Numerical characterization of CW CO_2 laser propulsion with vapor

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Propulsion system using continuous-wave (CW) CO_2 laser has several advantages in comparison with other systems. This system does not require strong structure compared with propulsion with chemical propellant, plasma and gas arc jet. Laser propulsion can produce high specific impulse which determines propellant efficiency since the highest energy density is limited simply by laser system capability. Furthermore, propellant selection is free from the combination of fuel and oxidizer and therefore can be made according to propulsion performance. Using system of water vapor and CO_2 laser which can offer large power system and has large absorption coefficient with water molecule, we consider rocket lunching from the ground to the earth orbits. On the other hand, laser propulsion uses high temperature propellant compared to the chemical rocket and gets high specific impulse under subsonic speed. We examine the performance of propellant that is heated with laser from downstream of the flow and estimate specific impulse and thrust using numerical calculations. We found that specific impulse can be increased by selecting proper combination of laser power and propellant mass flux.

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In general, the propulsion consists of chemical and non-chemical propulsion. Chemical propulsion is a system using solid and liquid fuel. Non-chemical propulsion can be divided into electrical, laser, atomic and solar-thermal propulsion. In non-chemical propulsion, research on laser propulsion evokes from the proposal by Kantrowitz describing possibility of launching 1-kg payload from ground to the orbits around the earth with 1-MW laser[1].

Basic relation in propulsion is what rate of the input power changes kinetic energy of the system per unit time,

$$\eta P_{\text{Energy source}} = \frac{1}{2}\dot{M}_{\text{Propellant}} u^2, \tag{1}$$

where u, $\dot{M}_{\text{Propellant}}$, and η are the exhaust velocity of the propellant, the mass flow rate of the propellant, and the fluid efficiency which indicates the conversion efficiency from laser power to the fluid kinetic power, respectively. Generally in propulsion system, the important parameters to express performance of the propulsion system are $I_{\text{sp}} = \dot{M}_{\text{Propellant}} u/(\dot{M}_{\text{Propellant}} g)$ (specific impulse) and $C_{\text{m}} = \dot{M}_{\text{Propellant}} u/P_{\text{Energy source}}$ (momentum coupling coefficient). By introducing these parameters, we can discuss a propulsion system regardless of its size since they are intensive variables. Using these parameters, we can get

$$I_{\text{sp}} \cdot C_{\text{m}} = \frac{2}{g}\eta, \tag{2}$$

where g is the gravity acceleration. In this research, we aim the system with large specific impulse compared to conventional rocket systems.

For chemical rocket, the highest energy density is limited by chemical potential of propellant. On the other hand, for laser propulsion it is as large as limit of laser system capability. This is the most significant advantage of laser propulsion.

We consider an isentropic and isenthalpic system. In this system, the specific impulse is proportional to the function of $1/\sqrt{M_{\text{mol}}}$,

$$I_{\text{sp}} = \frac{1}{g}\sqrt{\frac{2\gamma}{\lambda-1}\frac{R}{M_{\text{mol}}}T} \propto \sqrt{\frac{T}{M_{\text{mol}}}}, \tag{3}$$

where M_{mol} is the molecular mass of the propellant. Then to increase specific impulse of the system, we must select the material that has the small molecular mass.

If we use liquid helium or liquid hydrogen as the propellant, their molecular mass is very small but they require highly pressurized propellant tank for elongated flight. Water and ammonia have relatively small molecular masses and liquid phase at room temperature. We chose water as a propellant for its easy handling and laser interaction properties.

Laser propulsion with the heat exchanger is suitable for the launching from the ground because we can tolerate optical beam distortion through atmosphere. The estimation of Kare's 100-MW-class heat exchanger can be realized by using some lasers which have the power from 10 kW to 1 MW[2]. This system has great advantage of allowing the laser to use incoherent beam and large spot size on target. This means the laser beams do not have to be from single source. If a lot of laser supply points are allocated at top of some mountains above clouds, large power can be built up by gathering smaller laser power units that can be readily manufactured up to budget. Thus, we use laser oscillation type not of pulsed one but continuous-wave (CW) one.

CO_2 laser has large absorption coefficient of water molecule[3] (see Fig. 1). It can make large power easily by sizing up the gas discharge tube of laser device. On the other hand, solid laser needs large laser medium to get large power. But it is difficult to get large in size and high optical quality. Furthermore, less thermal load can be expected in the heat exchange system where propellant directly absorbs laser power.

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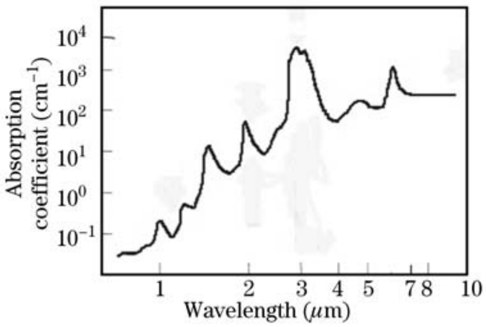

Fig. 1. Absorption coefficient of water for some kind of lasers[4].

Tolerance of optical components to damages due to break down can be also lower with CW laser radiation. With these advantages, we propose the laser propulsion system with CW CO_2 laser and water.

In this paper, we consider quasi-one-dimensional (1D) steady flow along nozzle for compressible fluid (see Fig. 2). Under chemical propulsion for thruster with Laval-nozzle, the choke condition of $M = 1$ at the throat is realized. For the CW CO_2 laser propulsion with heat exchanger proposed in this paper, laser beam is poured in throat. The power deposition inside the nozzle causes the propellant flow subsonic. However, if the temperature on the propellant is sufficiently high, even the subsonic flow can give enough velocity. Thus, it is not appropriate to use Mach number as a parameter of compressible flow for the heat exchange type laser propulsion.

For the compressible fluid of vapor, equation of continuity, Bernoulli's law, equation of state and energy conservation law are taken into account. Solving these simultaneously, the following equation satisfies the propellant conditions between two faces perpendicular to the flow each of which contains an optional point[5]:

$$\frac{\mathrm{d}u}{u} = \frac{\gamma RT}{\gamma RT - u^2}\frac{\mathrm{d}A}{A} - \frac{\gamma RT}{\gamma RT - u^2}\frac{P_{\mathrm{laser}}}{\rho A u c_p (T - T_0)}, \quad (4)$$

where A, R, γ, T, T_0, ρ, c_p, P_{laser} are the cross section of the nozzle, gas constant, the ratio of specific heat of the gas, the temperature, boiling point of water, the density of the gas, isobaric specific heat of the gas, and laser power, respectively. For chemical rocket, only the first term exists. On the other hand, for laser propulsion, the second term is also needed. Solving this expression for compressible fluid numerically, specific impulse and thrust can be calculated.

A 1-kW CW CO_2 laser is incident from downstream of the nozzle that is not a Laval one, specific impulse is evaluated to be about 50 s.

In a cross section surface, CW CO_2 laser focuses along the vapor flow by a ZnSe lens. By space integral of equation numerically, exhaust velocity is obtained and thrust and specific impulse are calculated.

We calculated in three cases in terms of focusing configuration of laser (see Fig. 3). In the first case, the laser beam is absorbed at the upstream of the propellant flow which is equivalent to the system of chemical rocket. In the second one, the laser intensity increases along the nozzle, that is, the laser beam is converging. In the last one, the laser intensity decreases or beam is diverging. The procedure is to calculate the density of propellant when there is no laser radiation at first. With this density of propellant, we calculate laser intensity at the position along the flow. Finally, we calculate the exhaust velocity along the flow with Eq. (4). By these calculations, we find that specific impulse of the first one gives the maximum value. That is, the specific impulse of the propellant heated from downstream is larger than the one heated at upstream. Furthermore, larger specific impulse is obtained when increasing laser intensity is incident from downstream of the propellant flow. By these calculations, the specific impulse is estimated to reach up to about 400 s. With these results, we radiate laser from downstream of the nozzle in the experiments.

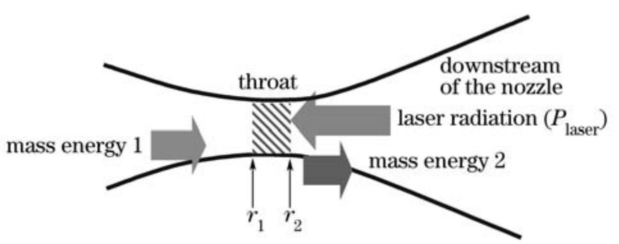

Fig. 2. Quasi-1D steady flow.

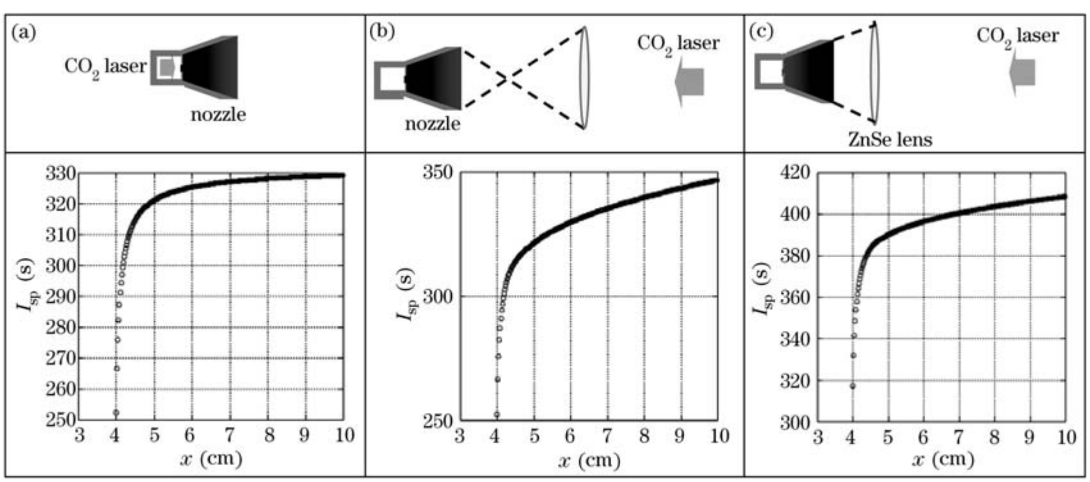

Fig. 3. Numerical calculations for quasi-1D steady flow. (a) Laser power in the chamber; (b) converging beam along the flow; (c) diverging beam along the flow.

With CW CO_2 laser, thrust of heat exchange system of vapor is measured (Fig. 4). Load cell is used to measure thrust and using Eq. (2). We calculate specific impulse at gauge pressure of 0 MPa. As the heat exchanger, porous SUS circular disk is used. In this case, the power of laser is 1 kW.

On the other hand, with high speed camera we measured exhaust velocity of reheated vapor by CW CO_2 laser at gauge pressure of 0.1 MPa. In this experiment, the power of laser was changed from 0 to 800 W. By this method, we got specific impulse as 46 s in this experiment, as shown in Fig. 5(a). In addition to the experiment, specific impulse is calculated in this model, the result is also shown in Fig. 5(a). Comparing the results of experiment and calculation, they agree with each other very well. According to this result of specific impulse, momentum coupling constant is calculated when η is 0.6, as shown in Fig. 5(b).

By solving simultaneous equation of energy conservation equation, mass conservation equation and equation of motion, relation between payload ratio ξ and laser power P_{laser} is acquired by analysis in Fig. 6(a). There is the relations between them as

$$\xi = 1 + \frac{\dot{M}}{M_0}\frac{V_{\text{Propellant}}\ln\xi + U}{g}, \tag{5}$$

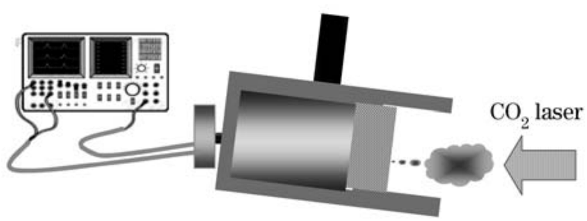

Fig. 4. Measuring thrust with the pendulum.

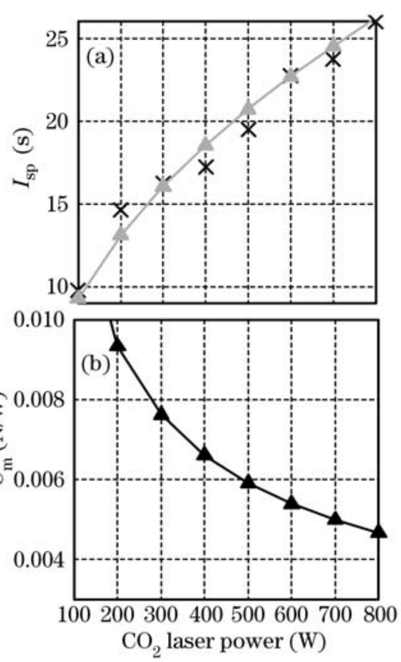

Fig. 5. (a) Comparison of specific impulse between experiment (crosses) and calculation (triangles) (high-speed camera); (b) calculated momentum coupling constant (in case of $\eta = 0.6$).

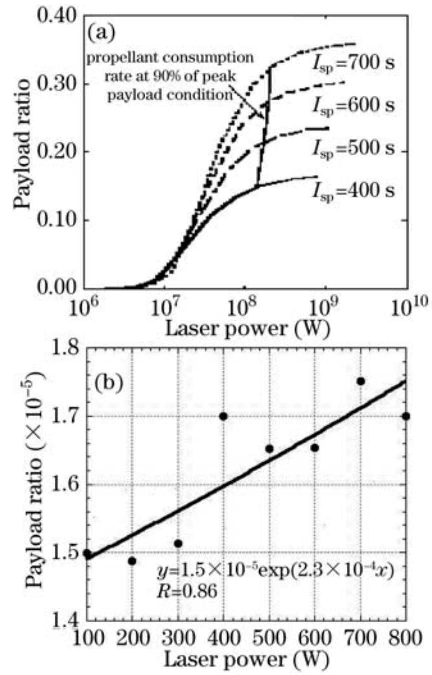

Fig. 6. Relation between laser power and payload ratio. (a) Analyzed result; (b) experimental result.

where $\dot{M}$, M_0, $V_{\text{Propellant}}$, U, g are the propellant mass flux, the propellant weight on the ground, exhaust velocity of the propellant, space velocity, and gravity acceleration, respectively.

On the other hand, the result of that relation for experiment is shown in Fig. 6(b). The payload ratio is increased as the laser power increases. The line in this figure shows the interpolation of exponential function. The experimental results can be said almost on the function of Eq. (5).

With numerical calculation, theoretical and experimental studies are conducted for effectiveness of laser propulsion in the case when laser radiates from downstream of the flow. As a result, we reach the following conclusions. 1) Both numerical and experimental investigation was conducted and they are in good agreement with each other. We got specific impulse dependence on laser power. 2) Conditions on laser irradiation for large specific impulse have been clarified. 3) Based on the calculation model, payload ratio for a ground launching system has been calculated as a function of laser power and specific impulse. 4) By experiment, the relation between the laser power and payload ratio is on the one by theoretical analysis.

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References

1. A. Kantrowitz, Astronautics and Aeronautics **9,** 34 (1971).
2. J. T. Kare, in *Proceedings of the 2nd International Syposium on Beamed Energy Propulsion* (2004).
3. H. Hagiya, S. Uchida, and T. Yabe, Rev. Laser Eng. (in Japanese) **34,** 442 (2006).
4. M. S. Shumate, Appl. Opt. **15,** 2480 (1976).
5. S. Schreier, *Compressible Flow* (Wiley, New York, 1982).