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Pulsed Laser Propulsion

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I. Introduction

EXPERIMENTS have been carried out to assess the performance of a rocket propelled by absorption of radiant energy from a remotely stationed, repetitively pulsed laser. The concept, deceptively simple, is to provide a high-energy density for propulsion without the encumbrance of a massive on-board energy source by absorbing radiation from a remotely stationed high-powered laser. Since the radiation-absorbing propellant may be a high-temperature plasma, the specific impulse can be very large (i.e., >1000 s), and the available laser power will limit the achievable thrust. Larger payload/vehicle weight ratios are clearly possible with a 1000 s specific impulse laser-powered rocket than with chemical propulsion rockets. In the following sections a theoretical update[1] and extension of previously analyses[2] to 1 atm operation of such a device are provided; experimental results for both 1 atm and vacuum environments are presented.

II. Theoretical Studies

A fluid mechanical model has been developed to assess the performance of the laser-powered thruster concept in a vacuum environment utilizing blast-wave theory to calculate the thrust and specific impulse.[2] When the pulsed laser-powered thruster operates in a finite-pressure environment, the laser requirements are altered by two effects. First, propellant flow into the nozzle is characterized as flow through a highly overexpanded nozzle. A normal shock stands close to the nozzle's throat (prior to laser breakdown), and most of the flow is subsonic in the nozzle's diverging section. This results in a reduction of the repetition frequency necessary to attain a given specific impulse. In addition, since background pressure reduces the propellant expulsion velocity after breakdown, it is possible for shocks from subsequent laser breakdowns to propagate into the hot propellant from a previous laser pulse. It has been shown[1] that the specific impulse, I_{sp}, obtained for operation in a background gas be related to the vacuum specific impulse by

$$I_{sp} = \frac{3}{4}\frac{t_{conv}}{\Delta t}[I_{sp}]_{vac,\,\Delta t = t_{conv}} \tag{1}$$

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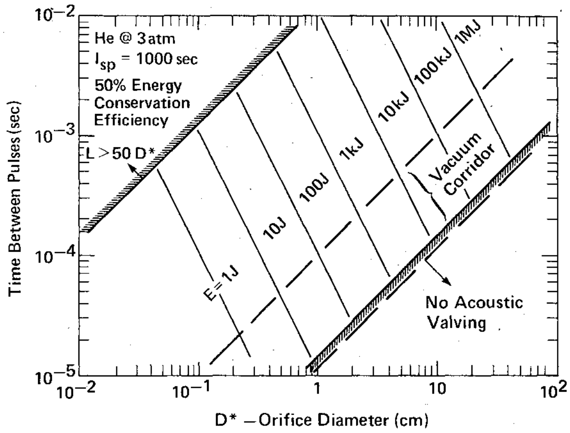

Fig. 1 Laser energy requirements, 1 atm background.

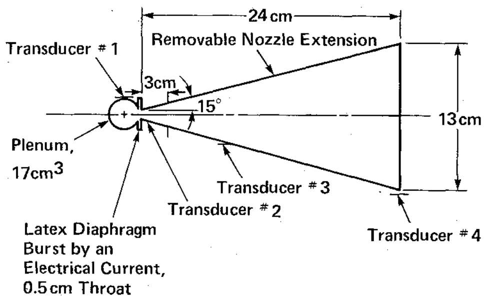

Fig. 2 Conical nozzle design.

where t_{conv} is the time it takes the unshocked propellant to reach the exhaust plane in ambient gas environment, Δt is the time between pulses, and $[I_{sp}]_{vac,\,\Delta t_{conv}}$ is the calculated vacuum specific impulse when the time between pulses Δt is set equal to the convection time. Laser energy requirements for operation in a 1 atm background gas are mapped in Fig. 1. The operating corridor is delineated between the shaded zones. The limits are provided by acoustic valving and an expansive nozzle length (L) to throat diameter ratio (D^*).[1,2] Shorter nozzles and slower repetition rates are required for operation in a 1 atm environment than in a vacuum (see Fig. 10 of Ref. 1).

III. Experimental Studies

Using the theory just summarized to design the nozzle and laser system parameters, we have performed small-scale experiments to 1) verify theoretical predictions of high specific impulse obtainable with the pulsed laser-powered thruster concept, 2) measure time-averaged specific impulse and thrust vs laser parameters, and 3) study the effect of finite exit plane pressure on thrust and specific impulse. The experiments were carried out using several independently triggered 10.6 μm CO_2 TEA lasers (Lumonics, Model 103). Each laser delivers up to 11 J in energy over a pulse time of approximately 3 μs. Two nozzle geometries were investigated. A conical nozzle was used first for direct comparison with the theory. Each laser beam was focused externally with 30 cm focal length mirrors into the nozzle, resulting in a focal point at the throat. A schematic of the conical nozzle design is shown in Fig. 3. The length shown is the design length for vacuum operation. However, since nozzle length for 1 atm operation is less than 4 cm, the nozzle skirt was constructed in removable sections. A self-contained plenum attached to the nozzle contains sufficient propellant for operation with up to four laser pulses with a plenum pressure drop of less than 10%. A latex diaphragm was used to maintain plenum pressure at 3 atm until the experiments began, and a spark was used to break the diaphragm. Lasers were triggered in

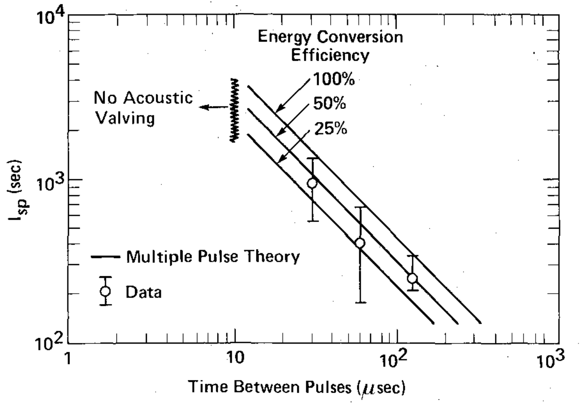

Fig. 3 Two pulse data with conical nozzle, 1 atm background.

sequence at a programmed time between pulses. The sequence of events, consisting of the diaphragm breaking, throat opening in less than 60 μs, propellant flowing down the nozzle for approximately 130 μs, and the lasers firing, was verified with pressure transducer and optical transmission data.

Experiments with the conical nozzle were performed in a 1 atm environment with up to two laser pulses. Helium was chosen as the propellant because it is a low molecular weight inert gas. The practical problems of storage of helium for a real rocket were not considered in making the choice of propellants because the goal of these experiments was solely proof of principle. The principal diagnostic method for determining the specific impulse was a ballistic pendulum that measured impulse. Pressure transducer results were used along with blast wave theory to verify results obtained with the pendulum. Determination of the specific impulse proceeds as follows: specific impulse is defined as

$$I_{sp} = T/\dot{m}g = \text{impulse}/\Delta m g \tag{2}$$

where T is the average thrust obtained per pulse, $\dot{m}$ the average propellant mass flow rate between pulses, g the acceleration of gravity, and "impulse" the incremental increase in impulse between the first and second laser pulses. Furthermore,

$$\Delta m = \dot{m}\Delta t \tag{3}$$

For the experimental conditions, $\dot{m} = 5.5$ g/s. This is an upper limit to the mass flow rate, since it assumes that immediately after the diaphragm opens, the propellant efflux is at the steady-state rate.

Data were taken at a time between pulses Δt of 30, 60, and 120 μs. An impulse of 17 dyne-s/J was observed. Figure 3 shows results for the specific impulse vs the time between laser pulses for the two CO_2 pulses. It is only appropriate to compute I_{sp} for the second pulse because the proper gasdynamic flowfield has to be established by the first pulse. The specific impulse was calculated using Eq. (1). In particular, the experiments were performed with one and then with two laser pulses. The added impulse due to the second pulse was used in the numerator of the equation for I_{sp}. Each value of I_{sp} on the graph was an average of 3-8 measurements. The incremental mass Δm was determined using Eq. (3) and the time between pulses Δt. In reality, there will be a finite time during which there is no flow, so the Δm computation will be an upper bound. This means that the I_{sp} numbers are lower bounds. The error bars were determined using the standard deviation of the single and double laser pulse impulse measurements. Also shown in Fig. 3 are the theoretical predictions using the theory for 1 atm background operation outlined in Sec. II and Ref. 1. Theoretical results were obtained for energy conversion efficiencies of 100, 50 and 25%. From the theory/data comparison it may be concluded that an energy conversion efficiency of 50% is most representative of the data obtained for these chosen laser parameters. The theoretical limiting specific impulse occurs when the period between laser pulses becomes so short there is not enough time for the propellant to flow into the breakdown region downstream of the throat. This "no acoustic valving" limit is also denoted in Fig. 3.

Results were also obtained at 10^{-4} atm with a 10 cm long, 7 cm diam parabolic nozzle. Again, helium was used as the propellant, and the time between pulses was 30 μs. Experiments with up to three laser pulses were performed, each laser pulse energy being approximately 8 J. The ballistic pendulum measurements of impulse and the Δm technique described for the conical nozzle experiments could not be used in this case. This is because cold propellant flow before and after the laser phenomena is supersonic at an ambient pressure of 10^{-4} atm. Therefore, the total impulse is dominated by the cold propellant impulse, and not by laser induced waves. The alternative was to measure the stagnation and static pressure as a function of time in the rocket's exhaust plane.

The theoretical model predicts that the transit time and travel distance of the laser-generated wave will accurately measure exhaust velocity when operating in a vacuum. I_{sp} values of 610 s for the second pulse and 500 s for the third pulse were determined, using this technique, for a mass flow of 5.5 g/s (I_{sp} for the steady-state cold flow was 170 s). An energy conversion efficiency based on ½ (Δm) $(I_{sp}g)^2/E$ yields 35% for the second pulse and 25% for the third pulse. A coupling coefficient of 10 dyne-s/J is calculated from the exhaust velocity, laser energy, and calculated propellant mass.

IV. Conclusions

The experimental and theoretical results presented above demonstrated the feasibility of high specific impulse pulsed laser propulsion devices. In the proof of principle experiments described: 1) a parabolic, (self-focusing) nozzle resulted in strong laser breakdown in the propellant and significant thrust-to-laser power ratios; 2) a 610 s specific impulse was obtained in vacuum using helium as a propellant; 3) a 900 s specific impulse was obtained at 1 atm background pressure using helium as a propellant; and 4) experimental results are consistent with theoretical predictions from earlier studies.

Acknowledgment

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