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Influencing Factors on Propulsive Performances of Water Droplets for Laser Propulsion

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A transversely excited at atmospheric pressure CO_2 laser operated at 10.6 μm and 5 μs pulse width was employed to ablate atomized water droplets for laser propulsion. The momentum was derived from the force sensor data. Experimental results indicated that coupling coefficient C_m, specific impulse I_{sp}, and internal efficiency η were increased remarkably. The maximum value of C_m was 52.1 dyne/W. The measured value of I_{sp} was 102 s. Internal efficiency η of 26.1% was achieved. Total impulse I and coupling coefficient C_m were dependent largely on the droplets' Sauter mean diameter and speed and their combined interaction. Specific impulse I_{sp} and internal efficiency η were dependent on the droplets' Sauter mean diameter, speed, flow rate of liquid propellant feeding system, and their combined interaction. The flow rate of the liquid feeding system dominated the influencing factors on specific impulse I_{sp} and internal efficiency η.

Nomenclature

C_m	=	momentum coupling coefficient
D_{32}	=	Sauter mean diameter
E	=	the pulse-to-pulse energy
F	=	force imparted to the nozzle
g	=	the acceleration of gravity
I	=	impulse imparted to the nozzle
I_{sp}	=	specific impulse
v	=	mean speed of water droplets
α	=	absorption coefficient
Δm	=	supplied droplet mass each time
η	=	internal efficiency
ρ	=	water mass density
Φ_{th}	=	explosion threshold of water
τ_m	=	transmissivity of incident laser

I. Introduction

LASER propulsion (LP) is perhaps one of the most realistic advanced propulsion concepts and an effective alternative to conventional rocket launching techniques. A laser is used in LP as a remote energy source for propulsion. The thrust is produced by the high-energy exhaust stream caused by the laser-induced vaporization of material (i.e., liquid, gaseous, or solid propellant) producing the transfer of momentum to the rocket.

Recent research on water propellants for LP has been intense and international in scope. Because the waste of propellants outstood the unsolved problems, the experimental results of specific impulse and internal efficiency were very small. Internal efficiency was less than 1% [1] while coupling coefficient was 350 dyne/W [2] in the water cannon study of Japan. The specific impulse of bulk water was 0.4 s [3]. Recently, Sinko and Pakhomov [4] studied the propulsive performance of thin films on solid substrates. The absorbing (water) thin films formed on Delrin substrates for the laser system operating at 10.6 μm exhibited the highest internal efficiency of 5%. Specific impulse and internal efficiency reported in [5,6] was also very small.

Trying to increase propulsive performances of water propellants for LP with CO_2 laser, we kept the water droplet size in the same order of magnitude with its absorption depth ($\sim$10 μm). In this paper, we report on the propulsive characteristics of atomized water droplets for LP.

II. Experimental Details

Figure 1 shows the experimental setup. Water droplets were supplied by a liquid propellant feeding system. The droplet mean size (Sauter mean diameter D_{32}) ranged from 40 to 80 μm. Mean speed v of droplets was in the range of 5–20 m/s. We can control the water flow rate by changing the backpressure.

All experiments were performed in air at atmospheric pressure. The pulse temporal profile consists of a 5 μs full-width at half-maximum (FWHM) peak width with a 15 μs FWHM tail. In the experiments, the incident laser energy density was about 6.0 J/cm^2.

The energy of laser pulse (about 10 J) was attenuated by passing it through a series of 80-μm-thick Teflon sheets with experimentally determined absorption properties. Each sheet was characterized by $\sim$20% transmission. The laser beam was focused to the site 5 mm away from the rear (right side in Fig. 1) of parabolic aluminum nozzle using a ZnSe lens with 30 mm focal length. The parabolic aluminum nozzle is 52.5 mm height and 70 mm in diameter. The pulse-to-pulse energy E) was measured with a Gentec ED-500L energy meter downstream of the lens.

The liquid propellant feeding system was attached to the nozzle. There was a 12-mm-diam hole in the rear of the nozzle through which droplets were sprayed into the laser focal site. The trigger signals from a digital delay/pulse generator (DG535) controlled the simultaneous arrival of laser pulse and droplets. The operation time of the liquid propellant feeding system was 10 ms for each laser pulse. The supplied droplet mass Δm each time was measured by a precision balance with 10^{-7} g resolution and a flowmeter with 10^{-3} g/s resolution.

Force measurements were performed with piezoelectric force sensors (SINOCERA CL-YD-301) characterized by $\sim$6 μs rise time and at least 10^{-3} N resolution. The sensors were connected through a

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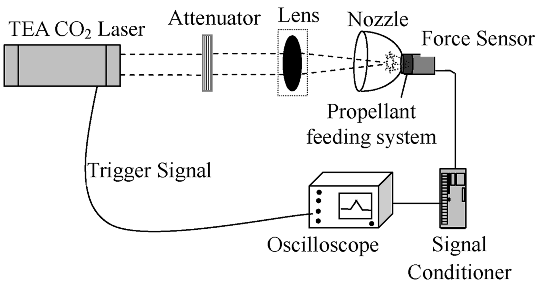

Fig. 1 Experimental setup diagram for force measurement.

signal conditioner (PCB-482B11) to a digital oscilloscope (Tektronix TDS 2024) triggered by a signal from the laser.

Data files were retrieved from the oscilloscope and processed using Origin 6.0 and Microsoft Excel to derive force F, impulse I imparted to nozzle, momentum coupling coefficient C_m, specific impulse I_{sp}, and internal efficiency η using the following formulas [7]:

$$I = \int_0^t F \, dt \tag{1}$$

$$C_m = I/E \tag{2}$$

$$I_{sp} = I/\Delta m \tag{3}$$

$$\eta = g C_m I_{sp}/2 \tag{4}$$

where g is acceleration of gravity, and $[0, t]$ is the duration time of force F. Figure 2 shows a typical temporal profile of force imparted to parabolic nozzle.

Droplet mean size (Sauter mean diameter D_{32}), mean speed v, their interaction, and flow rate were carefully varied to investigate the respective influences on propulsive performance. The experimental measurements were repeated three–five times for each case.

III. Results and Discussions

Table 1 shows the main experimental results. It was found that C_m and I_{sp} were affected by the droplet mean size D_{32}, mean velocity v, and the mutual interaction.

The relation between C_m, I_{sp}, and D_{32} is almost the same as that of C_m, I_{sp}, and v over the whole experimental range (Figs. 3 and 4). C_m and I_{sp} decrease when D_{32} and v increase, respectively.

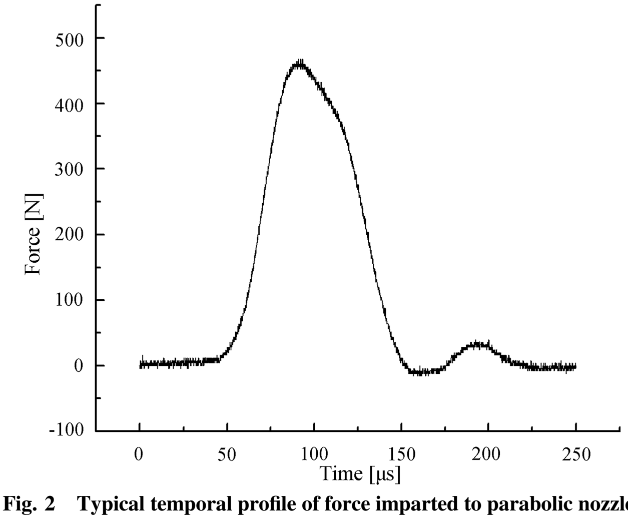

Fig. 2 Typical temporal profile of force imparted to parabolic nozzle.

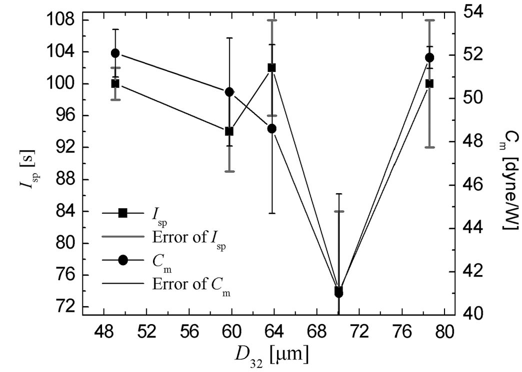

Fig. 3 I_{sp} and C_m vs D_{32}.

A. Influences of D_{32} and v on C_m and I_{sp}

The surface area to mass ratio was larger for smaller droplets. Based on the simple assumption that the optical field near the focal spot was uniform (beam diameter at the focus was much larger than the droplet size), the amount of laser energy absorbed per surface area was the same for the same angle of incidence. Hence, droplets with a larger ratio of surface to mass were easier to ablate and evaporated. Hence, the values of impulse, coupling coefficient, and specific impulse increase as the droplet size decreases.

It should be pointed out that there is a break point in Figs. 3 and 4. In a spray, the size and the speed of droplets are not independent events. As clearly shown in Table 1, droplet size D_{32} has the largest value (78.6 μm) when v has the lowest value (6.9 m/s) of the whole experimental range. D_{32} has the smallest value (49.1 μm) when the value of v is the largest (16 m/s). The joint effect of D_{32} and v on C_m together caused the break in Figs. 3 and 4.

Figures 5a and 5b compare the droplet velocity distribution near the focal point when v was equal to 16 and 6.9 m/s. As was observed in Fig. 5, the droplets' speed covered a wider range of values when its mean speed was 16 m/s.

The thrusts were produced over relatively short time intervals (about 100 μs). The probability of droplets entering the focal area and their subsequent breakdown increase as the droplet mean speed decreases and the speed distribution covers a narrower range of values. Hence, droplets with a lower speed and a narrower distribution of speeds lead to a higher impulse and a higher coupling coefficient and specific impulse.

Based on the analysis of the experimental results, it can be concluded that coupling coefficient and specific impulse are correlated to the droplet size, speed and the total interaction.

B. Effects of Flow Rate of Propellant Feeding System on I_{sp} and η

Specific impulse and internal efficiency of water droplets for LP were largely dependent on flow rate of water [formulas (3) and (4) and Fig. 6]. Specific impulse and internal efficiency decreased rapidly when flow rate was increased from 2.858 to 3.323 g/s

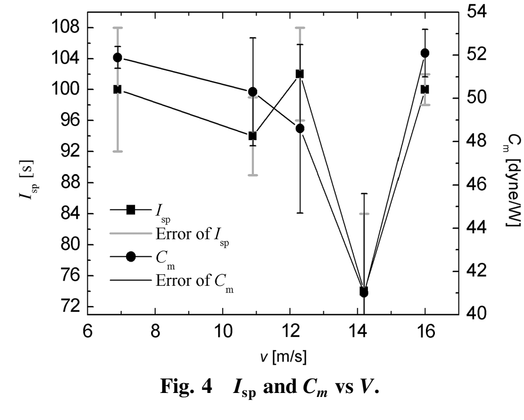

Fig. 4 I_{sp} and C_m vs V.

Table 1 Main experimental results of propulsive characteristics of water droplets for LP

D_{32}, μm	v, m/s	Flow rate, g/s	Supplied mass, mg	C_m, dyne/W	I_{sp}, s	η, %
49.1 ± 0.1	16 ± 0.9	3.121 ± 0.001	31.21 ± 0.01	52.1 ± 1.1	100 ± 2	26.1 ± 1.0
59.8 ± 0.9	10.9 ± 0.1	3.231 ± 0.009	32.31 ± 0.09	50.3 ± 2.5	94 ± 5	23.6 ± 2.5
63.8 ± 0.4	12.3 ± 0.6	2.858 ± 0.006	28.58 ± 0.06	48.6 ± 3.9	102 ± 6	24.8 ± 3.6
70.1 ± 0.7	14.2 ± 0.4	3.323 ± 0.008	33.23 ± 0.08	41.0 ± 4.6	74 ± 10	15.2 ± 4.0
78.6 ± 0.6	6.9 ± 0.7	3.087 ± 0.003	30.87 ± 0.03	51.9 ± 0.5	100 ± 8	26.0 ± 2.3

(Fig. 6). When the flow rate was set to 3.087 and 3.121 g/s, there was a little increase of specific impulse and internal efficiency. This phenomenon was caused mainly by the changes of water droplet mean size and velocity. In Figs. 3 and 4, when D_{32} and V was increased to 63.8 μm and 12.3 m/s, respectively, there was an increase of I_{sp}.

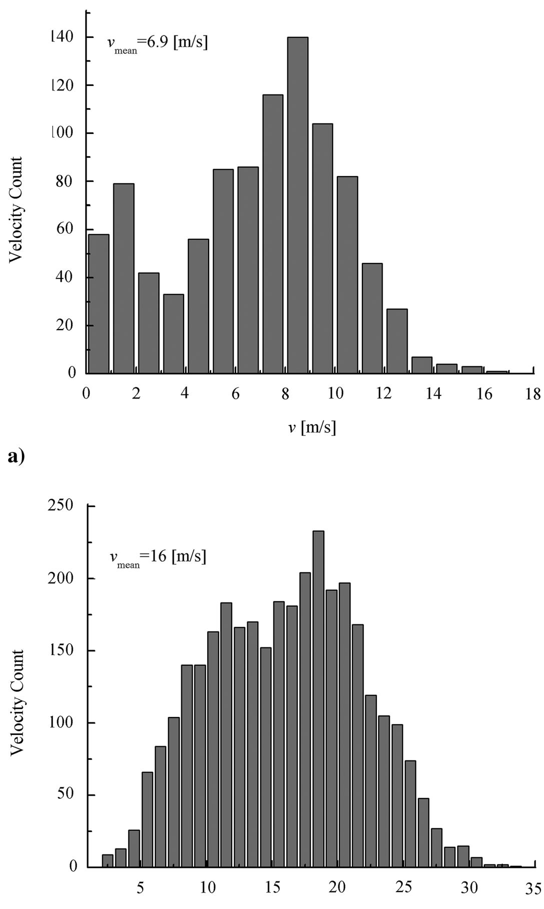

Fig. 5 Distribution of droplet speed V.

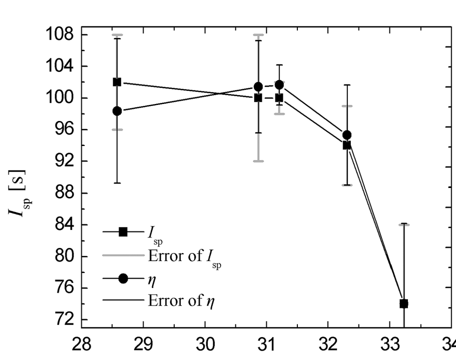

Fig. 6 I_{sp} and η vs supplied mass each time.

C. Comparisons to Different Authors' Results and Theoretical Results

Figure 7 compares the different research results of water propellants for LP. It can be seen that water droplets outstood the others. In the authors' opinions, control of supplied mass each time and use of atomized water droplets warrant the remarkable increase of propulsive performances of water droplets for laser propulsion.

Sinko and Phipps [8] described a theoretical model of irradiance effect on propulsive characteristics of condensed materials for LP. The effect of laser energy density Φ_L on momentum coupling coefficient and specific impulse can expressed as [8]

$$C_m = \sqrt{\frac{2\rho\tau_m}{\alpha}\frac{\Phi_L - \Phi_{th}}{\Phi_L^2}\ln\frac{\Phi_L}{\Phi_{th}}} \tag{5}$$

$$I_{sp} = \sqrt{\frac{2\alpha\tau_m}{\rho g^2}\frac{\Phi_L - \Phi_{th}}{\ln\Phi_L - \ln\Phi_{th}}} \tag{6}$$

where ρ is water mass density, α is absorption coefficient, Φ_{th} is explosion threshold of water, and τ_m is transmissivity of laser.

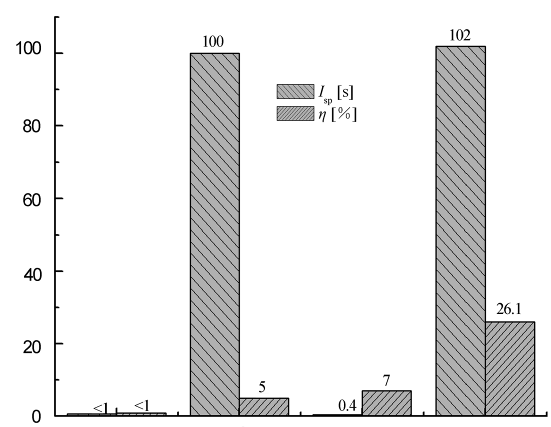

Fig. 7 Comparisons of different propulsive performances of water propellants (1: water canon [1], 2: Delrin and water [4], 3: bulk water [3], and 4 water droplets).

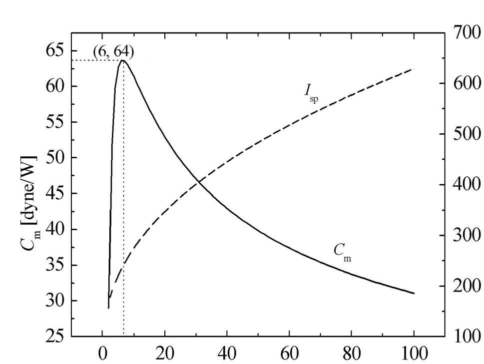

Fig. 8 C_m and I_{sp} vs irradiance.

We assumed that the absorption coefficient and transmissivity did not change in the irradiation process. Water's characteristics can be expressed as follows [8]: $\rho = 1\ \mathrm{g/cm^3}$, $\alpha = 850\ \mathrm{cm^{-1}}$, $\tau_m = 0.993$, and $\Phi_{\mathrm{th}} = 1.5\ \mathrm{J/cm^2}$. The effects of laser energy density on momentum coupling coefficient and specific impulse calculated by Eqs. (5) and (6) are shown in Fig. 8.

When laser energy density equals to $6.0\ \mathrm{J/cm^2}$, theoretical result of C_m is 64 dyne/W and that of I_{sp} is 235 s. There is a good agreement between experimental and theoretical results of C_m. If the operation time of the liquid propellant feeding system can be controlled to shorter than 5 ms, the experimental result of I_{sp} will be increased to theoretical result easily. Fortunately, this technology is not very difficult.

IV. Conclusions

In summary, propulsive performances of water propellants were increased remarkably by the use of water droplets. To our knowledge, specific impulse of 102 s and internal efficiency of 26.1% is the highest value of water propellants for LP to date.

Total impulse and momentum coupling coefficient were dependent largely on the droplets' Sauter mean diameter and speed and their combined interaction. The flow rate of the liquid feeding system outstood the main influencing factors on specific impulse and internal efficiency. Experimental results will be helpful in the design of LP thrusters with water propellants.

Acknowledgments

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