Thrust Generation of Laser Ablation in Helium and Argon Ambient Gases with Repetitive Laser Pulses

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Abstract: Thrust generated by irradiating repetitive laser pulses on Al target in ambient helium and argon gases was studied with a torsion pendulum impulse measurement system. The pulse repetition rate is up to 1 kHz. The result indicates that the ablation generated thrust is strongly dependent on the molecular weight of the ambient gas, majorly owing to a confinement effect. The momentum coupling coefficient can be improved while using inert gas with higher molecular weight. For both gases, it decreases monotonously while the ambient pressure reduced from 101 kPa to 0.1 kPa which may be due to the weakening on the confinement effect. This pressure dependence has a good agreement with our corresponding data obtained in air.

Nomenclature

A	=	initial amplitude of pendulum oscillation
C_m	=	Momentum Coupling Coefficient
D	=	temporal deflection of the torsion pendulum
E_p	=	single pulse energy
N_b	=	number of pulses in one burst
f	=	laser pulse repetition frequency
p_0	=	ambient gas pressure
t	=	time
t_o	=	time of the occurrence of laser ablation
ω	=	angular velocity

I. Introduction

When irradiating high power laser beam on to a solid target, recoil force is generated as a result of matter ejection from the ablated area. Taking the advantage of rapid developing on high power laser technique during the past decades, laser ablation propulsion has been intensively studied owing to its importance in a wide range of applications, which includes lunching of micro-satellite to a near earth orbit[1], laser micro-thruster[2] or space debris removal[3, 4].

In addition to laser irradiation condition and ablator characteristics, the impulse generation also strongly depends on the environment condition such as the ambient gas species and its pressure p_0. The impulse generation process in gas environment is complex because it includes phenomena like plasma expansion to backgrounds and shock wave dynamics. Enhanced impulse in inert gas with high molecular weight was reported by Sasoh as obtained on a laser-

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driven in-tube accelerator (LITA) apparatus[5]. Pakhomov investigated the effect of air pressure on the propulsion impulse generation both experimentally and theoretically with a TEA-CO_2 laser[6]. However, past works were mainly conducted with single pulse laser or repetitive pulsed laser with low repetition rate of 10~100 Hz. The ambient gas effect on laser propulsion performance with 1 kHz level pulse repetition rate have not been paid enough attention. For this high repetition rate, some other effects might influence the thrust performance. The accumulation of heat at the ablation area will reduce the ablation threshold for following pulses in a same burst[7]. Besides, the ambient gas pulsation is also different from that in low repetition rate case.

In this study, we present impulse measurements of repetitive pulses laser ablation onto Al target conducted in inert ambient gases on a torsion pendulum system. Besides of gas species, the effect of gas pressure, p_0, which is another important factor for thrust performance optimization, is investigated in a moderate pressure range considering the LITA launching system.

II. Experimental Description

The experiment is conducted using a Nd:YLF laser at the wavelength λ=1047 ns. The solid-state laser is capable to irradiate pulses at a repetition rate up to 10 kHz. The laser is running in burst output mode, means that a burst of pulses with controllable number of pulses N_b and fixed single pulse energy E_p could be irradiated at selected repetition frequency f after receiving regulated trigger signals from a function generator. In the measurement, 1 burst consists N_b=200 pulses with f= 1 kHz is output on to fresh surface of an Al target. The FWHM pulse width (full width at half maximum) is 9 ns. In order to generate ablation on the target, laser beam is focused by a lens with 150 mm focusing length. The beam incidents normally to the target surface with less than 2 degrees of angular uncertainty. The target is placed slightly befor the focusing plane to avoid the occurring of gas breakdown before ablation on its surface.

The impulse measurement is performed by recording and analyzing the temporal deflection signal D of the torsion pendulum, which can be fitted to a damped oscillation expression:

$$D = A \sin\left(\omega(t - t_0) \exp\{-c(t-t_0)\} \right) \quad (1)$$

in which A denotes the initial amplitude of the oscillation signal when the impulse is generated at the time t_0; ω is the angular velocity of the pendulum. The relation between A and impulse is calibrated by impact hammer. The pendulum is capable for tiny impulse (sub-μNs level) measurement. It is placed in a vacuum chamber (0.7 m diameter, 2.2m in length) filled with Argon or Helium gas. Before testing, the chamber is firstly vacuumed to 10^{-2} Pa by a combined system consists of a rotary pump (Alcate, T2033SD) and a turbo molecular pump (Shimatsu, TMP-2003LM), then filled with inert gas to required pressure. The ablation spot area is measured with a microscope (Keyence Company, VK-9500) to determine the fluence in each case.

III. Results and Discussion

A. Effect of gas species and pressure

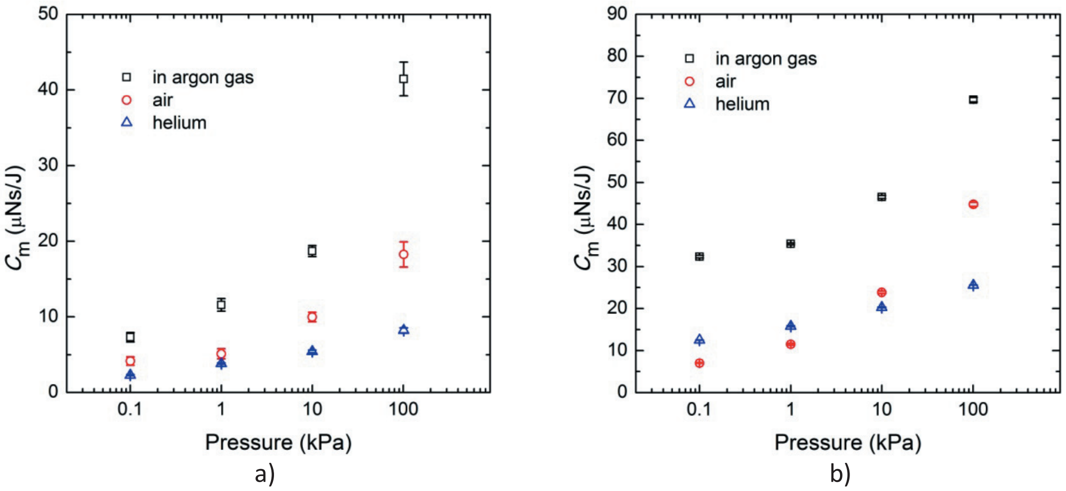

Figure 1. The momentum coupling coefficient at different pressures, in argon, air and helium gases with 1 kHz laser irradiation, the fluence is a) 9.9 J/cm^2 and b) 17.0 J/cm^2.

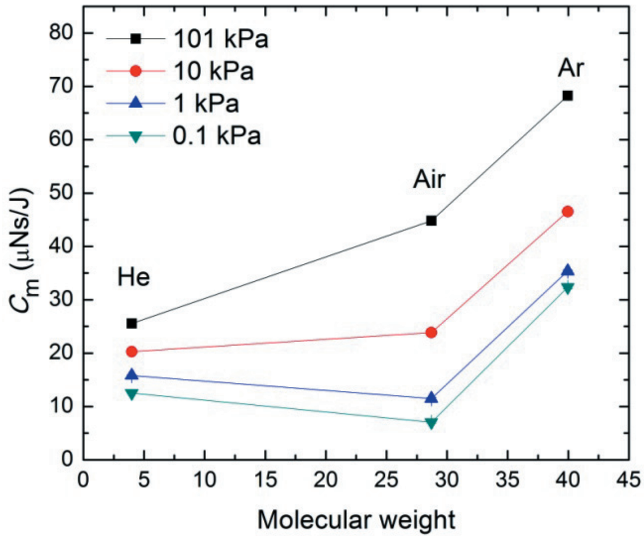

Figure 2. The C_m-molecular weight relation at the laser fluence of 17.0 J/cm^2.

Argon and helium gases were selected as ambient gases based on the consideration of their difference on confinement effect. In gas environment, the laser ablation impulse is generated from majorly two mechanisms: the high pressure of plasma plume near the target surface and the dynamics of following shockwave expansion. For the confinement effect on plasma expansion, a noble gas with higher molecular weight is expected to slow down the plume expansion more rapidly (8). Sasoh (5) found that the impulse is in inverse proportion relation with the sound speed of the filled gas base on similarity analyzing of shock wave expansion. Both indicate that better impulsive thrust (or momentum coupling coefficient, $C_{m,}$ defined as impulse divided by incident laser energy) could be expected in ambient gas with higher molecular weight at higher pressure.

In Fig. 1, the momentum coupling coefficient in different sorts of ambient gases with 1 kHz laser repetition rate is shown. The studied pressure p ranged from 0.1 to 101 kPa, which is moderate for the proposed LITA device. The laser fluence is 9.9 J/cm^2 and 17.0 J/cm^2. Each plot in the figure represents an average of 4 times measurements while the error bar indicates the standard deviation of the date. The result obtained in air is also plotted for comparison. It is shown that C_m decease monotonously with the declination of ambient pressure from 101 to 0.1 kPa for all tested gases. The changing on fluence does not show significant influence on this trend. For the gas species, the C_m obtained in Argon gas is the highest for each pressure case, which is in accordance with the expectation, even at this high repetition rate condition. However, compares between the result in Air and Helium gas at low pressure (1 and 0.1 kPa) range shows a contrary dependency on molecular weight (as shown in Fig. 2). The impulse decreasing is more rapidly in air with reducing on p_0. Therefore, it is considered that, in low pressure conditions, there are other mechanisms rather than confinement maybe playing a more important role which needs further investigation.

B. C_m dependency on fluence

Laser fluence is another important factor for thrust optimization. The C_m-fluence relation obtained experimentally at various p_0 is plotted in Fig. 3.

It is shown that C_m keeps increase with fluence in the studied fluence range for 2 noble gases. However, the increasing slops decline with fluence. An optimized fluence between 16 ~17 J/cm^2 is observed for 101 and 10 kPa with argon gas. However, in lower pressure of argon gas (1 kPa), the C_m keeps increasing for fluence up to about 18 J/cm^2, which shows a possibility to achieve high C_m in low pressure argon gas environment which is economical for a LITA device.

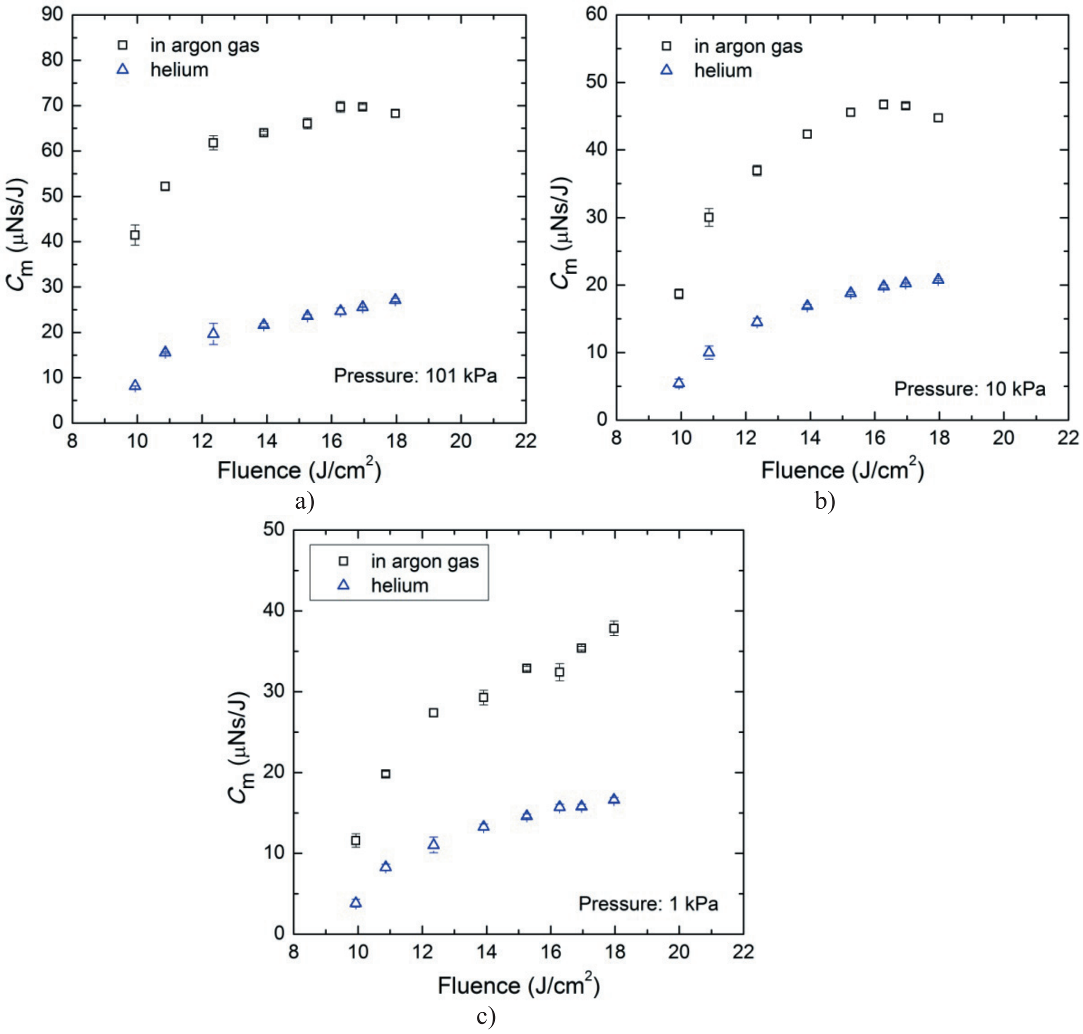

Figure 3. Influence of laser fluence on Cm obtained in argon, air and helium gases, ambient gas pressure is a)101 kPa, b)10 kPa and, c)1 kPa.

IV. Conclusion

To study the effect of ambient gas on the laser ablation thrust generation characteristics, impulse measurement is performed in argon and helium gas environment with at 1 kHz laser pulse repetition rate. The momentum coupling coefficient decreases monotonously with declination in p_0 which is mainly attributed to the weakling on gas confinement effects. Highest C_m is obtained in p_0= 101 kPa of argon gas. The impulse generation also shows strong dependency on gas species. Better thrust performance is achieved for gas with heavier molecular weight.

References

1. Sasoh, A. "Laser-Driven In-Tube Accelerator", *Rev. Sci. Instrum.*, Vol. 72 , 2001, pp. 1893‐1898.

2. Phipps, C. R., Luke, J. R., Helgeson, W. and Johnson, R., "Performance Test Results for the Laser-Powered Microthruster" in *Beamed Energy Propulsion*, AIP Conference Proceedings 706, Melville, New York, 2004, pp. 224-234.

3. Schall, W. O., "Laser Radiation for Cleaning Space Debris from Lower Earth Orbits" *Journal of Spacecraft and Rockets*, Vol. 39, No. 1, 2002, pp. 81–91.

4. Phipps, C. R., Albrecht, G., Friedman, H., et al., "ORION: Clearing near-Earth space debris using a 20-kW, 530-nm, Earth-based, repetitively pulsed laser", *Laser and Particle Beams*, Vol. 14, No. 1, 1996, pp. 1–44

5. Sosoh, A., Urabe, N., Kim, S., and Jeung I. S, "Impulse Dependence on Propellant Condition in a Laser-Driven In-Tube Accelerator", Trans. Japan Soc. Aero. Space Sci., Vol. 48, No. 160, 2005, pp. 63-70.

6. Pakhomov, A.V., Lin, J., and Tan, R.Q., "Air Pressure Effect` on Propulsion with Transversly Excited Atmospheric CO2 Laser" *AIAA Journal*, Vol. 44, No. 1, 2006, pp. 136-141.

7. Colao, F., Lazic, V., and Fantoni, R., "A Comparison of Single and Double Pulse Laser-Induced Breakdown Spectroscopy of Aluminum Samples," *Spectrochimica Acta, Part B: Atomic Spectroscopy*, Vol. 57, No. 7, 2002, pp. 1167–1179.

8. Bulgakov, A. V. and Bulgakova, N. M., "Gas-dynamic effects of the interaction between a pulsed laser-ablation plume and the ambient gas: analogy with an underexpanded jet" *J. Phys. D: Appl. Phys.* Vol. 31, 1998, pp. 693-703.