# Thrust Measurement of a CW Laser Thruster in Vacuum*

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**This paper reports results of fundamental experiments on a continuous-wave $CO_2$ laser thruster. The Laser-Sustained Plasma (LSP) was maintained under pressures ranging from 2 to 7 atm with laser power level of more than 300 watts. The location of LSP was controlled by adjusting laser power and focus position . Thruster performance was then evaluated by measuring thrust using a simple thrust stand equipped with a load-cell sensor. Finally, energy balance in the thruster was understood by measuring heat loss and transparent laser loss.**

## Introduction

Laser propulsion has been studied as one of the propulsions that are used in space or atmosphere. In the1970's many studies using laser beam were progressing, as high power laser devices were developed. Raizer [1] suggested the plasma generation using high power laser beam. After that, Generalov et. al. succeeded in sustaining air plasma continuously using CW $CO_2$ laser beam [2]. Kantrowitz proposed the concept of laser propulsion that the laser-sustained plasma was applied to rocket propulsion [3].

Laser propulsion has an acceleration mechanism that propellant gas is heated by laser-sustained plasma (LSP), which absorbs the high power laser beam supported from a remote site and is maintained in the thruster, and the gas enthalpy is recovered as thrust by a nozzle. Its payload fraction is expected to become higher than other propulsions because space vehicles need not load power sources [4]. Especially as the launcher from the ground, laser propulsion has the advantage of using the air flowing around a rocket as a propellant.

Laser propulsion is classified into two types by laser devices, continuous or pulse. In this study, a CW laser devise is employed for laser propulsion experiments. Keefer et al. [5] investigated the fundamental behavior of the LSP and developed a numerical code for the LSP for the purpose of designing a laser thruster. Mazumder et al. [6] performed experiments similar to Keefer's experiments and the LSP was maintained on higher power condition (∼10kW) than that of keefer [7]. However, there has been a limited number of experimental studies on laser propulsion, and in these studies, only thrust has been measured to evaluate thruster performance. They were not sufficient experiments for investigating energy transfer from LSP to kinetic energy of a working fluid.

In our previous works, the LSP (laser-supported plasma) was produced even in a low power condition and the shape and the position of LSP were observed using a CCD camera. In addition, thrust in atmosphere, heat loss to walls and laser power loss passing through a throat were measured and the energy balance of the thruster was observed. From these experiments, it was clear that thrust increased with increasing pressure ratio.

In this paper, the thrust in vacuum was measured to investigate the effect of pressure ratio on thrust.

## Concept of Laser Propulsion

The model of laser propulsion is shown in Fig. 1. A laser beam is focused into a plasma production chamber through a set of condensing lens and window. Once a plasma is produced near a focal point, the plasma effi-

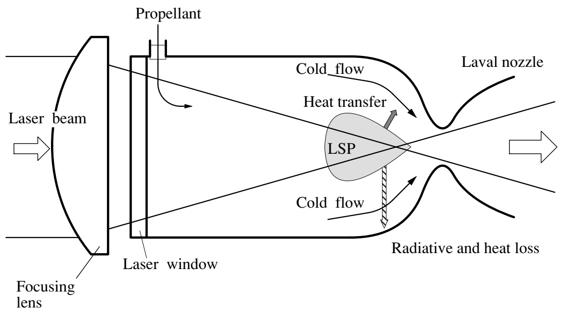


Figure 1: Concept of laser propulsion

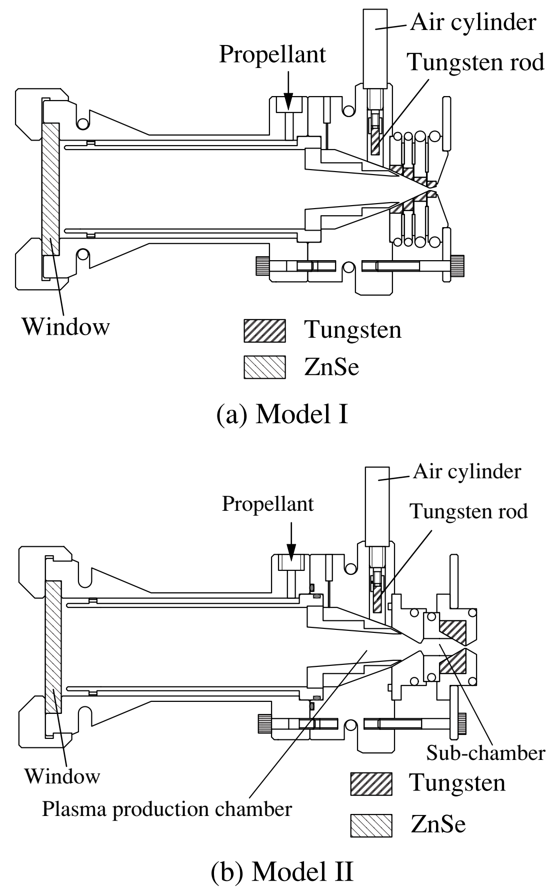


Figure 2: Cross section of laser thrusters.

ciently absorbs a beamed laser power through inverse bremsstrahlung radiation. The high temperature LSP (about 10,000 $\sim$ 20,000 K) heats a propellant gas, and then the thermal energy of the gas is converted to the kinetic energy through a convergent-divergent nozzle. The convective heat transfer to the chamber wall is usually small because the core of LSP doesn't attach directly to the wall and the cold flow surrounds the LSP. On the other hand, the radiative loss from the LSP increases with an increase in temperature of LSP. In this way, the performance of laser propulsion depends on the energy balance in the energy transfer processes.

## Experimental Apparatus

Figure 2 shows cross sections of two laser thrusters. Thrusters were composed of a laser window, a plasma production chamber and a nozzle. The laser window was a zinc selenide (ZnSe) disk with anti reflection coating and could transmit laser beam of 10.6 $\mu$m wave length efficiently. It withstands up to 10 atm. This window was sealed by silicone sheets. The chamber and window were cooled by regenerative cooling of propellant gases. Argon and nitrogen were used as the propellant and were supplied up to 50 l/min (1.48 g/sec in argon, 1.04 g/sec in nitrogen).

In the case of the thruster model I, the nozzle is made of tungsten in order to withstand high heat flux from the laser beam and plasma radiation. The throat is 1mm in diameter and the convergence corn half angle of nozzle is 25° the divergence corn half angle is 30° the nozzle area expansion ratio is 4. The nozzle and body were water-cooled to measure the heat loss.

The thruster model II has a sub-chamber upstream from the throat. The diameters of the sub-chamber entrance, the straight section, and the throat were 3 mm, 6 mm and 1 mm, respectively. The throat was made of tungsten in order to withstand high heat flux from laser beam and plasma radiation. The nozzle was water-cooled to measure the heat loss to the wall.

To ignite a plasma, a rod was used as the source of electron emission. This tungsten rod was inserted into the focal point and then was pulled back after a plasma was ignited.

Figure 3 shows the schematic of experimental apparatus in atmospheric pressure. The thruster was mounted on two parallel rails and the friction in the thrust direction could be reduced. The thrust was measured by a load-cell censor, and an array of weights was used for thrust calibration. As the result, the drift of zero point was quite few and the reproducibility of thrust measure-

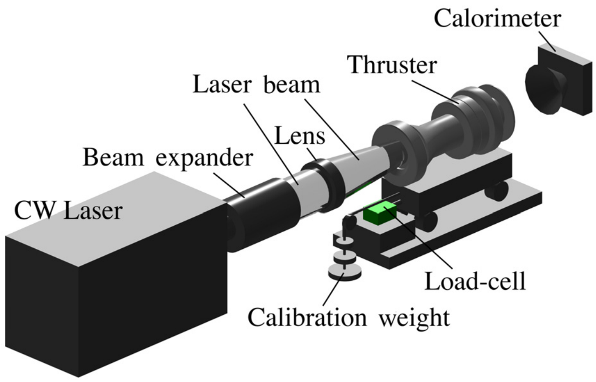


Figure 3: Schetch of thrust measurement system.

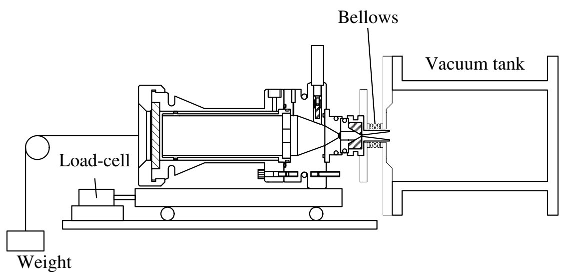


Figure 4: Thrust measurement system in vacuum.

ment was confirmed.

Figure 4 shows the thrust measurement system in vacuum. This system was composed of a bellows and a vacuum tank. The thruster, which was mounted on two rails, was connected to the vacuum chamber with the bellows. The thruster can move back and forth along the laser axis. The bellows was made of stainless steel and its spring constant was 300 gf/mm. The nozzle expansion ratio was 36 and the divergence half cone angle was 7° When the vacuum chamber was evacuated, the pressure in chamber was about 5 Torr with mass flow rate of 0.3 g/sec. The pressure difference between outside and inside of chamber generated the downstream force in thruster, about 1 kgf. To reduce the effect of the downstream force, the upstream force was applied to the thruster using a weight. Before measuring the thrust, the propellant gas was fed directly into the chamber and this value of thrust was defined as a zero point. In measuring the thrust, the feeding way of propellant gas was changed and the gas was fed only into the thruster.

The heat loss to the wall was acquired by measuring the increase in cooling water temperature measured by thermocouple. The laser energy passing through the throat was measured by a calorimeter. In these experiments, a 2 kW (CW) $CO_2$ laser (Panasonic YB-L200B7T4) was utilized. The laser power was variable during operation. The beam diameter was magnified by 2.2 using a ZnSe beam expander, and the magnified beam was focused into the thruster by a ZnSe plano-convex lens of 250 mm focal length. This lens was mounted on an one-axis stage movable in the laser beam direction. The LSP moved with a movement of the focal point. Both the beam expander and the condensing lens were cooled by circulating oil.

## Experimental Results and Discussion

### Thrust measurement in atmosphere

Argon and nitrogen were used as the propellant for experiments. Figure 5 shows the relation between the thrust and the gas pressure with thruster model I.

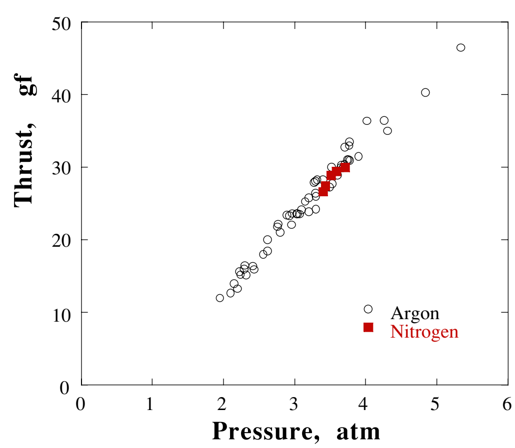


Figure 5: Relation between thrust and pressure on thruster model I.

As shown in this figure, the thrust is given by the pressure. Therefore, it seems that the ideal aerodynamic acceleration through the Laval nozzle is valid for this thruster and thrust is given by the following equations [8].

$$F = C_F A_t p_c \quad (1)$$

$$C_F = \sqrt{\frac{2k^2}{k-1}\left(\frac{2}{k+1}\right)^{(k+1)/(k-1)}\left[1-\left(\frac{p_e}{p_c}\right)^{(k-1)/k}\right]} + \frac{p_e - p_b}{p_c}\frac{A_e}{A_t} \quad (2)$$

where F is thrust, $C_F$ thrust coefficient, $A_t$ cross-sectional area of the throat, $p_c$ chamber pressure, $p_e$ nozzle exit pressure, and k specific heat ratio.

Figure 6 shows the thrust coefficient obtained from the measured thrust and pressure.

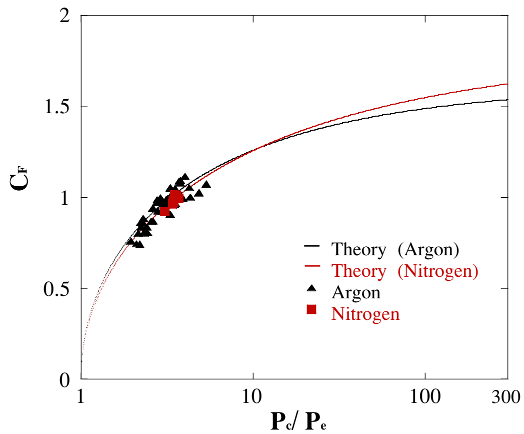


Figure 6: Thrust coefficient calculated using measured thrust and pressure as a function of pressure ratio.

In this figure, the solid line represents the theoretical value calculated from Eq. 2. In this experiment, the measured CF was close to 1.0 at around 4 atm and agreed with the theoretical value. If high pressure ratio Pc/Pe were given, thruster performance would be enhanced.

In the case of the thruster model II, the thrust increased in changing the plasma position. Figure 7 shows the time sequence of the change in thrust as the focal point moves from the production chamber to the sub-chamber. The gas pressure increases gradually when the plasma approaches the entrance of the sub-chamber, and increases remarkably when the LSP entered the sub-chamber. From this result, it was found that the thrust increased by changing the shape at where the plasma was sustained.

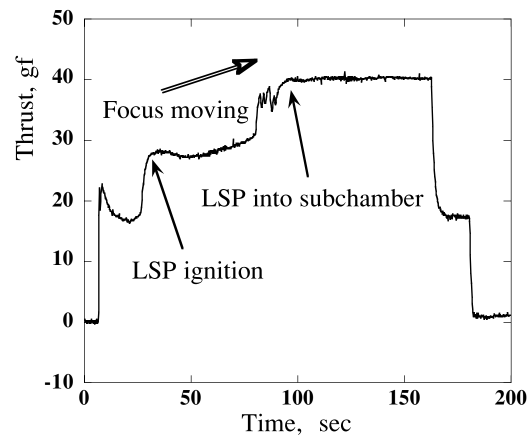


Figure 7: Time sequence of thrust at 700W and Ar 0.593 g/sec on thruster model II.

## Thrust measurement in vacuum

The thrust in vacuum was measured using the apparatus shown in Fig. 4. The results calculated from thrusts were shown in Table 1.

where $C_F$ was calculated from Eq. 2. In these experiments, two nozzles were used. The nozzle area ratio, $A_e/A_t$ was 4 for measurements in atmosphere, 36 for that in vacuum. In every case, the measured $C_F$ agreed well with the calculated one. The experimental value of $C_F$ increased from 1 to 1.7 with increasing pressure ratio. From this result, the thrust was found to be represented by Eq. 1. The efficiency of energy conversion from the incident laser power to the kinetic energy in the thrust direction was defined as the energy conversion efficiency. It was calculated as,

$$\eta = \frac{F^2 - {F_{cold}}^2}{2\dot{m}P} \quad (3)$$

where P is the incident laser power and $F_{cold}$ is the thrust of cold gas. From Table 1, the energy conversion efficiency was found to be enhanced with increasing pressure ratio.

Table 1: Relation between thrust coefficinet and pressure ratio.

| | $p_c/p_b$ | $A_e/A_t$ | $C_F$ Theory | $C_F$ Experiment | $\eta_e$ | $I_{sp}$, sec |
|---|---|---|---|---|---|---|
| Ar Model I | 4 | 4 | 0.77 | 1.07 | 0.07 | 50 |
| | 60 | 36 | 0.99 | 1.13 | 0.08 | 59 |
| | 410 | 36 | 1.52 | 1.59 | 0.14 | 81 |
| $N_2$ Model I | 4 | 4 | 0.56 | 0.99 | 0.04 | 54 |
| | 300 | 36 | 1.60 | 1.62 | 0.17 | 108 |
| Ar Model II | 5 | 4 | 0.69 | 1.03 | 0.16 | 68 |
| | 420 | 36 | 1.60 | 1.79 | 0.37 | 113 |

Table 2: Energy distribution.

| | $p_c/p_b$ | $\eta_e$ | Heat loss | Laser loss | Other losses |
|---|---|---|---|---|---|
| Ar Model I | 4 | 0.06 | 0.45 | 0.06 | 0.43 |
| | 410 | 0.16 | 0.44 | n/a | 0.40 |
| $N_2$ Model I | 4 | 0.04 | 0.35 | 0.20 | 0.41 |
| | 300 | 0.17 | 0.51 | n/a | 0.32 |
| Ar Model II | 5 | 0.16 | 0.46 | 0.11 | 0.37 |
| | 420 | 0.37 | 0.55 | n/a | 0.08 |

### Energy distribution

Table 2 shows the energy distribution. In this table, the ratio to incident laser power was shown. The heat loss flux to the surrounding walls was estimated by the product of the flow rate of cooling water and its temperature difference between inlet and outlet. The laser power passing through the throat was measured using the calorimeter and was defined as the laser loss. Other loss is calculated by subtracting the energy conversion efficiency and the losses from 1. The other loss consists of the radiation from plasma, the gas enthalpy, the other laser loss and so on. In vacuum, the laser loss wasn't measured.

In increasing the pressure ratio, the energy conversion efficiency increased and the other loss decreased. This is because that the gas enthalpy was converted efficiently to the kinetic energy through the nozzle. In every case, the heat loss was about 50%. In the real case, the heat loss is expected to be used as propellant enthalpy by regenerative cooling.

## Conclusions

The measurement in atmosphere and vacuum was performed for a CW laser thruster, and the following results were obtained.

1) Thruster performance was evaluated by means of the thrust measurement in both atmosphere and vacuum. As the result, it was found that the thrust was represented by the thrust coefficient and the thruster performance improved with increasing pressure ratio.

2) The energy distribution became clear from the measurement of thrust, heat loss and power loss through the nozzle. The energy converted from the incident laser power to the thrust increased up to 36% in high pressure ratio.

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