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# Technical Notes

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## Investigation of $CO_2$ Laser-Sustained Hydrogen Plasmas

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### Introduction

LASER propulsion is an orbital transfer technology based on the use of a remote laser as the power source. In such a system, energy from the laser would be converted to propellant thermal energy within a spacecraft absorption chamber by means of a laser-sustained plasma (LSP). The LSP would absorb a major portion of the incident beam (ideally 100%) and the propellant gas flowing through the absorption chamber would be heated by the plasma.

The feasibility of laser propulsion is contingent upon a large fraction of the incident laser power being converted to propellant thermal energy. Two figures of merit based on measured quantities are used to describe the efficiency of the energy conversion process. The fraction of the incident energy that is absorbed is defined as the global absorption, and the fraction of the incident energy retained by the propellant gas as thermal energy is defined as the thermal efficiency. The difference between energy absorbed and energy retained by the gas represents the LSP radiation loss.

It is known that the LSP will occupy a position in the focusing beam where power absorbed from the laser is balanced by power lost by conduction, convection, and radiation.[1,2] The position of the LSP changes to accommodate changes in operating conditions and maintain an energy balance. If conditions result in more energy lost than absorbed by the LSP, the LSP becomes unstable and extinguishes—a phenomenon commonly referred to as blowout. The goal of this research was to establish measurements of global absorption and thermal efficiency, and to identify stability limits vs variations in the four control parameters (gas pressure, gas mole flux, incident laser power, and beam-focusing geometry) using hydrogen as the propellant gas.

In a paper examining the feasibility of laser propulsion as an orbital transfer technology, Frisbee et al.[3] determined that an overall efficiency (including the nozzle) of 30% is required. Previous experimental results using argon have demonstrated thermal efficiencies as high as 46% for single and 58% for dual plasmas.[2,4] The current work includes results for thermal efficiency as high as 80.2% using hydrogen.

### Experimental Facility and Data Analysis

A 10 kW continuous wave $CO_2$ laser was the power source used to initiate and sustain the LSPs in this work. The experimental facility remains as described in Ref. 2, except that all zinc selenide optics are now being used. Beam geometry was varied by using two lenses of 300- and 530-mm focal length. The f-number is defined as the ratio of the focal length to the outer diameter of the beam annulus.[2] The estimated spot diameter of the focused laser based on ray tracing, including the effects of spherical aberration and diffraction was 0.2 mm. Based on 7 kW maximum incident power, the focal power flux was approximately $10^7$ W/cm.[2]

Transmitted laser power as measured by a water-cooled copper cone calorimeter was used to determine indirectly the quantity of power absorbed by the plasma. Plasma irradiation of the copper cone and beam reflection were assumed to be negligible. The critical electron density for plasma reflection of 10.6 micron radiation is $9.9 \times 10^{24}$ $m^{-3}$, that is approximately two orders of magnitude greater than the maximum electron number density expected at our conditions based upon theoretical number density computations.[5]

Inlet and exhaust gas temperatures as measured by millisecond response type K thermocouples were used to determine the thermal energy increase of the propellant. A detailed account of the errors associated with these measurements is given in Ref. 6 and is not repeated here.

Global absorption was determined from Eq. 1 with an absolute error of $\pm 1\%$

$$\alpha = \frac{P_{\text{incident}} - P_{\text{transmitted}}}{P_{\text{incident}}} \tag{1}$$

Thermal efficiency was determined from Eq. 2 with an absolute error of $\pm 5\%$

$$\eta = \frac{\dot{m} C_p (T_{\text{exhaust}} - T_{\text{inlet}})}{P_{\text{incident}}} \tag{2}$$

where $\dot{m}$ is the measured mass flow rate, $C_p$ is the gas specific heat, $T_{\text{exhaust}}$ is the mass averaged exhaust gas stagnation temperature, and $T_{\text{inlet}}$ is the mass averaged inlet gas stagnation temperature. The typical inlet temperature was approximately 295 K, whereas the average exhaust temperature varied anywhere from approximately 315 to 400 K, depending upon operating conditions. A value of 14,490 J/kg K was used for the gas specific heat.

### Experimental Results

The global absorption and thermal efficiency results for hydrogen LSPs are presented in four sections, each section discussing the effect of the variation of one control parameter. Incident laser power is considered first.

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For reference purposes, 2000 mole/m$^2$s of hydrogen corresponds to 7.3 g/s, while at 3.5 atm corresponds to an average flow speed of 14.1 m/s upstream of the LSP.

The global absorption of a hydrogen LSP has been found to be strongly influenced by the laser power. It is evident from the plot in Fig. 1 that, for a given gas pressure, global absorption is determinied by the incident power and is relatively independent of the mole flux. In addition, the LSP blowout limit was observed to increase with incident power. Note that at 3.5 kW incident power no plasmas could be held stable at mole fluxes beyond approximately 2023 moles/m$^2$s. None of the 5 or 7 kW LSPs was observed to become unstable at this pressure at the mole fluxes investigated.

Although for a given mole flux and gas pressure, greater absorption is achieved at greater power, the LSP thermal efficiency does not follow such a simple relation. For a given mole flux and pressure, the thermal efficiency depends on how close the conditions are to the optimal mole flux. Due to the shift in upstream position of the LSP with increased power, an increase in mole flux is required to force the LSP back downstream to its optimal position. It is evident from the previous discussion that, because increased incident power results in increased absorption and an increased mole flux stability limit, greater thermal efficiencies are possible at increased incident power and mole fluxes beyond the stability limit of low powers.

Gas pressure variation affects global absorption and thermal efficiency in a way analogous with incident power variation. An increase in gas pressure results in an increase in the mole flux stability limit. At 7 kW incident power, and f/4 focusing geometry, LSPs at 1.80 atm are not stable beyond 1011 moles/m$^2$s. However at the same conditions and 3.52 atm, the LSPs exhibit no instabilities and are stable at the maximum mole flux tested, 2355 moles/m$^2$s. Similarly, LSPs at 5 kW, f/4, 2.14 atm are not stable at mole fluxes greater than 1075 moles/m$^2$s, but at the same conditions and 3.55 atm, the LSPs again exhibit no instabilities and are stable at the maximum mole flux tested at 5 kW, 2247 moles/m$^2$s.

Increases in gas pressure also result in increases in global absorption, although present evidence indicates that absorption levels off at the highest pressures tested, 3.53 and 4.08 atm, as indicated by the plot in Fig. 2. More data at higher pressure and possibly at a different power level are required to verify this absorption plateau.

As is the case with increased incident power, increased gas pressure causes an increase in optimal mole flux. As indicated by the data in Fig. 2, increased global absorption from increased gas pressure allows for the possiblity of increased thermal efficiency, assuming the mole flux can be optimized. Referring to the data in Fig. 2, the thermal efficiency at 4.08 atm was not at the optimal mole flux and, therefore, seems slightly low.

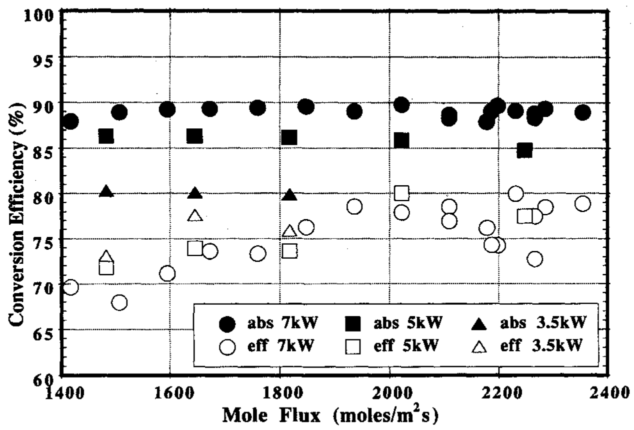


**Fig. 1 Global absorption and thermal efficiency of f/4 hydrogen LSPs plotted vs mole flux for incident laser powers of 3.5, 5, and 7 kW, at 3.53 ± 0.11 atm gas pressure.**

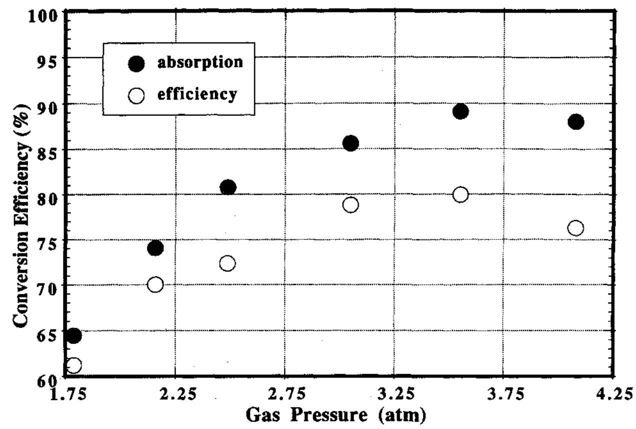


**Fig. 2 Maximum measured thermal efficiency and corresponding global absorption for 7 kW, f/4 hydrogen LSPs at the indicated pressures.**

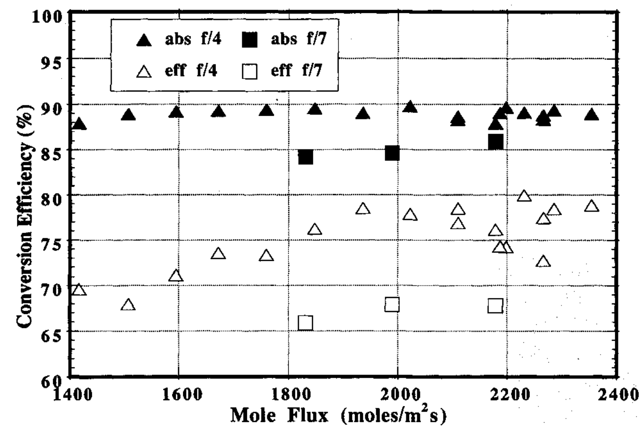


**Fig. 3 Global absorption and thermal efficiency of 7 kW, f/4, hydrogen LSPs at 3.52 ± 0.10 atm, and 7 kW, f/7, hydrogen LSPs at 3.54 ± 0.01 atm.**

In order to observe the effects of varying focusing geometry, 7 kW, f/7 LSP experiments were done at 2.52, 3.05, and 3.54 atm for comparison with 7 kW, f/4 experiments at those pressures. In all cases, f/7 LSPs produced lower global absorption and thermal efficiency than f/4 LSPs. A comparison of f/4 and f/7 LSP performance can be seen in Fig. 3. In addition, it was observed that the f/4 geometry produced LSP that were stable at greater mole fluxes than the f/7 geometry. At 7 kW incident power and f/4 focusing geometry, LSPs at 1.80 atm were not stable at mole fluxes greater than 1011 moles/m$^2$s, however 7 kW, 1.84 atm, f/7 LSPs were not stable at mole fluxes greater than 882 moles/m$^2$s.

The effect of mole flux variation was briefly touched upon above. It is important to have a physical understanding of what the variation of mole flux does to LSP behavior. A stable LSP exists in a state of balance where energy gained through absorption of the incident beam equals energy lost through plasma radiation as well as convection and conduction to the propellant gas. A stable LSP will occupy a position such that the LSP leading edge is upstream of the beam focus. An increase in the mole flux results in an increase in the LSP convective transfer to the propellant and causes the LSP front to shift position downstream (closer to the focus) to a position in the focused beam with a higher power flux. The LSP will restabilize at a position where the energy absorbed once again balances the energy lost. However, if the incident beam power is insufficient, the LSP front will be forced downstream of the beam focus where the LSP extinguishes.

Following this reasoning, it is apparent why the mole flux for optimum thermal efficiency increases with both incident power and gas pressure. An increase in laser power causes an increase in incident power flux and causes the LSP to reposition upstream where the beam is less focused and where power absorbed balances power lost. Similarly, an increase in gas pressure increases the local absorption coefficient (due to an overall increase in electron number density) causing the LSP again to reposition upstream to a beam position with a lower power flux where the energy balance is again re-established. Optimally, the LSP is positioned where the losses to the propellant (conductive and convective) are maximized, while the radiative losses to the chamber walls are minimized. Both increased incident laser power and gas pressure cause the LSP to shift upstream requiring increased mole fluxes to force the LSP back downstream to optimal position.

## Conclusions

Measurements of global absorption and thermal efficiency of hydrogen LSPs have been presented. Global absorption of the incident laser power was observed to increase with increases in both incident power and gas pressure. Although the highest measured value for global absorption was 89.8%, it is expected that 100% absorption is possible with higher incident laser powers. Higher global absorption and thermal efficiency as well as an extended blowout stability limit can be expected from lower f/No. focusing geometry as compared to higher f/No. focusing geometry. The minimum overall efficiency required for the feasibility of laser propulsion as an orbital transfer technology was determined to be 30% in Ref. 3. Although we cannot guarantee that laboratory results will scale to the power levels in excess of 1 MW required in an actual laser thruster, the results presented in this work indicate that laser propulsion is a feasible orbital transfer technology in the context of Ref. 3.

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# Unsteady Internal Ballistic Calculations of Solid Rocket Motors

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## Nomenclature

$A$ = cross-sectional area, m$^2$
$AP$ = ammonium perchlorate
$a$ = burning rate coefficient, m/s
$D$ = diameter, m
$e$ = total energy per unit volume, J/m$^3$
$f_k$ = $k^{th}$ frequency, Hz
$G_{yy}$ = power spectrum of $y$
$H_{in}$ = input total enthalpy per unit mass, J/kg
HTPB = hydroxy terminated polybutadiene
$L$ = motor length, m
$N_k$ = $k^{th}$ sample
$n$ = burning rate pressure exponent
$p$ = pressure, N/m$^2$
$R$ = gas constant, J/kg K
$\dot{r}$ = burning rate, m/s
$S$ = surface area, m$^2$
$T_F$ = flame temperature, K
$t$ = time, s
$u$ = axial velocity, m/s
$x$ = axial distance, m
$Y_k$ = $k^{th}$ harmonic content
$\gamma$ = specific heat ratio
$\rho$ = gas density, kg/m$^3$
$\rho_p$ = propellant density, kg/m$^3$

## Introduction

THE performance of a solid rocket motor depends heavily on the flow characteristics, the chemical composition of the grain, the temperature distribution, and the combustion products. These parameters can be quantified by grouping variables such as velocity, pressure, temperature, density, entropy, species concentrations, and area distributions. Thus, an accurate calculation of the internal ballistics would permit the evaluation of the intensity of combustion and would lead to the determination of efficient size and shape of the com-

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