Laser-Sustained Argon Plasmas for Thermal Rocket Propulsion

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The results of the ongoing investigation of laser-sustained argon plasmas in the forced convective flow regime are reported. Plasma absorption and thermal efficiency are the key parameters measured. Flow velocities of up to 30 m/s at one atm to 13.6 m/s at 2.5 atm are imposed upon plasmas sustained at 2.5, 5.0, and 7.0 kW input laser powers, using either f/4 or f/7 beam focusing geometries. Absorption ranged from 55 to 97% and thermal efficiency ranged from 11 to 46%, depending upon the operating conditions. Absorptions and efficiencies this high have never before been reported and demonstrate that laser propulsion could be a practical orbital transfer concept. Spectroscopic analysis of the plasma core is used concurrently with conventional techniques to analyze plasma behavior.

Introduction

LASER sustained plasmas (LSP) are being studied as a mechanism for converting laser energy into thermal energy of a propellant gas. Laser propulsion is a high specific impulse advanced orbital transfer propulsion concept that is based on the use of an LSP to provide moderate levels of thrust.[1]

Such a propulsion system would utilize a remote high-power laser beam focused into an onboard absorption chamber. The absorption chamber would contain the LSP that absorbs laser energy predominantly via inverse bremsstrahlung. The gas thus convectively heated in the plasma would then be exhausted out of a conventional rocket nozzle. Thrust levels as high as 10 kN with specific impulses of 1000 s appear achievable using hydrogen as the propellant gas, and bulk exhaust gas temperatures in excess of the combustion regime are expected. Utilization of a remote laser source, either ground based or in low-Earth orbit, results in a relatively lightweight spacecraft with a good thrust-to-weight ratio. Thus, if made feasible, laser propulsion systems could fill the performance gap between thrust limited electric propulsion systems and specific impulse limited chemical propulsion systems. A more detailed discussion of laser (beamed energy) propulsion is given in Ref. 2.

In order to make laser propulsion a feasible means of orbital transfer, an LSP must efficiently convert laser energy into thermal energy of a propellant gas. It is generally believed that a thermal efficiency of at least 50% will be necessary to make this propulsion concept feasible. Thus, the study of LSP energy conversion characteristics is the key experimental issue for laser propulsion. Nearly complete absorption of the laser energy is essential for an efficient LSP. However, due to substantial radiation losses from a plasma at temperatures approaching 20,000 K, thermal efficiency is not necessarily maximized at maximum absorption. Therefore, the fundamental task is to determine operating conditions at which high absorption is combined with relatively low-radiation loss, producing an optimum thermal efficiency.

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In an effort to understand the physics of LSP behavior in a forced convective flow, experiments are being conducted with argon plasmas. These experiments are intended to map plasma absorption, thermal efficiency, size, stability, and core temperature distribution at the available laboratory conditions. These conditions are limited to values of laser power, gas velocity, and gas pressure below those that might exist in an actual laser propulsion rocket thruster. These experiments are intended to provide insight into argon LSP behavioral trends that could then be associated with trends in a hydrogen LSP at actual thruster conditions. Argon is used instead of hydrogen in experiments because it is very safe to handle and it possesses similar absorptive and radiative properties.

Continuous wave LSPs have been studied experimentally for over a decade, but only a few studies have considered argon plasmas in a forced convective flow at velocities significantly above those generated by buoyancy effects (~30 cm/s). Keefer and co-workers have studied argon plasmas at less than 1 kW input laser power, flow velocities up to 4.5 m/s, gas pressures up to 4 atm, and several beam geometries.[3,4] They have reported absorption efficiency as high as 86%, with a thermal efficiency of 38% for a plasma at 2.5 atm argon pressure. Work under Krier and Mazumder[5] has included plasma studies at over 7 kW and velocities up to 1.2 m/s at atmospheric pressure. Results at atmospheric pressure predating the current work include absorption as high as 85% for 5.5 kW plasmas and efficiency of 21% for 2.5 kW plasmas at 50 cm/s argon flow velocity.

The work here utilizes two independent diagnostic techniques to analyze LSP behavior. Conventional calorimeter and thermocouple data is used to determine absorption and thermal efficiency, respectively. In addition, spectroscopic analysis of plasma emission provides data that is used to determine plasma size, position, and core temperature distributions.

In this paper, results are presented from experiments measuring absorption and thermal efficiency as a function of argon mass flux (which is related to velocity), laser power, argon pressure, and beam geometry. Laser powers of up to 7 kW, pressures of 1.0 and 2.5 atm, beam focusing geometries of f/4 and f/7, and argon mass flux of up to 54.6 kg/sm^2 (a velocity of 13.6 m/s at 2.5 atm) were utilized in this study. The highest velocity used was 30 m/s at a mass flux of 48.2 kg/sm^2 and 1 atm.

Experimental Facility

These experiments utilized a 10 kW (CW) CO_2 laser that outputs a horizontal annular beam with an o.d. of 70 mm and an i.d. of 50 mm. The energy distribution across the beam annulus was nearly Gaussian. The horizontal beam was reflected by three water-cooled copper turning mirrors that directed the beam under the flow chamber and turned it vertically upward.

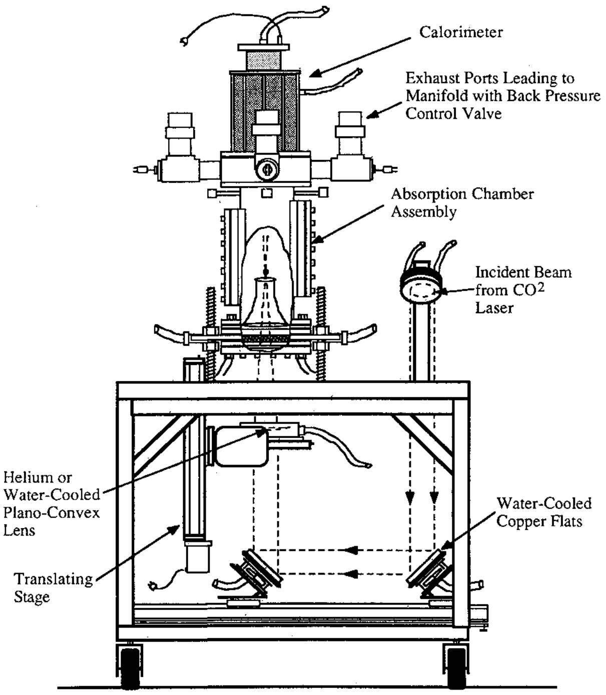

Fig. 1 Schematic of the test stand used in this study. Precision beam steering optics and the absorption chamber are highlighted.

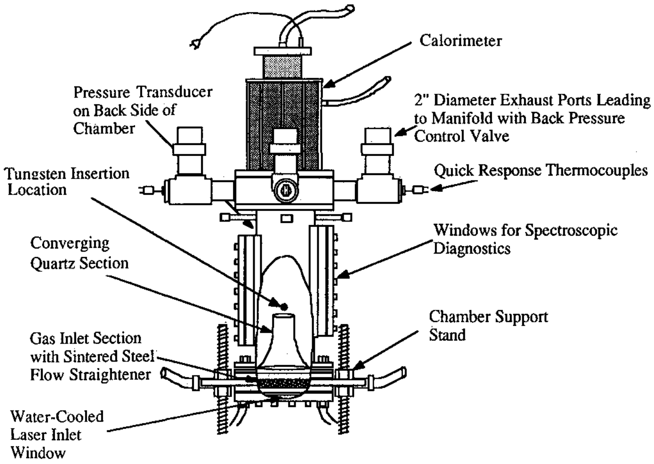

Fig. 2 Detailed schematic of the absorption chamber used in this study. Note the flow straightener and the quartz section in the cutaway view.

The beam was then focused by a plano-convex lens mounted on a motor driven translation stage up into a 127 mm i.d. stainless steel flow chamber through a water-cooled zinc selenide (ZnSe) window.

The data in this paper was taken using either a water-cooled 305 mm focal length ZnSe lens or a helium cooled 530 mm focal length sodium chloride (NaCl) lens to focus the beam. These focal lengths yield f-numbers of 4 and 7 based on a beam diameter of 75 mm at the lens. The NaCl lenses and windows used in earlier experiments have all been replaced by ZnSe components due to their greater durability, rupture strength, and ease of cleaning, with the exception of the 530 mm focal length NaCl lens. The ZnSe window withstood energy fluxes greater than 1600 W/cm^2 with no damage. Figure 1 is a schematic of the test stand used in this study. The beam path is shown, including the turning mirrors, translating lens, and absorption chamber.

Gas was introduced radially into the bottom of the flow chamber through a sintered steel flow straightener that diminished inlet flow turbulence. This inlet turbulence previously limited flow velocities by causing plasma instability (or blowout). A converging quartz tube with a 48 mm i.d. straight section was mounted inside the flow chamber downstream of the flow straightener. The quartz tube allowed flow velocities of over 30 m/s at 1 atm pressure while not blocking spectroscopic access to the plasma. Figure 2 is a schematic of the chamber assembly showing many of the significant components.

Plasma initiation was achieved in the same manner as described in Ref. 6, except that a tungsten rod rather than a zinc foil was used as the target. The plasma was then lowered into the quartz tube by moving the lens via the computer controlled motor driven translation stage. The spot radius of the laser focus was approximately 1 mm; thus, at 5 kW the energy flux at the focus was $\sim 10^5$ W/cm^2. This flux was sufficient to maintain plasmas at a wide range of mass fluxes. Laser energy not absorbed by the plasma was collected by a water-cooled copper cone calorimeter to facilitate transmitted power calculations. This power was recorded and used in calculating the plasma global absorption percentage.

Heated gas left the flow chamber through four 2-in. insulated exit ports. A millisecond response, type K thermocouple in each exit port measured exhaust gas temperatures. The data acquisition system scanned the exhaust gas temperatures as well as inlet gas and main chamber wall temperatures, the chamber pressure, and the calorimeter power once every 1.5 s and entered this data in a file. The four exhaust gas temperatures were averaged and used in the calculation of thermal efficiency. The four exhaust pipes were joined into a single pipe that was valved for chamber pressure control. Figure 2 shows the flow chamber, including the quartz tube, the calorimeter, and the exhaust piping. For further description of the experimental facility, see Refs. 6 and 7. The equipment and procedures used in the spectroscopic analysis of plasmas are described in Ref. 8.

Data Analysis

Laser power was calibrated as described in Ref. 5. This allowed the determination of laser power (post optics) available to the plasma for specific laser output powers. Power calibrations were also made with and without a NaCl laser inlet window installed so the amount of energy attenuated (reflected and absorbed) by the window could be determined. A ½-in. thick NaCl window was found to attenuate approximately 7.5% of the energy incident upon it, almost all through reflection.

Laser plasma absorption was defined as the ratio of laser power absorbed by the plasma to incident laser power. Plasma absorption measurements were indirectly made using a calibrated water-cooled copper cone calorimeter. Irradiation of the calorimeter by the plasma is a source of error in this analysis and is dependent upon the actual absorption and thermal efficiency of the plasma. Calorimeter thermocouple errors and inaccurate reading of the cooling water flow rates around the copper cone also contributed to the error in absorption measurements. Beam scattering by the plasma was assumed to be negligible in this analysis.

The complex interaction of the various sources of absorption errors made the determination of experimental uncertainty very difficult. It is helpful to recognize, however, that error in calorimeter calibration and error due to irradiation were biased and tended not to scatter the data. Therefore, the trends represented by these single-sample experiments are believed to be valid but are uncertain by some small absolute shift. This idea has been substantiated by good repeatability of the data trends.

Originally, a ½-in. thick NaCl laser exit window (identical to the NaCl inlet window) was placed between the chamber and calorimeter. This window, while attenuating a certain amount of transmitted laser energy, would prevent the hot plasma exhaust gas from entering the water-cooled cone and affecting both the absorption and efficiency measurements. The amount of energy attenuated by the window could be calculated using the calibration mentioned previously. To determine the true amount of laser energy absorbed by the plasma, the amount of energy collected by the calorimeter was added to the calculated amount attenuated by the window.

The uncooled exit windows, however, were very prone to cracking because of transmitted laser power, the momentum of the gas exiting at high velocity from the quartz converging section, and convective heating. The transmittance of NaCl windows was uncertain at high operating temperatures because transmittance is a function of temperature and calibrations were done with a cool window. In an effort to investigate the effect of laser exit windows on diagnostic data, a set of experimental runs with identical operating conditions was performed with and without exit windows installed. The decrease in the amount of energy collected by the calorimeter with a window installed represented about a 2% increase in absolute absorption (e.g., 82 to 84%) for a typical experiment for which no windows would be used. As this error always tends to bias the data on the low side, as does irradiation error, all of the results presented here were acquired without an exit window between the chamber and calorimeter, and tend to underpredict true absorption.

The thermal efficiency of the LSP was defined as the ratio of laser power retained by the working gas to the incident laser power. The laser power retained by the gas was determined by the change in the gas enthalpy ($\Delta \dot{H}$), using

$$\Delta \dot{H} = \dot{m} C_p (T_e - T_i) \tag{1}$$

where $\dot{m}$ was the measured mass flow rate, C_p was the specific heat of the gas, T_e was the mass-averaged exhaust gas stagnation temperature, and T_i was the mass-averaged inlet gas stagnation temperature. The efficiency was then determined by the ratio of $\Delta \dot{H}$ to the laser power input to the plasma.

The root mean square (rms) uncertainty method described by Kline and McClintock[9] predicts that the uncertainty in the bulk exhaust gas temperature was ± 0.5 K. This estimate does not take into account heat loss from the exhaust gas prior to temperature measurement. Mass flow measurements were considered to be accurate to within $\pm 3\%$. Flow rate errors were due to flow meter inaccuracies and human error in the reading of analog scales. Laser power was known to within $\pm 3\%$, which was the uncertainty associated with the power probe calibration. The absolute rms uncertainty in efficiency will depend on the nominal operating conditions. At high flow rate and low power, the absolute uncertainty was 2.4%, giving a relative uncertainty of 5.6%.

For the trends in efficiency, like the trends in absorption, much of the error is biased and does not add to the scatter in the data. The absolute uncertainty here is fairly good but may be viewed as conservative, as the efficiency trends have also proven to be repeatable.

In general, efficiencies based on exit port gas temperature measurements were found to increase as a given experiment progressed. This was due to decreasing convection from the hot plasma exhaust gas to the cool exit port walls. As time went on the walls became hotter and the gas lost less energy before reaching the thermocouple. In high mass flow rate experiments, the exhaust gas temperature became steady very quickly, whereas at low mass flow rate (higher gas temperature) there was a long, slow rise with time due to greater heat loss potential. This circumstance introduced some subjectivity into the efficiency measurements at low mass flow rates because for these cases the experiments had to be limited in time (by material temperature limitations) before a true steady-state could be reached. It should be noted that the cases of most interest are the ones at high mass flux and for these the efficiency uncertainty brought on by heat loss is very small and the uncertainty mentioned above can be assumed.

In prior studies,[5] all experiments were performed without a quartz tube in the chamber. Relatively high mass flow rates were required to match even the lowest mass fluxes attainable with the current quartz tube chamber configuration. In comparing efficiencies measured with these two systems at similar mass flux, a significantly lower efficiency was found with the quartz tube in place. This was due to the significant heat loss from the hotter gas at low mass flow rate, and the inherent subjectivity mentioned previously. This condition indicates that the system had not yet come to steady state for the current low mass flux experiments. It is believed that for all current experiments with mass flux above approximately 12 kg/sm^2, the rms uncertainty is accurate.

Correct measurement of gas stagnation temperature incident to the plasma was required to make an accurate calculation of LSP thermal efficiency. Inlet gas stagnation temperature was determined by placing an exposed thermocouple in the chamber without the presence of a plasma and matching the flow conditions to those of the actual experimental runs. This measured temperature was then used as the stagnation temperature of gas incident on the plasma during an experiment. The inlet stagnation temperature was found to drop with increasing mass flow rates. This is because the rapid pressure drop of gas in the supply tanks causes the temperature of the gas to drop significantly.

Recently, four 2-in. diam insulated exit ports were added to the test facility, replacing four ½-in. diam uninsulated exit ports. The larger exit ports were required for operation at mass flow rates greater than 30 g/s without inducing compressibility in the operating gas in the exit ports.

Mass flux will be the parameter used when referring to the effects of changing the incident gas flow rate. The mass flux was given by

$$\dot{m}/A = \rho u \tag{2}$$

where $\dot{m}$ was measured mass flow rate, A was the area of the test section, ρ was the operating gas density, and u was the mean gas velocity. Mass flux represents the volume averaged gas momentum and thus the governing factor in convective transfer in the plasma. Using mass flux allows for the comparison of experiments at different operating pressures. At a given mass flux, chamber pressure affects gas density and, therefore, gas velocity.

The techniques used for the analysis of spectroscopic data are thoroughly described in Ref. 8.

Experimental Results

The main objective of these experiments was to determine the effect that argon mass flux variations have on the absorption and thermal conversion efficiency of an LSP. This effect was investigated at 2.5, 5.0, and 7.0 kW laser powers, 1 and 2.5 atm ambient argon pressure, and with f/4 and f/7 beam focusing geometries. No experiments have yet been performed at 7 kW with an f/4 geometry.

Plasma position relative to the laser focus, plasma size, and plasma shape proved to be important factors in the observed LSP performance trends. Photographs of plasmas at different operating conditions were taken to demonstrate how these factors related to measured absorption and thermal conversion efficiency.

An LSP stabilized in a region of the focusing laser beam where the incident laser power density resulted in absorption. This absorption was balanced by incoming cold argon convection and losses due to radiation and conduction. In general, a plasma front stabilized upstream of the focus, but, depending on argon mass flux, laser power, ambient pressure, and focusing geometry, the size, shape, and axial position of the plasma front varied. Results will be discussed that indicate the general effect of increasing laser power, ambient pressure, and beam focusing geometry with respect to variations in mass flux. Also discussed will be how plasma size, shape, and position

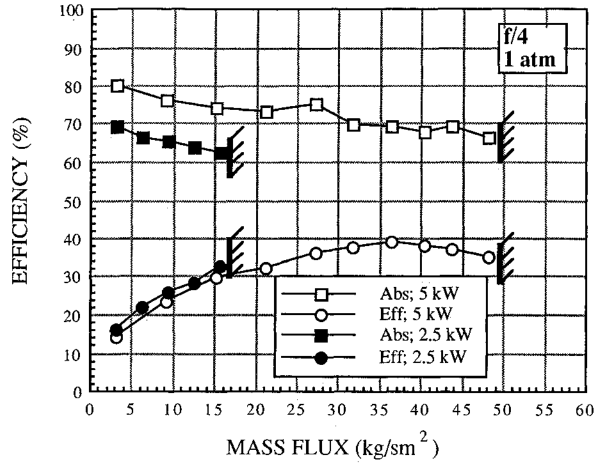

Fig. 3 Absorption and thermal efficiency as a function of argon mass flux at 1 atm with an f/4 beam geometry; 2.5 and 5 kW are being compared.

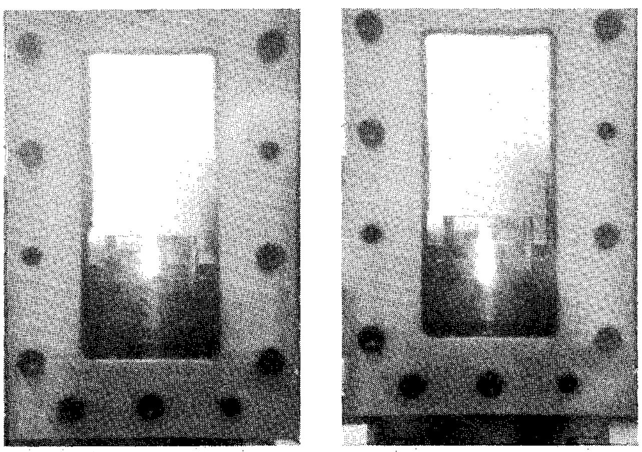

Fig. 4 Photographs comparing plasmas at 2.5 kW (left) and 5 kW (right). Mass flux is 3.1 kg/sm^2, pressure 1 atm, with an f/4 beam geometry. Converging, diverging rays represent the beam path.

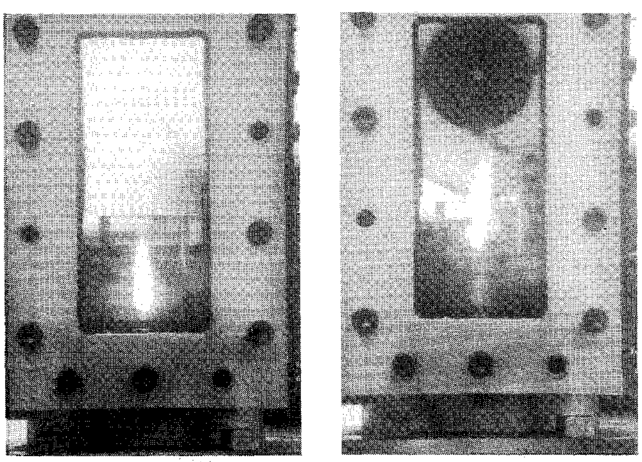

Fig. 5 Photographs comparing plasmas at 3.1 kg/sm^2 (left) and 32.3 kg/sm^2 (right). Power is 7 kW, pressure 1 atm, with an f/7 beam geometry. Converging, diverging rays represent the beam path.

relate to plasma performance with regard to these changes in operating conditions. Welle et al.[3] have investigated these interrelated effects at gas pressures up to 4 atm, but laser powers limited to only 0.9 kW and incident flow velocities of 4.3 m/s.

Figure 3 shows data comparing the absorption and thermal conversion efficiency of 2.5 kW and 5 kW plasmas at one atmosphere and with an f/4 focusing geometry. The 2.5 kW plasma became unstable at approximately 17 kg/sm^2, whereas the 5 kW plasma remained stable to almost 50 kg/sm^2. (Wall symbol indicates stability threshold.) This is likely due to the fact that the 5 kW plasma stabilized further upstream than the 2.5 kW plasma at a given mass flux, and therefore required greater mass flux to push it far enough downstream to cause instabilities to arise. Figure 4 is a comparison of two photographs showing this effect. The 5 kW plasma is both lower and slightly larger than the 2.5 kW plasma at low mass flux.

The data in Fig. 3 also show that the 5 kW plasma had higher absorption for all mass fluxes at this pressure and f-number. Absorption coefficient increased with local gas temperature, and the 5 kW plasma not only produced slightly higher temperatures, but was longer and so more energy could be absorbed along the beam path. For both powers, absorption decreased with increasing mass flux. The 5 kW plasma had a maximum of 80% absorption compared to 69% for the 2.5 kW plasma, and decreased to 66% compared to just 62% at the plasma's respective stability thresholds. For these conditions, the plasmas initiated fairly close to the laser focus even at low mass flux. As mass flux was increased, a greater proportion of the plasma tail was downstream of the focus and out of the beam path, and, hence, absorption fraction decreased.

The thermal conversion efficiency trend shown by the data in Fig. 3 is that both plasmas became more efficient with increasing mass flux, and the 2.5 kW plasma was more efficient until it became unstable. The 5 kW plasma was stable at much higher mass fluxes and eventually attained an efficiency greater than the 2.5 kW plasma maximum efficiency. The 2.5 kW plasma became unstable with an efficiency of 33%, whereas the 5 kW continued to a peak efficiency of 39% at 36 kg/sm^2 before decreasing to 36% at its stability threshold.

The increase in measured thermal conversion efficiency, despite decreasing absorption, was due to an accompanying decrease in radiation loss from the plasmas at increasing mass flux. Figure 5 shows a comparison of two 7 kW plasmas at two different mass fluxes. The low mass flux plasma was almost fully upstream of the focus and fills the incoming beam, and also produced a relatively large hot region at the plasma front. The high mass flux plasma was almost fully downstream of the focus, which resulted in its hottest region being in a very narrow portion of the plasma near the focus, with a relatively cool tail extending downstream. The large hot region of the low mass flux plasma radiated a greater proportion of absorbed energy than the narrow hot region of the high mass flux plasma, due to the larger radiating volume. For the 5 kW case, the decrease in radiation loss was overtaken by the decrease in absorption at about 36 kg/sm^2, and, thus, produced the peak in thermal conversion efficiency shown in Fig. 3.

Figure 6 contains data comparing 7 kW plasmas to 5 and 2.5 kW plasmas at 1 atm and with an f/7 focusing geometry. The same trends in absorption and efficiency were found as with the f/4 geometry of Fig. 3, except that absorption did not decrease so consistently with increasing mass flux. This was due to the f/7 beam intercepting a greater portion of the downstream region of a plasma tail than did the f/4 beam because of the f/7 beam's less rapid defocusing. Radiation losses decreased as before, which resulted in increasing efficiencies with increasing mass flux. Again, the 5 kW plasma is stable at higher mass fluxes than the 2.5 kW plasma, and the 7 kW plasma is stable at higher mass fluxes still. The highest efficiency measured for each plasma occurred near its stability threshold, and higher maximum efficiency was observed for higher power plasmas (i.e., 32% at 2.5 kW, 36% at 5 kW, and 37% at 7 kW).

The data in Fig. 7 show the effect of raising the ambient argon pressure from 1 to 2.5 atm at 5 kW and with an f/4 focusing geometry. The most striking feature of this figure is that the absorption at 2.5 atm increased with increasing mass flux, contrary to the behavior at 1 atm. In addition, limitations on the argon supply prevented experiments with mass fluxes for which any of the 2.5 atm plasmas became unstable. Figure 8 is a comparison of plasmas at 1 and 2.5 atm. Both plasmas are subjected to a mass flux of about 47 kg/sm^2, which is near the stability threshold of the 1 atm plasma.

Clearly the plasma at 2.5 atm was much smaller and further upstream than the 1 atm plasma, which had been forced almost completely downstream of the focus. The 2.5 atm plasma absorbed more laser energy despite its small size due to its greater absorption coefficient. Its absorption was increasing with mass flux because the plasma was still approaching the laser focus, and, therefore, greater mass flux produces even higher plasma temperatures as the laser intensity increases toward the focus. The greatest absorption recorded was 97% at just over 50 kg/sm^2 for the 2.5 atm, 5 kW plasma. This indicates nearly complete absorption of the incident laser power. It is unclear whether absorption will reach a peak as the 2.5 atm plasma is forced through the focus. Experiments at even higher mass flux are necessary to determine the complete behavior of high pressure LSPs.

The thermal conversion efficiency data in Fig. 7 indicate that the radiation loss from the 2.5 atm plasma was constant with increasing mass flux, whereas the 1 atm plasma exhibited decreasing radiation loss. The overall radiation loss was greater from the 2.5 atm plasma due to its elevated emission coefficient, despite its small size. At approximately 45 kg/sm^2, the 2.5 atm plasma became more efficient than the 1 atm plasma, due to the decline in efficiency of the 1 atm plasma past its peak. An efficiency of almost 40% was recorded for the 2.5 atm plasma, and further experiments at higher mass flux will determine if this trend will produce a peak efficiency or if efficiency will continue to rise until a stability threshold is reached. These higher mass fluxes should be capable of forcing the 2.5 atm plasma through the laser focus to completely describe the energy conversion behavior.

Figure 9 contains data from experiments with 2.5 kW plasmas and an f/4 focusing geometry. Again, the comparison is for plasmas at 1 and 2.5 atm ambient argon pressure. This figure demonstrates the value of operating at high pressure, as the peak efficiency of the 2.5 atm plasma well exceeded that of the 1 atm plasma at its stability threshold. The highest effi-

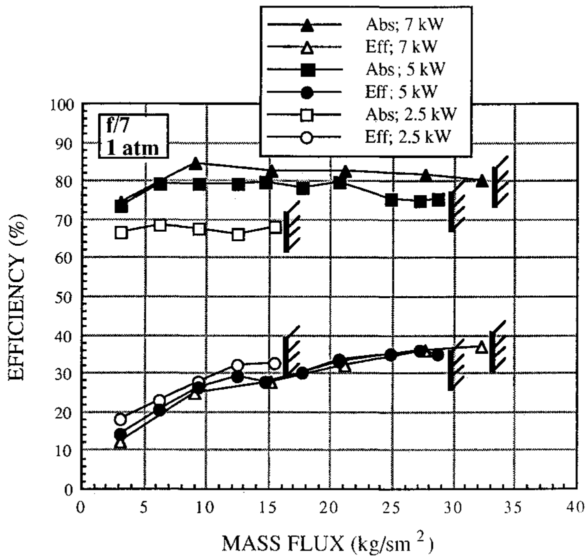

Fig. 6 Absorption and thermal efficiency as a function of mass flux at 1 atm and an f/7 beam geometry; 2.5, 5, and 7 kW are being compared.

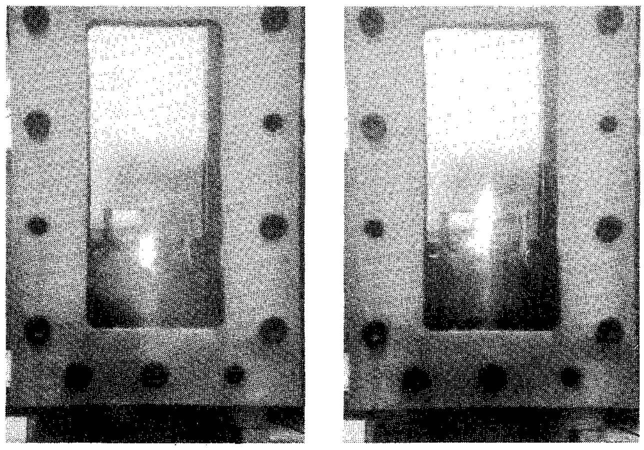

Fig. 8 Photographs comparing plasmas at 1 and 2.5 atm. Mass flux is 47.6 kg/sm^2, power is 5 kW, beam geometry is f/4. Converging, diverging rays represent the beam path.

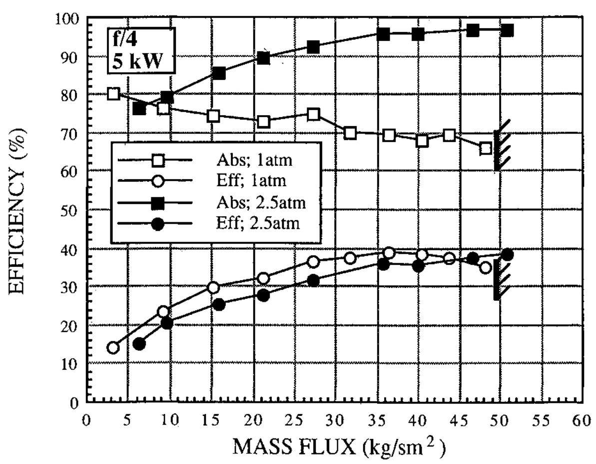

Fig. 7 Absorption and thermal efficiency as a function of mass flux for 5 kW plasmas with an f/4 beam geometry; 1 and 2.5 atm are being compared.

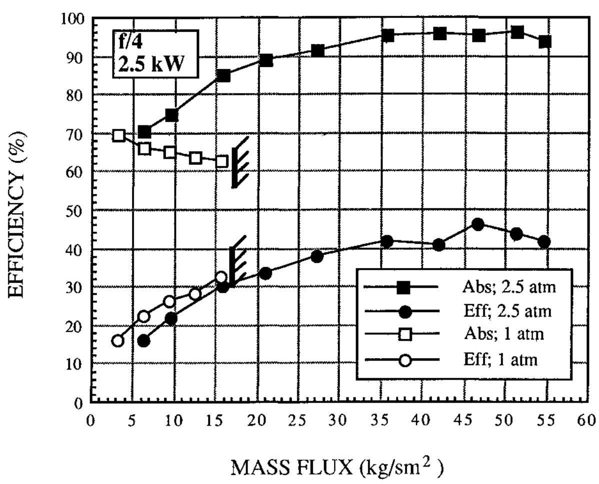

Fig. 9 Absorption and thermal efficiency as a function of mass flux for 2.5 kW plasmas with an f/4 beam geometry; 1 and 2.5 atm are being compared.

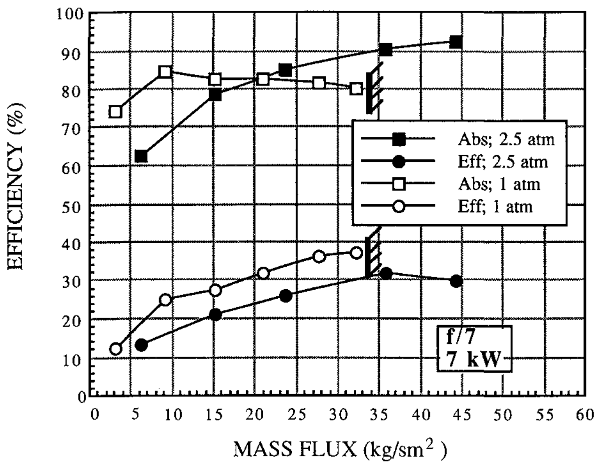

Fig. 10 Absorption and thermal efficiency as a function of mass flux for 7 kW plasmas with an f/7 beam geometry; 1 and 2.5 atm are being compared.

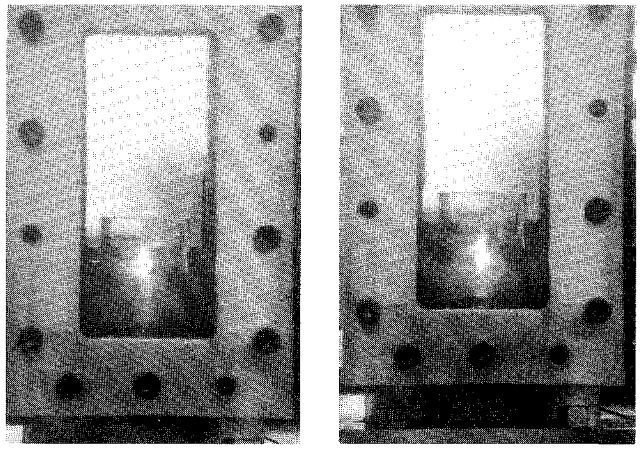

Fig. 12 Photographs comparing f/4 and f/7 beam geometries. Mass flux is 16 kg/sm^2, power is 2.5 kW, and pressure is 2.5 atm. Converging, diverging rays represent the beam path.

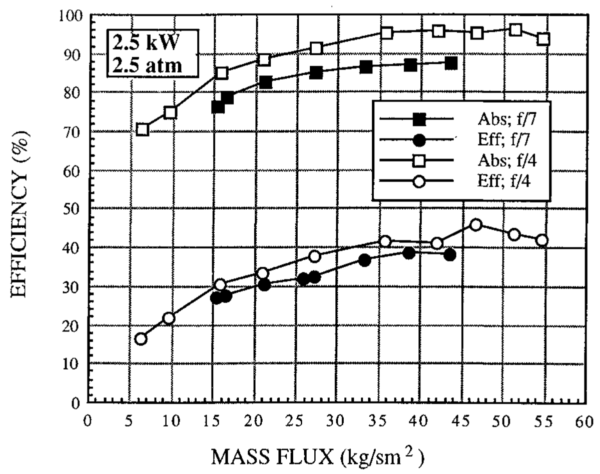

Fig. 11 Absorption and thermal efficiency as a function of mass flux for 2.5 kW plasmas at 2.5 atm. Beam geometries of f/4 and f/7 are being compared.

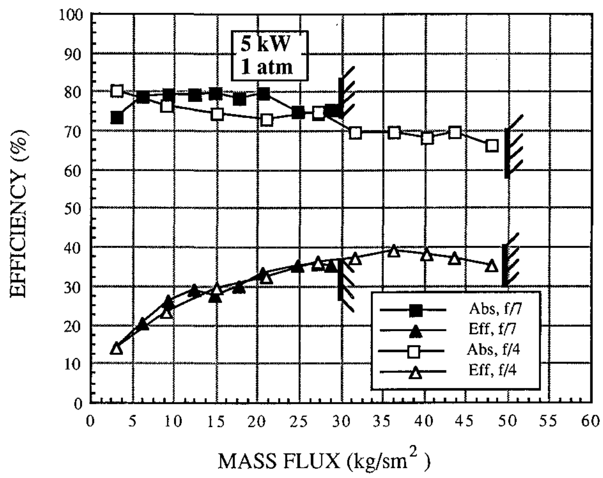

Fig. 13 Absorption and thermal efficiency as a function of mass flux for 5 kW plasmas at 1 atm. Beam geometries of f/4 and f/7 are being compared.

ciency recorded was 46% for the 2.5 atm plasma at about 47 kg/sm^2 mass flux compared to only 32% for the 1 atm plasma at 16 kg/sm^2. The next two efficiency data points on the 2.5 atm curve are below 46%, and it is believed to indicate a true efficiency peak and not simply scatter due to experimental error. The drop in absorption at the highest mass flux used in this series of experiments is not so certain to indicate that a peak has been reached, as the drop in absorption was not considered significant. Further experiments at higher mass flux could determine the validity of the observed trend.

Even at the relatively low power of 2.5 kW, the absorption at 2.5 atm was found to be as high as 96%. This indicates that even if all the laser energy is not directly retained by the flowing gas, there is the possibility of recovering almost all of the incident laser energy through regenerative techniques. Jeng and Keefer[10] have discussed radiation recovery for several operating conditions of one specific thruster design.

Figure 10 contains another comparison between 1 and 2.5 atm plasmas, but these data were taken for 7 kW plasmas with an f/7 focusing geometry. The combination of high power and high f-number means that at low mass flux the plasmas initiated well upstream of the focus, especially for the 2.5 atm plasma with its higher absorption coefficient. At low mass flux, the 1 atm plasma had higher overall absorption, but as mass flux was increased the increasing absorption of the 2.5 atm plasma eventually became greater than the 1 atm plasma. The thermal conversion efficiency of the 2.5 atm plasma was found to be always less than the 1 atm plasma. This indicates that a substantial amount of absorbed energy was being radiated at 2.5 atm and these mass fluxes.

Experiments at higher mass fluxes will determine if 2.5 atm, 7 kW plasmas with an f/7 focusing geometry can be made more efficient than 1 atm plasmas at the same power and f-number. The small peak seen in the efficiency curve at 2.5 atm is not currently believed to be a true indication of plasma behavior. There is currently no explanation for such a peak, as increasing absorption indicates that the plasma was still upstream of the laser focus. The small decrease was within experimental uncertainty, and in all other experiments efficiency has been found to increase if absorption was increasing with mass flux. Further experimentation at high mass flux will help determine the validity of the peak seen in Fig. 10.

The effect of operating with either an f/4 or an f/7 focusing geometry is more clearly shown by examining Figs. 11–13. In Fig. 11, the results of experiments with 2.5 kW plasmas at 2.5 atm argon pressure are compared. For all mass fluxes, the plasma with the f/4 geometry absorbed more laser energy and was more efficient than the plasma with the f/7 geometry.

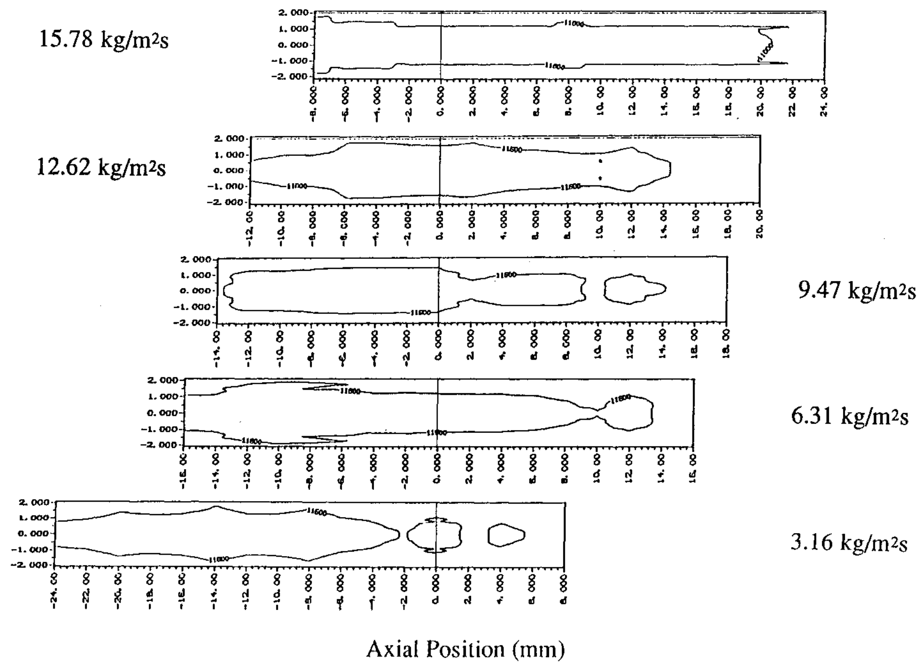

Fig. 14 Series of 11,600 K isotherms for 2.5 kW plasmas at 1 atm with an f/7 beam geometry. Mass flux increases from bottom to top. Vertical line through all contours indicates the origin of the horizontal axis. All major horizontal divisions are 2 mm apart, vertical are 1 mm.

Both absorption and efficiency increased with mass flux, with the exception being the efficiency peak in the f/4 data discussed above. The photographs compared in Fig. 12 indicate that the f/4 plasma is closer to the focus than the f/7 plasma at a mass flux of about 29 kg/sm^2. It is believed that even though the laser intensity at the plasma front for each f-number was similar, the more rapid, sharper focusing with the f/4 geometry led to a hotter plasma with higher local absorption coefficients and overall higher absorption percentage. This is despite the longer absorption length associated with the longer f/7 plasma. However, as the f/4 plasma also had the greater thermal conversion efficiency, it is believed that the larger f/7 plasma was radiating a greater proportion of its absorbed laser energy.

Note that in Fig. 11 there are no data points below 15 kg/sm^2 for the f/7 plasma. This is because that plasma did not stabilize at mass fluxes below that mass flux level, but, as the mass flux was increased, the plasma was easily maintained. This unstable behavior at high pressure, high f-number, and low mass flux is difficult to explain but has also been noted by Keefer in experiments performed in the buoyancy dominated flow regime.[11]

Figure 13 shows data from experiments with 5 kW plasmas at 1 atm argon pressure. The effects of using either an f/4 or an f/7 geometry are somewhat different at 1 atm than at 2.5 atm. Neither geometry results in increasing absorption with mass flux at 1 atm nor does the f/4 geometry result in a higher overall absorption. At 1 atm, the f/4 plasma initiated almost right at the focus even at low mass flux, whereas the f/7 plasma was slightly upstream due to higher upstream laser intensities. In fact, the absorption trend for the f/7 plasma includes a slight increase at low mass flux before reaching a relatively constant value, as compared to the steadily decreasing f/4 absorption. Once both plasmas had been forced far enough downstream to have large portions beyond the focus, the more slowly defocusing f/7 beam remained in the plasma longer than did the f/4 beam. This gives reason for the greater absorption of the f/7 plasma at high mass fluxes. The thermal efficiency of both f-number plasmas is approximately the same.

The most surprising feature of Fig. 13 is that the f/7 plasma became unstable at a lower mass flux than the f/4 plasma. Because an f/7 stabilizes further upstream than an f/4 plasma, it was expected that a higher mass flux would be required to force it far enough downstream to produce instabilities. This unexpected result was first observed by Fowler[12] in 1974 while studying laser-sustained plasmas in nonforced flowing air. He attributed it to high f-number plasmas being unable to adjust quickly enough to slight variations in the flow. It also may be due to the lower peak intensity of the f/7 beam focus.

The results of spectroscopic analysis are shown in Fig. 14. This figure shows isotherms of 11,600 K in the plasma core region of a 2.5 kW, f/7 plasma at 1 atm. The laser focus is at 0.0 mm axial position. The five isotherms in the figure were each plotted for a different argon mass flux. From bottom to top, the mass flux goes from 3.16 to 15.78 kg/sm^2. It is shown that as mass flux increased the 11,600 K isotherm was forced downstream through the laser focus.

Conclusions

The energy conversion characteristics of laser-sustained plasmas in flowing argon have been studied. Laser power as high as 7 kW has been used with argon pressures of 1 and 2.5 atm, and with f/4 and f/7 beam focusing geometries. The absorption and thermal efficiency characteristics of plasmas at these operating conditions have been mapped as a function of argon mass flux.

Absorption at 1 atm was found to increase with increasing laser power at both f/4 and f/7 and all mass fluxes. Atmospheric plasmas at all available laser powers were found to become unstable if high enough mass flux was imposed, and the higher the power the higher the mass flux required to bring about instability. The highest absorption measured at 1 atm was 85% for a 7 kW, f/7 plasma that did not become unstable until a mass flux of 37.5 kg/sm^2 (23.4 m/s) was imposed.

Thermal efficiency at 1 atm decreased with increasing laser power at all mass fluxes, at which all power plasmas were stable. However, at high mass flux, a 5 kW plasma was found to obtain an efficiency greater than the maximum efficiency of a 2.5 kW plasma. The same was true for a 7 kW plasma when compared to both 2.5 and 5 kW plasmas at their maximum efficiencies. The highest efficiency recorded at 1 atm was 39% for a 5 kW, f/4 plasma at 36 kg/sm^2, above which efficiency was found to decrease. Experiments with 7 kW plasmas sustained with an f/4 beam have not yet been performed.

At 1 atm, absorption was found to decrease with mass flux for f/4 plasmas, whereas f/7 plasmas showed a slight increase at low mass flux, then remained relatively constant with mass flux. The 5 kW f/7 plasma only showed signs of decreasing absorption near the plasma stability threshold. At low mass flux, the f/4 plasmas had higher absorption, but the trend quickly reversed as mass flux was increased and the f/4 absorption declined.

The thermal efficiency of f/4 and f/7 plasmas at 1 atm was found to be nearly the same for a given power plasma at all mass fluxes at which both f/4 and f/7 plasmas were stable. Efficiency increased with mass flux until the f/7, 5 kW plasma became unstable, at which point the f/4, 5 kW plasma continued to its peak efficiency of 39%. The 1 atm, f/4, 5 kW plasma could not be sustained at a mass flux greater than 48 kg/sm^2 (30.0 m/s).

Plasmas sustained at 2.5 atm argon pressure displayed higher absorption with higher laser power at all available mass fluxes, just as at 1 atm. However, no 2.5 atm plasma in this study could be made to become unstable by increasing the mass flux. Plasmas at both f-numbers and all laser powers were found to display increasing absorption with mass flux, whereas 1 atm plasmas either had steady or decreasing absorption.

Absorption at 2.5 atm was found to be in the range of 90% or greater as mass flux was increased to the highest available levels. Absorption was especially high for the f/4 plasmas, with a measured absorption of 97% for a 5 kW plasma, and 96% for a 2.5 kW plasma. These are by far the highest absorption percentages reported for laser-sustained argon plasmas.

The efficiency of 2.5 atm plasmas was found to increase with mass flux and decrease with laser power. The highest measured value of efficiency was 46% for a 2.5 kW f/4 plasma at 47 kg/sm^2 (11.7 m/s). This thermal efficiency is also the highest value reported and approaches the 50% laser propulsion feasibility limit.

Typically, the 1 atm plasmas were found to be more efficient than the 2.5 atm plasmas at mass fluxes where both were stable. However, the 2.5 atm plasmas are stable at much greater mass fluxes and have been shown to achieve efficiencies in excess of the highest 1 atm plasmas at some conditions. For instance, the 1 atm 2.5 kW, f/4 plasmas became unstable at 16 kg/sm^2 with an efficiency of only 32% as compared to 46% for the 2.5 atm, 2.5 kW, f/4 plasmas. At higher power and f-number, higher mass fluxes may be required in order to demonstrate this same effect.

In general, it appears that plasmas exhibit the best performance when operating close to the laser focus. That is, plasmas that tend to stabilize relatively far upstream in low laser intensity regions (e.g., high power and/or high pressure plasmas) require increased mass flux in order to optimize absorption and thermal efficiency behavior.

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