レーザー推進のエネルギー変換過程に及ばす雰囲気圧の影響に関する実験的研究

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Experimental Study of Effect of Ambient Pressure to Energy Process of Laser Propulsion

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Abstract

Powerful laser propulsion has been expected to be a prominent launching method for small satellites in the future. The goal of this study is to investigate to effect of ambient pressure to energy conversion process of a laser pulse irradiated to a spherical target. By using Schlieren method the shock wave propagation is visualized and then the blast wave energy conversion efficiency is estimated at the different ambient pressure. The blast wave energy conversion efficiency was found to get maximum value at atmospheric pressure.

I. Introduction

The laser concept of laser propulsion firstly introduced in 1972 by Kantrowitz [1] which has been expected to reduce the launch cost of small satellite to the low Earth orbit in the near future. Theoretically, the laser propulsion is based on the laser ablation process which is the removing material on the solid surface by an incident laser beam. Firstly, when increasing the fluence of laser beam, the temperature of irradiated area increases to the critical temperature and then the material evaporates from the surface. A thin layer of very dense plume so-called Knudsen layer which includes ions, electrons and neutrals exists in front of the surface. The plasma plume continues to absorb energy from the incident laser beam and creates a high gradient temperature and high pressure domain. Thereafter, a blast wave is generated immediately in nanosecond scale, which plays a main role to propel the vehicle.

A number of researches about the laser propulsion have been studied. About the physics of laser propulsion, the characteristics of ablative laser propulsion in vacuum condition were examined by Phipps et al.[2]. The obtained results from five separate experiments showed a strong relation between the impulse and the parameters of the laser beam (wavelength, pulse width, and laser fluence). In 1999, the first free flight test of a laser-powered vehicle was performed by Myrabo [3]. The vehicle could climb up to the altitude of 71 m, but start to drift from the trajectory along the laser beam. A new open question which is how to maintain the stable state for the vehicle during the flight. Recently, [4] a new system design based on a combination of a spherical target and donut-mode laser beam was proposed by K.Mori, as shown in Fig.1. Unlike the conventional beam, in the cross-section of the beam, the energy is distributed around the spot of laser beam. This design is expected to realize the stable flight by generating the restoration force to the radial drift of the spherical vehicle from the center axis of the laser beam.

In order to study this new laser-powered launch system, the effect of ambient pressure to the phenomena concerning to laser propulsion such as blast wave expansion or blast wave energy conversion efficiency is clarified. Due to the complexity of the generation of donut-mode beam, firstly, the conventional beam is used to study about the laser propulsion in a wide range of ambient pressure in this study.

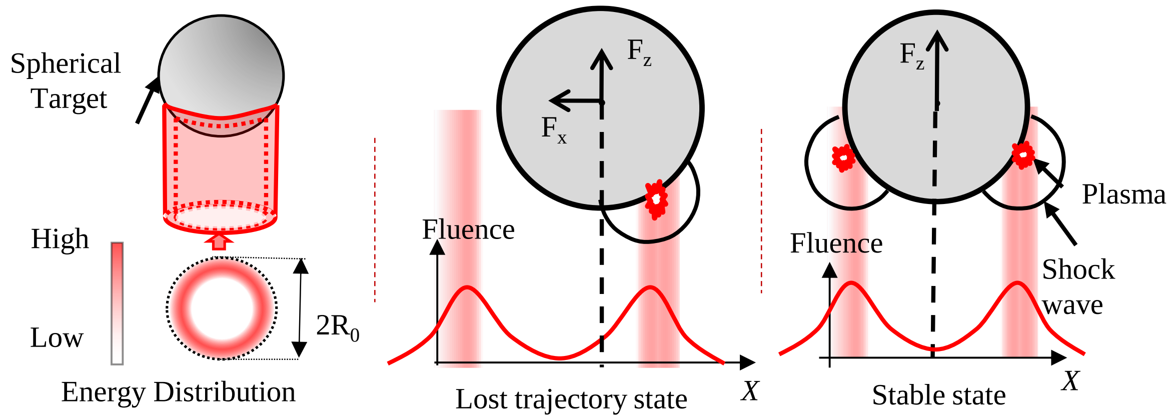


Fig. 1 The donut-mode beam system

II. Experimental setup

The schematic of the Schlieren experiment is presented in Fig. 2. In order to study about the effect of ambient pressure to the laser propulsion, all experiments were carried out in a vacuum chamber. The ambient pressure, p_a, was varied from 10 Pa to 100 kPa. The laser energy of a Nd:YAG laser source is 0.7 J. To measure and control the shot-to-shot laser energy, the beam splitter was used to separate the output laser beam. The total pulse energy was divided into 2 parts: the major energy was reflected by the splitter and minor energy passed through the splitter. The transition of the beam splitter is 0.01% whose energy was measured by the energy meter. The shot-to-shot variation of laser energy was controlled below 5%. The major laser beam was directed into the test section by a series of mirrors and then was sent through a BK7 window of the vacuum chamber. Finally, the beam was focused by a convex lens of focal length 200 mm.

About visualizing equipment, the high-intensity pulsed laser (Cavilux Ltd CAVILUX smart) was used as a probe light. It projected the Schlieren images of plasma formation and shock wave propagation on the high-speed camera HPV-X2 (Shimadzu Co., Ltd). In this study, the Schlieren images were captured up to 256 frames at 5×10^6 frames per second for each measurement that means the shock wave propagation was observed in the grey scale at steps of 0.2 μm.

The triggering process was also shown in Fig. 2. The electrical power supplied to the laser was used as a triggering signal. This signal was transmitted to a delay circuit, which allows us to delay the input signal. In this study, one channel was used for starting the laser beam and another channel was used to transmit to the high-speed camera. The synchronization signal between camera and light source was carried out by a cable.

The aluminum was chosen as the material of spherical target. The diameter of the target is 10 mm.

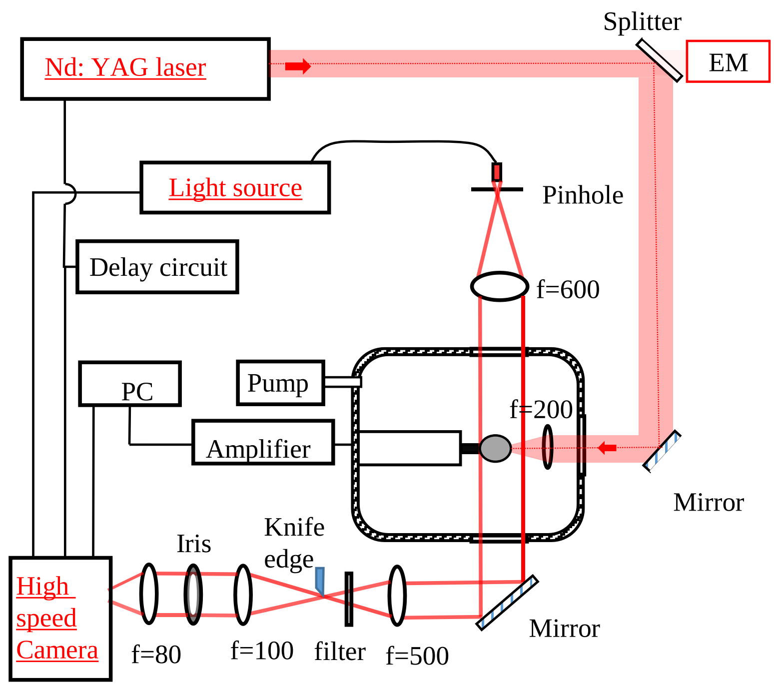
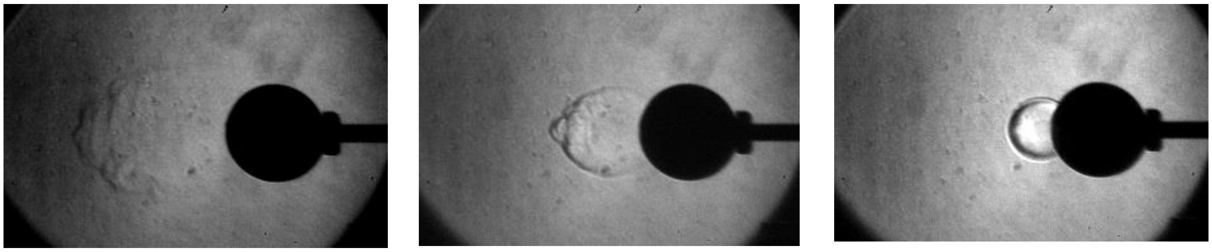


Fig. 2 The experimental set up for the Schlieren experiment and Impulse performance

III. Results

1. Shock wave expansion at different ambient pressure

The framing Schlieren images in Fig. 3 show the experimental data for the different cases of ambient pressure. The laser pulse started to irradiate at t =0 ns from the left side in the frame. t is defined as an elapsed time from the ignition. In this case, the spot diameter of the laser beam was kept at 1.3 mm corresponds with laser fluence at 52.7 J/cm^2. From obtained results, the dependence of ambient pressure to the spatial development of plasma plume and shock wave was indicated. It should be noted that the experiment was carried out at the lowest ambient pressure of p_a= 10 Pa. However, due to the low energy of shockwave, the Schlieren images could not be recorded at p_a= 10 Pa. In Fig. 3.a, at p_a= 100 Pa, the shock wave on the surface of the target is visualized at t =450 ns. The shock wave is accelerated by the anisotropic expansion of the ablation plume and expanded fast far from the target. In this case, due to low ambient pressure, the ablative plume freely exposes, so the shock wave is extremely weak and the expansion speed is very high. To our knowledge, this is the first such measurement for shock wave propagation which could be visualized below 100 Pa. At p_a= 1 kPa, as shown in Fig. 3.b, the effect of ambient pressure could be observed. The shape of shock wave becomes more spherical and the expansion speed decreases. Due to the high air density around the target, the duration plasma formation lasts more time. However, the shock wave also expands anisotropically, creates a tip of the shock wave. Finally, in the case of 10 kPa, as shown in Fig. 3.c, the shock wave expands spherically while the luminous plume stays longest on the target. The speed of shock wave is the smallest among three cases.



a. p_a=100 Pa b. p_a=1 kPa c. p_a=10 kPa

Fig. 3 Schlieren snapshot after 450 ns of laser ablation in a wide range of ambient pressure

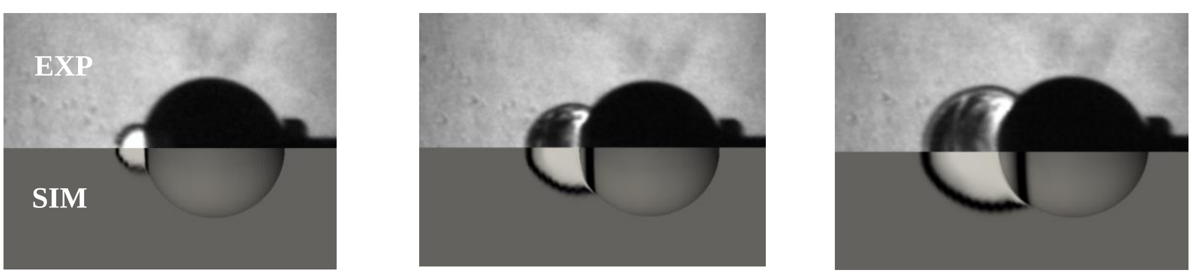
2. Blast wave conversion efficiency

The blast wave energy conversion efficiency is defined as the ratio between the blast wave energy and energy of incident laser beam, which is given by

$$\eta_{bw} = {E_{bw}}/{E_L} \tag{1}$$

In this study, η_{bw} was deduced based on the measurement of the temporal change in the shock wave propagation's radius by both experimental method (EXP) and numerical method (SIM). The history of shock wave propagation was obtained experimentally from a series of the Schlieren images. Besides, in the numerical method, three-dimensional compressible Euler Equations were used to simulate gas dynamics of laser ablation propulsion. An energy source which equals to blast wave energy was set up in front of the target to simulate the development of shock wave. In this study, the incident laser energy was kept at E_L=0.7 J with spot diameter d_{sp1}= 1.3 mm. According to the previous studies [5] [6], the blast wave energy conversion efficiency was in the range from 0.35 to 0.6. Therefore, the energy of blast wave was set up from 0.15J to 0.5 J with the step at 0.05J to find the exact value of blast wave energy.

Fig. 4 shows the framing Schlieren images of shock wave propagation at high ambient pressure, p_a=100 kPa. The upper part of these images is experimental results and the lower part of these images is the numerical method in the case of blast wave energy E_{bw}=0.35 J. The development of shock wave in the experimental method is consistent with the numerical method, so we can estimate roughly the blast wave energy from Schlieren images.



t=250 ns t=1050 ns t=2050 ns

Fig. 4. Comparison of shock wave expansion between experimental and numerical method at p_a=100 kPa (In the case of simulation, E_{bw}=0.35 J)

The comparison of non-dimension of radius of shock wave propagation is shown in Fig. 5. The blast wave energy was found to be between 0.25 J to 0.3 J. According to Eq.1, the blast wave energy conversion efficiency η_{bw} is in the range from 0.35 to 0.43 at the atmospheric pressure.

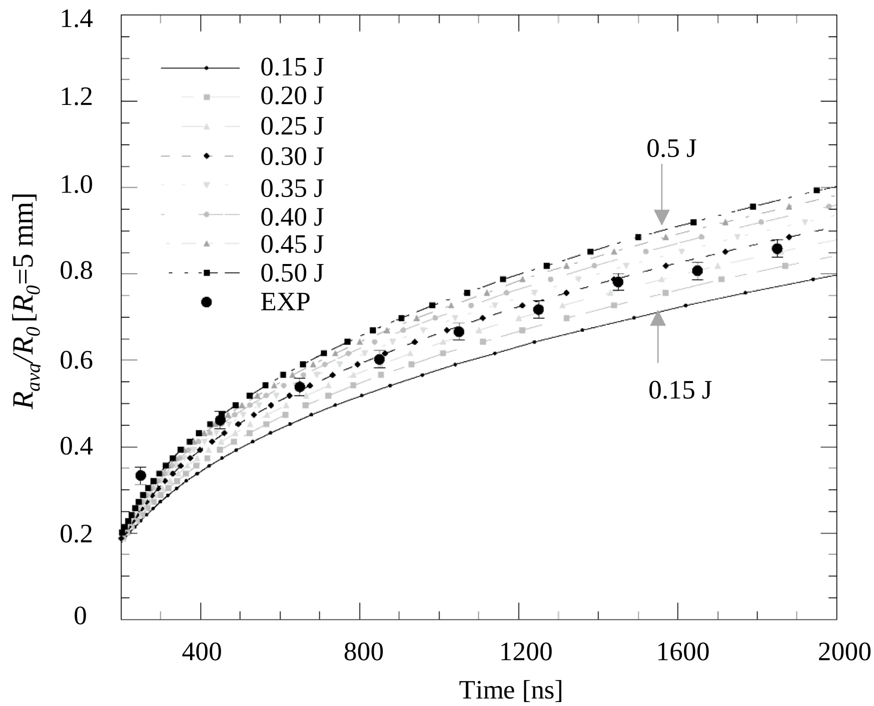


Fig. 5 Comparing of blast wave volume between SIM (dot-line) and EXP (point) at p_a=100 kPa

IV. Conclusion

The nanosecond Nd:YAG laser was used to irradiate the spherical target to study about the effect of the ambient pressure to the laser propulsion. The shock wave generation and expansion speed was found varying due to the reduction of the ambient pressure. The blast wave conversion coefficient was between 0.35 and 0.43 at the atmospheric pressure.

Reference

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