of sufficiently large $D$.

4. Conclusion

The influence of the ambient gas content on the propagation velocity of LID was investigated via shadowgraph experiments. An identical relationship was obtained between $u_{\text{LID}}$ and $S$ at sufficiently large $D$. These were 5.1 mm and 7.2 mm, respectively, for the He and Ar gases. He gas
showed the fastest propagation velocity.

The α values of the power law relation, $u_{\text{LID}} \propto S^\alpha$, were 1.18 in He gas and 0.23 in Ar gas. This difference is possibly explicable by the gas properties, such as atomic mass, cross-section of photoabsorption and electron production rate considering ionization potential and electron attachment frequency. Further experimental and analytical studies will be indispensable in order to verify these possible gas properties.

Acknowledgments

This work was supported by a Grant-in-Aid for Scientific Research (S), No. 15H05770, sponsored by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

References


Y. Ohkawa
Associate Editor

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