Experiments on Optical Discharges in Hydrogen

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The rudiments of a rocket thruster that receives its enthalpy from a remote energy source, a laser, are described. An experimental study is discussed that provides details of the physics for assessing the feasibility of using hydrogen plasmas for accepting and converting this energy to enthalpy. A plasma ignition scheme that uses a pulsed CO_2 laser has been developed and the properties of the ignition spark documented, including breakdown intensities in hydrogen. A complete diagnostic system, capable of determining plasma temperature and the plasma absorptivity for subsequent steady-state absorption of a high-power CO_2 laser beam, is developed and demonstrative use is discussed for the preliminary case study, a 2 atm laser-supported argon plasma.

Introduction

MANY space flight missions being contemplated require large structures operating at altitudes above those serviced by the space transportation system, i.e., the Space Shuttle. The fact that such structures may represent large masses that must be moved to high orbits presents a serious problem for the propulsion engineer. Contemporary propulsion systems suffer significantly when asked to raise such large masses. Capable of large thrusts, they operate at relatively low efficiencies and thus their payload mass fractions are quite low. For many applications, this precludes their usefulness. High-efficiency systems are currently available only for very low thrust devices. In many respects, low thrust level can be an attribute, especially when moving large flexible structures. Too small a thrust (subpound), however, leads to abnormally long (several years) trip times to move massive structures to high orbits. Thus, the need for at least moderate thrust but high-performance propulsion systems is established. A potential fulfillment to that need is the hydrogen-fueled laser thermal rocket.[5] This concept uses a hydrogen plasma as the "combustion" source that theoretically can be sustained and controlled to provide significant thrusts (hundreds of pounds) and high specific impulse (2500 s) using the laser systems currently envisioned as part of the Strategic Defense Initiative. Figure 1 indicates how such a system fills the need under discussion. It provides a bridge between high performance but low-thrust electric systems and high-thrust, low-performance chemical systems.

This article reports the results of a research effort designed to elucidate the physics associated with laser-sustained hydrogen plasmas. Inverse Bremsstrahlung absorption by the free electrons within the plasma is the energy conversion mechanism on which the laser thermal thruster concept is predicated. The discussion includes the characteristics of such a thruster, realistic performance levels, a pulsed laser spark ignition scheme, and the diagnostics to characterize the properties of laser-sustained low-pressure hydrogen plasmas.

Laser Thermal Thruster

The laser thermal thruster, in concept, is a relatively simple device as schematically presented in Fig. 2. The hydrogen plasma can be considered analogous to the flame combustion region that exists in a conventional rocket engine. The conventional system uses the internal chemical energy of the propellants as its source of enthalpy, whereas the laser thruster depends on an external source, the electromagnetic energy within the sustaining laser beam. The hydrogen plasma performs the work of both reactant and product, i.e., the electrons within the plasma absorb the laser energy and the high-enthalpy plasma is the high-temperature region that expands for thrust production. Thus, once the energy is absorbed, the thruster behaves in a conventional manner. In practice, the propellant would probably be distributed through the thruster walls as a regenerative coolant, then injected into the absorption chamber, heated by the plasma, and expanded out a nozzle for thrust generation.

Although a large variety of absorbing gases could be used for such a concept, hydrogen is the optimum choice as a working fluid because of its high performance (specific impulse) and good radiative transfer characteristics. This was shown by Shoji[1] and is indicated by simple inspection of the equation for specific impulse, Isp, which shows the simple dependence $\sqrt{T_c/M}$

$$Isp = \sqrt{\frac{1}{g}\cdot\frac{2\gamma}{\gamma-1}\cdot\frac{\bar{R}T_c}{M}\left[1-\left(\frac{Pe}{Pc}\right)^{(\gamma-1)/\gamma}\right]}$$

where

R = universal gas constant
g = acceleration due to gravity
γ = specific heat ratio
P_e/P_c = nozzle-exit pressure ratio
T_c = combustion (absorption) chamber temperature
M = molecular weight of working fluid.

In the case of hydrogen plasma, an obvious minimum in molecular weight is obtained and that, coupled with practical gas bulk temperatures of over 3000 K, makes it the most attractive of all gases from a pure performance point of view. When one includes the effect of storage (tankage), that edge is diminished somewhat but hydrogen remains the leading candidate. This research has, therefore, concentrated on investigating the physics of laser-sustained hydrogen plasmas. The following section addresses a practical aspect of the utility of a hydrogen plasma once it is created: how effectively the available energy can be extracted.

Chemical Kinetic Limitations

Even if all goes perfectly with regard to beaming and converting energy, there are still realistic concerns with regard to

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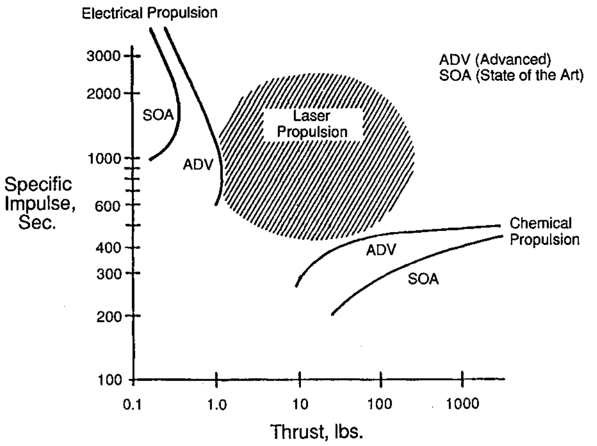

Fig. 1 **Performance and thrust for rocket engine systems.**

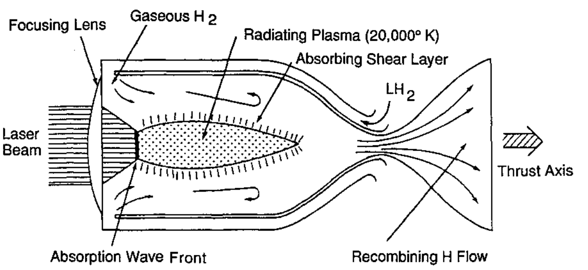

Fig. 2 **Schematic of a hydrogen-fueled laser thermal thruster.**

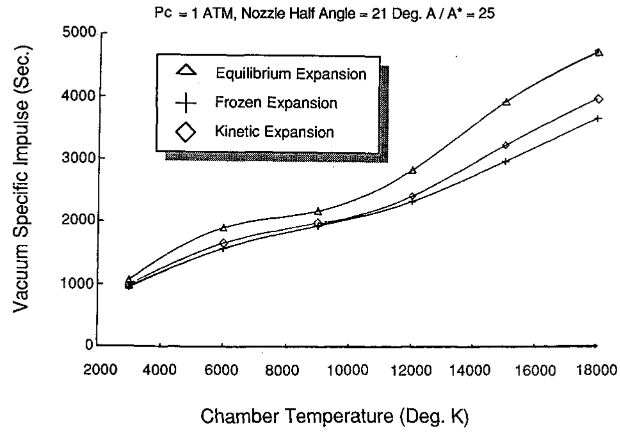

Fig. 3 **Laser propulsion kinetic performance analysis.**

the performance of such a thruster. This is both in the sense of pure theoretical specific impulse and with regard to the many practical concerns such as laser window and thrust chamber survival. These survival problems can probably be solved if the payoff potential is sufficient. Chemical kinetic and pure fluid mechanical limitations are unavoidable, but if determined to be small, then further investigation into the overall concept is warranted. In such a vein, the kinetic losses (only) for a typical laser thermal thruster were examined.

The details of the chemical kinetics evaluation have previously been presented.[2] Basically, the rudiments of the investigation consisted of performing a simple parametric study of the specific impulse obtainable for a prototype thruster sized to deliver 100 lbf thrust. The parameters examined included the chemical kinetic rates, combustion chamber pressure, combustion chamber (bulk gas) temperature, and nozzle-area ratio and half-angle. The chemical kinetic rates were chosen based on the best available literature for the hydrogen reaction system. The currently accepted rates were chosen as a baseline and a worst-case set of rates were determined by using accepted error bounds. This permitted an evaluation of the maximum reduction of specific impulse that might occur. The evaluation was performed in a manner very similar to that taken by Bray.[3] A one-dimensional inviscid analysis was performed using the two-dimensional kinetics (TDK) computer code.[4] In addition to the kinetics calculations, the computations were performed for both equilibrium and frozen chemistry assumptions to permit more complete comparisons.

A total of 432 cases were run. Typical results are shown in Fig. 3, which depicts the predicted specific impulse as a function of initial chamber temperature. For temperature levels believed to be compatible with heat-transfer considerations (below 5000 K), large differences in the performance are realized for the four sets of rates. The difference between equilibrium and frozen, for example, is over 500 s at 6000 K.

The curves in Fig. 3 can be used to make several points. First, improvement in specific impulse does not increase significantly between 6000 and 9000 K due to increased ionization energy that is not recovered. Since radiation losses are not included in the one-dimensional kinetics analysis, it appears that attempting to operate a thruster above 6000 K would not be very fruitful from a performance point of view. Also, for the simple convergent/divergent nozzle, a considerable performance loss, due to nonequilibrium chemistry, is realized. The best kinetics data show over a 100 s specific impulse loss for a chamber temperature of 5000 K. Another interesting effect not shown by Fig. 3, but which was a product of the study, is the effect of nozzle expansion ratio; large performance gain from increased nozzle expansion is not realized for nozzle expansion ratios $\epsilon > 5$. Thus, thrusters with small nozzles can be contemplated for the thrust class considered here (100 lbf). This is, of course, directly attributable to the low chamber pressures and the quick freezing of hydrogen atoms just downstream of the nozzle throat. For systems operating at other than these small chamber pressures, this effect would not be so pronounced.

The purpose of this discussion is not only to indicate that kinetics is important, but that this class of propulsion device, with very high specific impulse, can be drastically affected by normally small effects. Additional work is needed that evokes two-dimensionality, viscous effects, and radiation to evaluate additional performance losses. The kinetic study shows that a 1500 s specific impluse is a better estimate than the 2500 s generally quoted in the literature, but the additional effects must be considered to obtain a realistic lower limit.

Experimental Effort

The experimental program was broken down into two distinct efforts, hydrogen plasma ignition experiments and steady-state hydrogen plasma experiments. The ignition experiments were completed and are discussed in some detail in the following sections. The steady-state hydrogen experiments were never completed due to difficulties with the high-energy laser. A discussion of the progress is included, however.

Hydrogen Plasma Ignition

The power available from conventional continuous wave (cw) lasers is not sufficient to initiate an optical discharge due to the high breakdown threshold and low absorptivity of cool gases. To create and then sustain such a plasma, an adequate source of free electrons must be made available to absorb the incident laser energy. This source of electrons can be obtained by a variety of methods. Smith and Fowler ignited laser-sustained plasmas by using both electrical discharges[6] and laser impact onto solid targets.[7] Moody[8] ignited laser-sustained plasmas using the gas breakdown produced by a pulsed CO_2 laser.

The method used in this study was laser spark ignition by a pulsed CO_2 laser. This method was selected as being the cleanest, least intrusive, and most reliable of the available options that have been previously demonstrated. To achieve realiable ignition using this technique, it is necessary to superimpose the focal volume of the pulsed laser onto the focal volume of the sustaining (steady-state) laser beam. Since these focal volumes must be very small to produce the required large energy densities, alignment is critical.

In the past, pulsed CO_2 laser ignition has been used in two ways. Moody[8] injected the pulsed CO_2 laser beam as close to on-axis as possible to the main beam and Fowler et al.[9] injected the pulsed beam normal to the main beam. The approach here is unique in the fact that advantage is taken of the unstable resonator output of the available high-energy cw laser. The output profile of the cw laser resembles a torus with near-zero power at the center of the beam. The pulsed CO_2 laser beam is injected through this energy hole by using the same beam optics, as shown in Fig. 4. The advantage of using this technique is the ease of alignment of the two focal volumes and minimum required optical components.

The pulsed laser produces a spark within the gas, a high-electron density region that can precipitate a sustained plasma. The characteristics of the pulsed CO_2 laser spark were initially examined to determine the spatial location of the maximum electron density, the gas breakdown threshold, and the fraction of pulsed beam energy absorbed as a function of hydrogen pressure. This was done in an attempt to provide sufficient characterization of the spark to use it to ignite the cw laser-sustained plasmas.

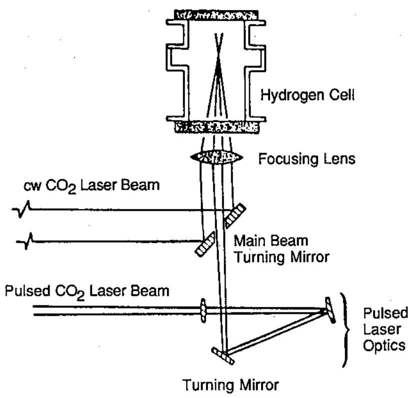

Fig. 4 Hydrogen plasma ignition schematic.

Experimental Apparatus: Hydrogen Plasma Ignition

The experimental setup for the laser spark experiments is shown schematically in Fig. 5. The laser used was a commercial Lumonics 103 Transverse Excitation Atmospheric (TEA) laser equipped with 0.09 μF capacitors. The energy and pulse length delivered were 7 J at 150 ns per pulse through unstable resonator optics. The output beam was directed through a variable number of polyethylene attenuators and turned up into the hydrogen test cell.

The hydrogen test cell is a cylindrical, 15 cm diam, 40 cm long, black anodized aluminium chamber. The hydrogen pressure within the cell can be remotely controlled from less than 0.1 atm up to approximately 5 atm, the limit being based on the yield strength of the NaCl windows. All the spark data were taken statically with regard to cell gas flow and no perceptible global temperature rise within the cell was observed for any test condition,

The diagnostics employed consisted of systems for the measurement of incident and transmitted beam power and for optical observation of the spark itself. An STL image converter camera was used to record streak photographs of the spark event and take short exposure frames of the spark behavior. Typically, the streak times were approximately 200 ns in duration. A two-mirror viewing system permitted the upbeam propagation of the breakdown plasma luminous front to be recorded. In addition to the streak photographs, frame photographs were obtained at various exposure levels and interframe delay times using an STL Model 4A (three-frame) frame unit. The remaining diagnostics consisted of simple 35 mm open shutter close-up photography and spectrographic surveys. A 1.25 m Spex Model 1269 f/9 scanning spectrometer with both photographic plate and photomultiplier outputs was employed to examine emission from the spark. A pair of flat ultraviolet overcoated mirrors allowed the spectrometer entrance slit to be focused at several locations within the plasma

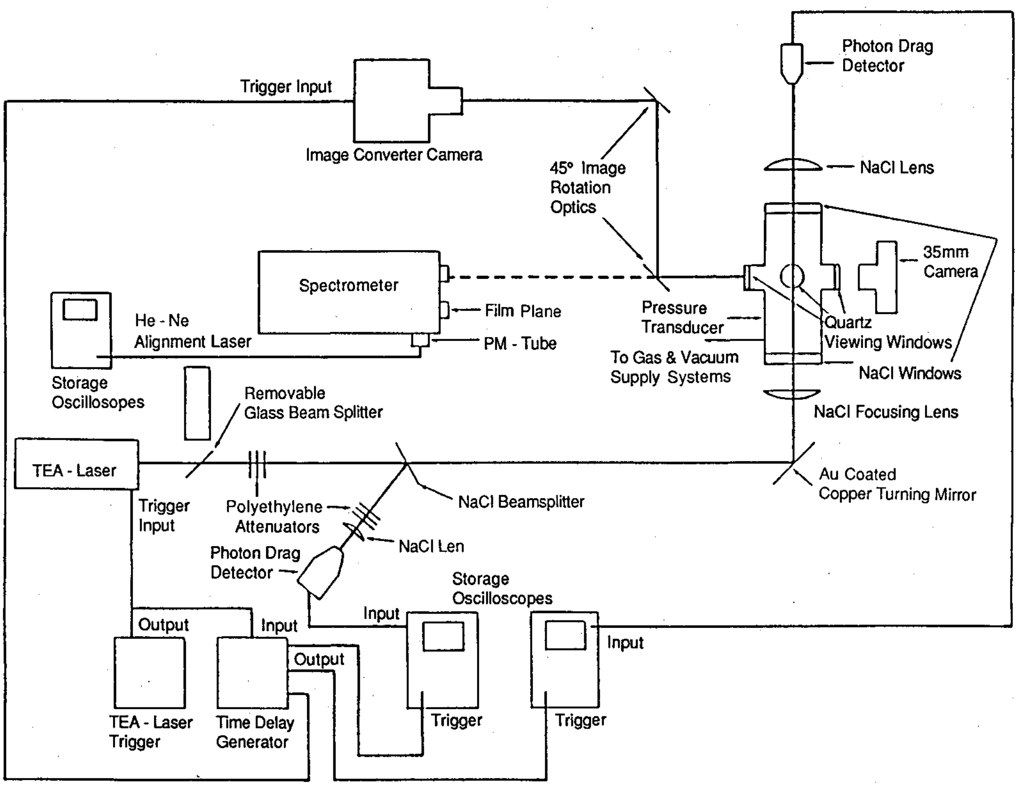

Fig. 5 Pulsed laser spark experiments schematic (illustration not to scale).

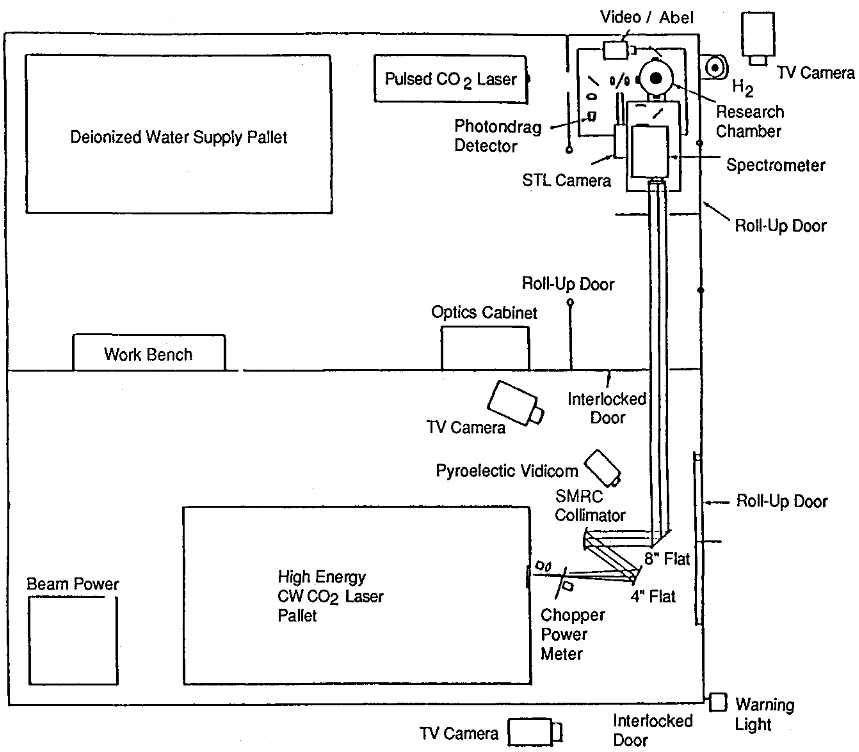

Fig. 6 Experimental setup: laser plasma experiments.

to examine the spatial dependence of radiance. Photographic plates and photomultiplier data were taken to permit integrated intensity and temporal radiance behavior to be examined, thus indicating the spatial location of maximum electron density.

Steady-State Hydrogen Plasma

The steady-state hydrogen plasma is the key element of the laser propulsion concept. Although there is a significant amount of data on laser-sustained plasmas in several gases, there is very little data available for hydrogen.

The major thrust of the program was to obtain and evaluate plasma-influencing parameters and determine the feasibility of the laser-supported hydrogen plasma as a candidate for further enthalpy-source thruster development. These parameters are the fractional absorption of beam power by the plasma, i.e., the conversion of plasma energy to propellant enthalpy, the chamber wall heat loading, and the fluid dynamic stability of the laser-sustained plasma.

Steady-state laser plasmas have been reported by several investigators, including Smith and Fowler,[6] Conrad et al.,[10] and Keefer et al.[11,12] These plasma experiments have been conducted in atmospheric air and inert gases, particularly argon. They concluded that a laser plasma can be maintained in a steady state for indefinite periods of time and can be created in any gas, if the proper irradiance, pressure, and temperature criteria are met.

A laser-supported plasma is created when the irradiance at the focus of the laser beam exceeds the ignition (breakdown) threshold irradiance of the gas at a given temperature and pressure. Once these conditions have been achieved, only maintenance threshold irradiance need be supplied to sustain the plasma. This threshold for maintenance of the plasma is typically orders of magnitude lower than the threshold for plasma ignition.

Laser-supported plasmas normally propagate from the focus of a high-energy laser beam back toward the laser. During this propagation upbeam, the plasma will extinguish if the beam spread is such that the maintenance energy threshold is not maintained along the beam. In this case, the laser plasma either completely disappears or, if the required ignition conditions are present, reforms at the focus. If it reforms, then the cycle repeats itself. Once the plasma is created, it can be convectively stabilized, either by free convection if small f-number optics are used, e.g., f/8 or lower, or by forced convection by flowing gas counter to the natural upbeam plasma propagation direction.[12] For a vertically oriented plasma, the natural convection through the plasma (due to buoyancy effects) can be sufficient to provide the stabilizing counter flow. This free convective stability point is near the maintenance threshold irradiance and does not produce as high a plasma temperature as possible if it were in a region of higher irradiance. The plasma may be forced farther downbeam by the application of a forced external flow. This method offers the ability to stabilize the plasma by forced convection and control the position with respect to irradiance level within the laser beam. Conrad et al.[10] demonstrated that the position of the plasma, with respect to the irradiance level, does control the laser beam absorption and, thereby, the plasma temperature. Keefer et al.[12] has actually demonstrated the effect of forced convective control on plasma properties. In order to operate a laser thruster in an optimum manner, laser beam absoption must approach 100%. Based on Conrad's and Keefer's work, this goal is obtainable.

Program experimental objectives were to determine the minimum irradiance threshold of a hydrogen plasma, the spatial temperature distribution within the plasma, and energy emission of the plasma as a function of pressure, beam power, and imposed flow conditions. This would then provide a sufficient data base to design and evaluate laser thrusters operating with laser-sustained hydrogen plasmas. The approach was verified in argon, but laser malfunction negated the planned hydrogen work.

Experimental Apparatus: Steady-State Plasma

The experimental setup for the steady-state plasma experiments is shown in Fig. 6. The lasers used in this setup are a 30 kW closed-cycle cw CO_2 electric discharge laser and the Lumonics 103 CO_2 TEA laser.

The output beam of the 30 kW laser is collimated and directed via gold-coated copper mirrors and focused into the plasma chamber. The plasma chamber used was the same one

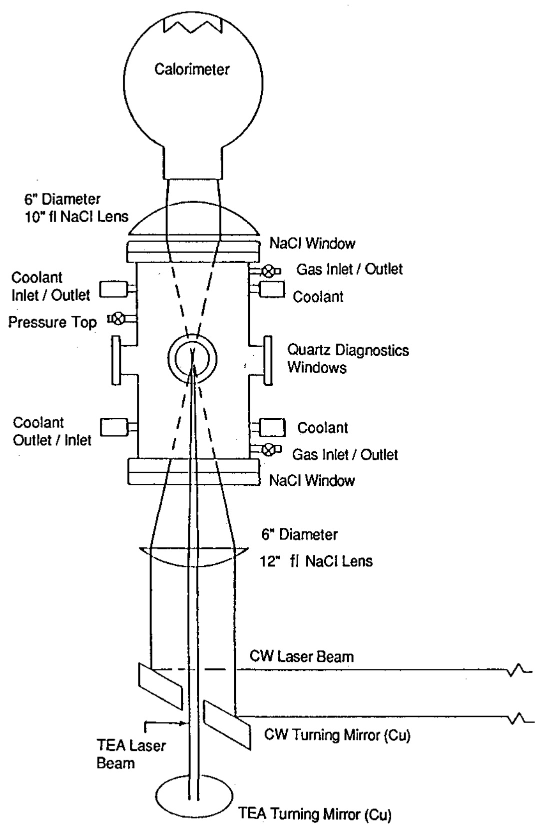

Fig. 7 Detailed chamber schematic: laser plasma experiments.

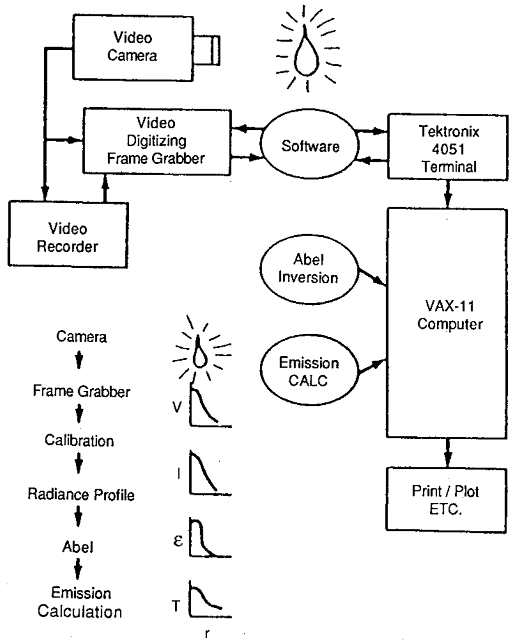

Fig. 8 Video camera Abel inversion scheme.

used in the hydrogen spark studies. Figure 7 gives a more detailed schematic of the plasma chamber and the associated instrumentation.

A plasma is initiated in the test chamber by a single TEA laser pulse focused coincident with the main 30 kW cw beam. Once the plasma has been ignited, a variety of diagnostics are employed for data acquisition.

The plasma energy coupling is measured by determining the main beam transmission through the plasma. The main beam power is initially measured with a Coherent Model 213 power meter before entering the test cell, and by a 25 cm water-cooled ball calorimeter after leaving the test cell. The difference between these two measurements yields the transmitted power. These measurements were taken for a variety of power levels, pressures, and plasma locations with respect to the focus.

The plasma location was varied by using a flow in opposition to the natural plasma propagation upbeam. This flow is throttled to obtain the specified flow rates and chamber pressures of interest. The flow is ultimately exhausted through a vacuum pump to a vent stack for disposal. The thermal wall loading produced by the plasma can be estimated in three ways. First, the test chamber is water-cooled to permit bulk calorimetric measurements of the chamber wall thermal loading. In addition, two optical estimates of the radiative losses can be made using a scanning radiometer and an optical spectrum analyzer.

The plasma temperature will be determined by a diagnostic technique developed[13] at the University of Tennessee Space Institute. This technique is based on an absolute measurement of plasma continuum radiation. The data are taken using a calibrated ITM densitometric video camera and a narrow bandpass filter. The video data are digitized using a Quantex frame memory unit and transferred to computer via an IEEE-488 interface. The radial distribution of plasma emission coefficient is determined for each video scan line through Abel inversion. A temperature value is assigned to each radial location by correlation with theoretical emission calculations obtained using the assumption of local thermodynamic equilibrium. The result is the three-dimensional spatial distribution of temperature within the plasma. This temperature field can be used for integration of plasma conduction and radiation losses. The absorption of the incident laser power may then also be tracked through the plasma using the temperature data and the relation for inverse Bremsstrahlung absorption. The data acquisition and reduction process for this technique is detailed schematically in Fig. 8.

Experimental Results

Plasma Ignition Experiments

The first experimental parameter examined was the breakdown threshold of hydrogen. The determination of breakdown intensity naturally requires a knowledge of the focal area. Since the beam intensity pattern did not lend itself to a facile estimate of the focal area, it was experimentally determined by axially varying the location of thermal sensitive paper through the focal region. With this approach, the focal diameter of the laser beam was determined to be 0.01 cm. That diameter was employed for all subsequent intensity calculations. Based on estimates of the thermal paper sensitivity, this diameter is slightly larger than the $1/e^2$ point.

The breakdown or threshold intensity, as it is sometimes called, is somewhat of a nebulous term. The definition of this intensity is that which provides gas breakdown at least half the time. Breakdown is generally accepted to be determined by observing a flash in a darkened room. If we assume it to be an off/on phenomenon, this is a reasonable although qualitative criteria. Since the spark is associated with a pulsed system, there are other ambiguities that enter into the analysis of the breakdown intensity. For most cases reported in the literature, the breakdown intensity is given with no indication of whether that intensity is computed using a peak power during the pulse, average power in the pulse, or some other measure. For a mode-spiking system, the difference in the various choices can be considerable. In addition to that concern, the distribution of energy at the focus is significant, as is the pulse length. Most researchers choose to assume a Gaussian intensity distribution at the focus, which is incorrect for most cases. The effects of pulse duration have been shown[14] to also be significant, but no general approach to accounting for pulse length has been recommended. Based on the assumption that most previously reported data for breakdown threshold are given in terms of average intensity within the pulse, the data in Fig. 9

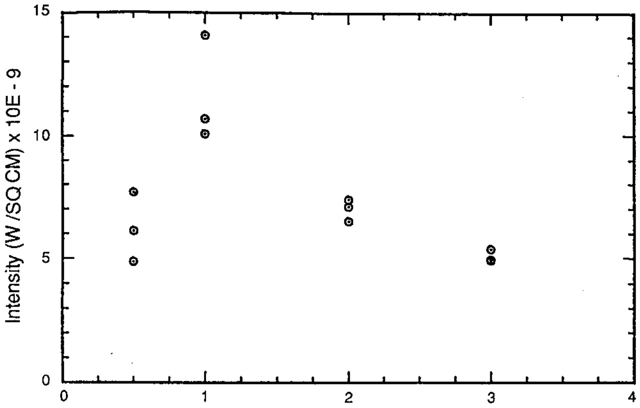

Fig. 9 Hydrogen breakdown intensity.

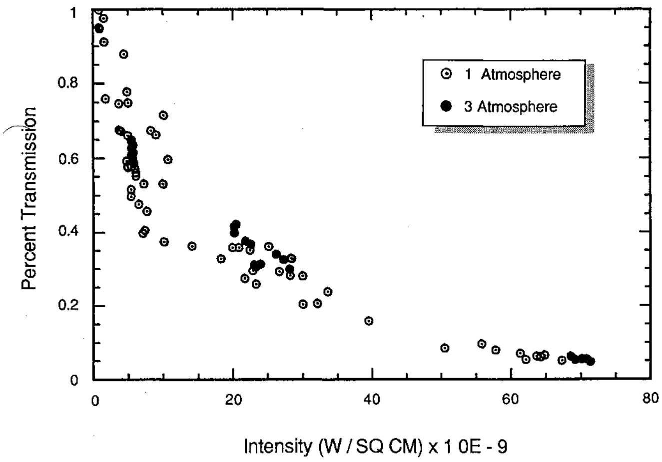

Fig. 10 Laser transmission as a function of input intensity.

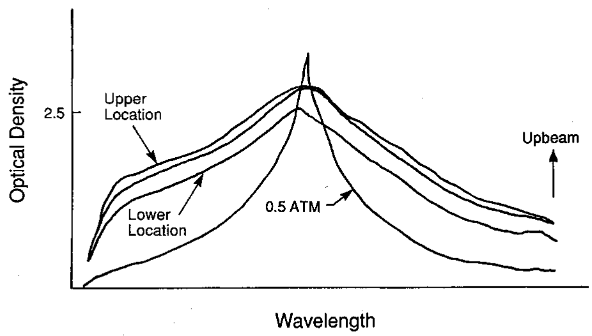

Fig. 11 Hydrogen α line radiation at 3 atm pressure.

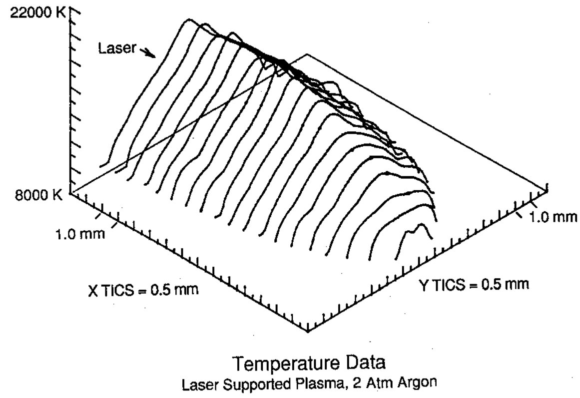

Fig. 12 Calculated temperature profiles for a 2 atm laser-sustained plasma in argon.

give the pressure dependence of hydrogen breakdown intensity over the limited pressure range in these experiments. The recorded intensity levels compare favorably with those for particulate free air, helium, and other gases. These breakdown intensities are estimated to be accurate within 50%. It should be recalled that some dependence on both pulse length and focal diameter has been previously noted.[14] This investigation did not encompass the variation of either of those parameters except for the small changes inherent in the shot-to-shot laser energy variance. The behavior of breakdown intensity at the lowest pressure (0.5 atm) was quite unexpected, and those data have been reexamined to assure that the cell evacuation procedure did not introduce impurities into the measurement breakdown intensity. The behavior at the higher pressures is consistent with the collision-dominated cascade breakdown mechanism. These breakdown intensities will serve as the baseline estimates for the necessary levels of pulsed power that must be available for routine ignition of clean hydrogen plasma. Currently, the low values for the 0.5 atm case appear to be correct, although unexplained.

Figure 10 presents the results of the simultaneous measure of transmitted energy using a second photon drag detector. These data compare qualitatively with those reported for air by Caressas et al.,[15] although their data covered much higher energies. Caressa et al. concluded that the f-number was very critical with regard to the transmitted power. In this investigation, only the operational f-number, approximately 12, was examined. Figure 10 does not indicate a strict transmission cutoff with regard to breakdown initiation. Although the functional dependence is steep, it does appear to be a smoothly varying function of input intensity (energy) and, thus, the mechanism that initiates breakdown appears to still be involved in the inception region. Included in these points are data both with and without observed breakdown flash. It is noteworthy that near an intensity of 7×10^9 W/cm^2, a significant break in the data occurs. This corresponds to the average breakdown intensity for the pressure range covered. Figure 10 does not seem to indicate any pressure dependence of the transmittance, although that dependence could easily be hidden in the considerable data scatter.

The final type of data taken was spectroscopic. The spectrograph was used to examine the Balmer series from α to δ. Figure 11 shows typical densitometer data for the indicated emission line at 3 atm pressure. A data scan for 0.5 atm has been added to show the effect of pressure on line broadening. There was insufficient light to permit single-shot spectra to be obtained and, thus, these densitometer data traces represent photographic plate density for 100 exposures. In the initial attempts to gather these spectra, the spectrometer slit was focused near the TEA laser focal point. Repeated attempts at obtaining spectra showed the gas cool in that region with only minimal radiation in terms of either line or continuum. The data in Fig. 11 is for a spatial location about 2 cm upbeam. The slit height (2 mm) was sufficient to permit the intensity gradient to be examined at that general location. The three data scans in Fig. 11 represent the upper, middle, and lower locations within the 2 cm. As can be seen from the increased broadening upbeam, the electron density within the spark plasma increased in that direction. The temperatures near the 2 cm point have been crudely estimated to be approximately 18,000 K based on the H_α line-to-continuum ratio. It does appear that nonequilibrium processes are involved since the ratios for β and shorter wavelengths indicate much higher temperatures. Additional pressure broadening is evident in spectra taken for higher pressures. The 18,000 K temperature is noted to correspond closely with the 17,400 K absorption maximum that occurs for hydrogen inverse Bremsstrahlung.

Steady-State Plasma Experiments

The experimental study of the maintenance of a steady-state plasma in hydrogen was not accomplished due to problems with the 30 kW cw laser. Some steady-state plasma results were obtained for argon that was used during system checkout. These preliminary tests demonstrated the validity of the TEA laser coaxial ignition technique. Radiance data were also obtained for a 2 atm argon plasma. Isothermal contours for the plasma are shown in Fig. 12. These data indicate that the diagnostic system is capable of extracting plasma temperature profiles. The data are consistent with the work of Keefer et al.[12]

Concluding Remarks

The principal goal of this research was the development of an experimental data base for the determination of laser thermal thruster operational feasibility. Once feasibility is proven through hydrogen experiments, the emphasis will then be shifted from a research-oriented investigation of the physics to the development of a first-generation prototype laser thruster.

The development of any flightworthy laser thruster will require not only the successful solution of the plasma absorption problem, but also several engineering problems that to date have not been addressed. These problems include an efficient scheme for plasma-fluid thermal mixing for enhanced nozzle performance, regenerative cooling designs for wall protection, and advanced film-cooled, high-power laser windows. These problems must be addressed during the course of prototype development and testing.

Acknowledgments

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References

[1]Shoji, J. M., "Laser-Heated Rocket Thruster," NASA CR-135128, May 1977.

[2]McCay, T. D. and Dexter, C. E., "Chemical Kinetic Performance Losses for a Hydrogen Laser Thermal Thruster," *Journal of Spacecraft and Rockets,* Vol. 24, July-Aug. 1987, pp. 372–377.

[3]Bray, K. N. C., "Atomic Recombination in a Hypersonic Wind Tunnel Nozzle," *Journal of Fluid Mechanics,* Vol. 6, June 1959, pp. 1–32.

[4]Nickerson, G. R., Coats, D. E., and Bartz, J. L., "TDK-Two Dimensional Kinetics Reference Computer Program," *Ultrasystems,* Dec. 1973.

[5]Jones, L. W. and Keefer, D. R., "The NASA Laser Propulsion Project: An Update," AIAA Paper 81-1248, June 1981.

[6]Smith, D. C. and Fowler, M. C., "Ignition and Maintenance of a CW Plasma in Atmospheric Pressure Air with CO_2 Laser Radiation," *Applied Physics Letters,* Vol. 22, May 15, 1973, pp. 500–502.

[7]Fowler, M. C. and Smith, D. C., "Ignition and Maintenance and Subsonic Plasma Waves in Atmospheric Pressure by CW CO_2 Laser Radiation and Their Effect on Laser Beam Propagation," *Journal of Applied Physics,* Vol. 46, Jan. 1975, pp. 138–150.

[8]Moody, C. D., "Maintenance of a Gas Breakdown in Argon Using 10.6-μ CW Radiation," *Journal of Applied Physics,* Vol. 46, June 1975, pp. 2475–2482.

[9]Fowler, M. C., Newman, L. A., and Smith, D. C., "Beamed Energy Coupling Studies," United Technology Research Center, East Hartford, CT, Rept. 203-727-F000, Jan. 1980.

[10]Conrad, R. W., Roy, E. L., Pyles, C. E., and Mangum, D. W., "Laser-Supported Combustion Wave Ignition in Hydrogen," U.S. Army Missile Command, TR RH-80-1, Oct. 1979.

[11]Keefer, D. R., Henrikson, B. B., and Braerman, W. F., "Experimental Study of a Stationary Laser-Sustained Air Plasma," *Journal of Applied Physics,* Vol. 46, May 1975, pp. 1080–1083.

[12]Keefer, D. R., Crowder, H., and Peters, C., "Laser Sustained Argon Plasmas in a Forced Convective Flow," AIAA Paper 85-0388, Jan. 1985.

[13]Eskridge, R. H., McCay, T. D., and Van Zandt, D. M., "An Experimental Study of Laser-Supported Plasmas for Laser Propulsion—Final Report," NASA TM-86583, Jan. 1987.

[14]Smith, D. C., "Gas-Breakdown Dependence on Beam Size and Pulse Duration with 10.6-μ Wavelength Radiation," *Applied Physics Letters,* Vol. 19, 1971, pp. 405–408.

[15]Caressa, J. P., Autric, M., Fresne, D. D., and Bournot, P., "Breakdown over Long Distances," *Journal of Applied Physics,* Vol. 50, Nov. 1979, pp. 6822–6825.