Laser Sustained Plasma Free Jet For The Generation Of Fast Atom Beam Of Interest In The Simulation Of Low Earth Orbit Environment

K. Amic*, J.D. Parisse+, A. Lebéhot*, and R. Campargue¶

*Laboratoire d'Aérothermique du CNRS, 1C Avenue de la Recherche Scientifique, 45071 Orléans, France
+ Institut Universitaire des Systèmes Thermiques Industriels, 13453 Marseille, France
¶CEA Saclay, 91191 Gif-sur-Yvette, France

Abstract. The plasma sustained by an infrared laser, upstream of a sonic nozzle, is used for the generation of a supersonic free jet. A fast atom beam is extracted from the axial part of the final stage of the free jet. As the expansion of the free jet is closely described by the classical isentropic laws, at least on the axis, an equivalent stagnation temperature T_0 can be deduced from the time-of-flight velocity distribution of the atom beam. In a similar way, the axial velocity at the nozzle throat V_{ax}* can be obtained from the mean velocity V_∞ of the atom beam. These data are compared with the values achieved from the calculation of the temperature and velocity fields of the plasma area, and of the free jet expansion. As an application, a fast oxygen atom beam is produced, and samples are exposed to its flux during 1 to 4 hours. Significant effects are observed on the surfaces and assigned specifically to the action of the oxygen atoms.

Keywords: atomic and molecular beam sources and techniques; plasma production and heating by laser; supersonic and hypersonic flows; SIMPLE numerical procedure; LCP-FCT numerical procedure; atom beam; atomic oxygen.
PACS: 39.10.+j; 52.30.-q; 47.40.Ki ; 52.50.Jm; 52.65.-y

INTRODUCTION

The fast atom beam extracted by a skimmer from a laser sustained plasma free jet has axial velocity distributions in quite good agreement with the usual Maxwellian distribution, solution of the Boltzmann equation for the expansion [1]. Also, this distribution is consistent with the model of a virtual neutral gas in isentropic expansion from stagnation conditions T_0, P_0 [2]. So, in spite of the very strong gradients in density, temperature, and velocity in the vicinity of the laser waist and near the nozzle throat, the expansion of the plasma behaves as though it was produced from a neutral perfect gas in equilibrium in the nozzle reservoir with uniform temperature T_0 and uniform pressure P_0. In this respect, the atom beam can be considered as a probe which reflects the properties of the plasma, inside the nozzle reservoir, where no other diagnostic is available. So, it is possible to compare the value of T_0, as obtained experimentally from time-of-flight measurements, with the axial temperature calculated at the nozzle throat, using the isentropic law [1]:

$$T_0 = T_{ax}^*\left(1+\frac{\gamma-1}{2}\right) \quad (1)$$

where the specific heat ratio γ is assumed to be constant. In a similar way, the measured mean velocity of the atom beam is the final longitudinal flow velocity V_∞ achieved at the skimmer entrance, which is related to the axial velocity at the nozzle throat V_{ax}* by [1]:

$$V_\infty \approx \sqrt{\frac{\gamma+1}{\gamma-1}} V_{ax}^* = 2V_{ax}^* \qquad (2)$$

These data, directly obtained from experimental measurements, can be compared with the calculated temperature and velocity fields of the plasma flow, through T_{ax}* and V_{ax}*, and also through the final value V_∞ calculated in the free jet. Two different calculation procedures are used. The first calculation is based on the SIMPLE procedure (Semi-Implicit Method for Pressure-Linked Equations) [3], and the second uses the LCP-FCT code (Laboratory of Computational Physics, Flux Corrected Transport) [4]. In a first step, they are applied to a pure argon expansion, but the LCP-FCT calculation can include the chemical dynamics of the plasma, and then be extended to a gas mixture, such as argon-O_2, which is used for the production of fast oxygen atom beams.

EXPERIMENTAL PROCEDURE

The experimental device was described previously [2, 5]. The scheme of the apparatus is represented in Fig. 1. The beam of a constant wave CO_2 laser (OPL 1501 from PRC Corporation, with maximum power 1500 W) is focused just upstream of a sonic nozzle (0.8 mm from the inside wall of the nozzle; nozzle diameter D* = 0.5 mm; nozzle wall thickness 0.5 mm). The plasma is ignited by a pulsed secondary CO_2 laser, or by an electric spark, and then maintained by the continuous laser alone (with W the power actually measured at the plasma location). The nozzle beam technique is based on the skimming in a free jet zone of silence unaffected by the background gas [6]. The distance between the nozzle and the skimmer tip is adjusted to 40-50 mm, in order to optimize the intensity of the extracted beam. The pressure P_0 in the nozzle reservoir is in the range 2-8×10^5 Pa; the pressure P_1 in the expansion chamber is maintained between 5 and 20 Pa by mechanical Roots pumps (4000 m^3 h^{-1}); after the skimmer, the pressure P_2 decreases to 10^{-4}-10^{-3} Pa, and becomes P_3 = 10^{-5} Pa in the third chamber. The quadrupole mass analyzer, used as a detector, is placed in the fourth chamber with pressure P_4 = 10^{-7} Pa. A high resolution time-of-flight device [7] allows the velocity distributions of the atom beam to be analyzed with mass selection, if needed.

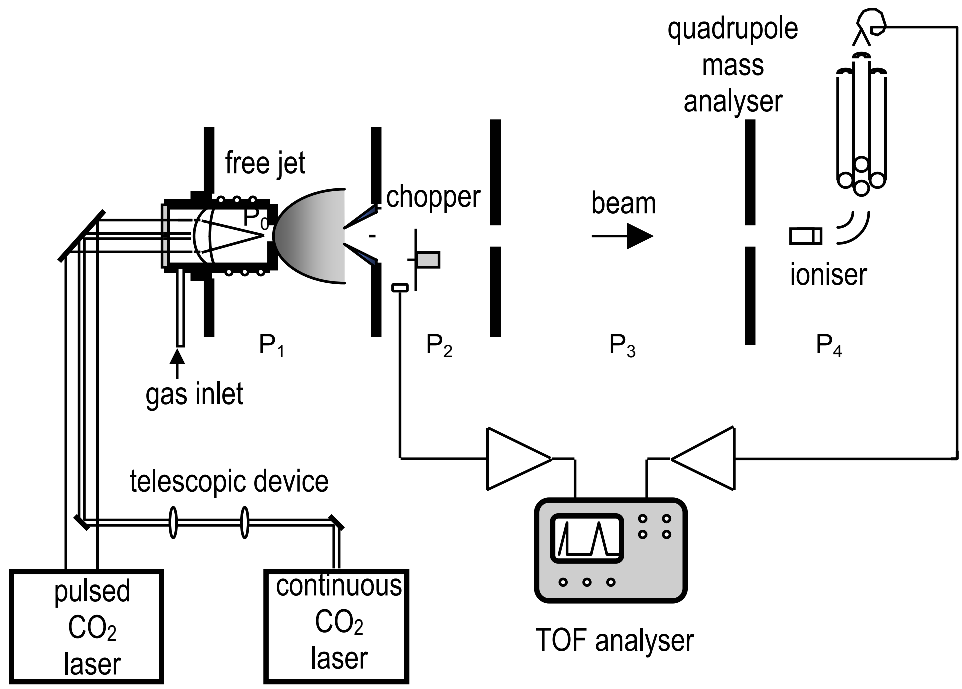

FIGURE 1. Scheme of the experimental device.

In order to check the numerical procedures, pure argon is first used as the test gas. Velocity distributions are measured for a lot of conditions (P_0, W), everything otherwise constant. A threshold line is observed in this reference frame, below which the plasma vanishes. In the stability region, the measured velocity distributions are fitted very accurately with Maxwellian distributions. In each case, the best fit gives an equivalent stagnation temperature T_0 and the final longitudinal translational temperature $T_{//}$ [2, 5].

NUMERICAL PROCEDURES

Calculation Based On The SIMPLE Procedure

This calculation is based on the procedure initially developed by Patankar [3]. The usual system of conservation equations is used and solved in cylindrical coordinates. The equation of density conservation is disregarded and replaced by a correction of the pressure field in order to minimize the error on the mass flow conservation, cell by cell. The action of the laser beam is added through an inverse bremsstrahlung absorption coefficient, assuming that the laser beam remains Gaussian. The medium is assumed to be in local thermal equilibrium. The calculation is stationary and limited to the subsonic region. The nozzle is then an open boundary where the sonic condition is applied to the axial velocity. No further condition is necessary here, except the fact that the sonic axial point must be fixed. This means that the nozzle wall must be assumed as infinitely thin. For each point (P_0, W), the corresponding mass flow rate, given by the experimental measurements, is applied at the entrance of the calculation area. The calculation procedure is first checked without laser power in order to compare the axial values with the usual isentropic data applied upstream of the nozzle [8]. The agreement is nearly perfect for Mach number, temperature, velocity, density, and pressure. When the laser power is applied, the absorption must be initiated by setting a small hot region around the waist of the laser beam (below about 10,000 K, the gas medium is transparent to the laser radiation and nothing occurs). In Fig. 2 is shown a temperature map together with the corresponding stream lines for the case $P_0 = 3\times10^5$ Pa, W = 330 W.

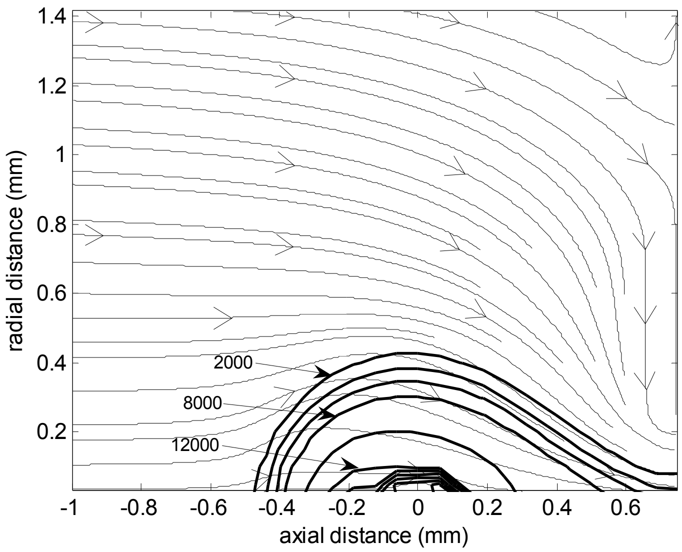

FIGURE 2. Contour plot of the plasma temperature (in K) superimposed with the streamlines of the flow field towards the nozzle. The laser waist is at axial distance z = 0. The distance of the nozzle wall is z = 0.8 mm. The radius of the nozzle orifice is r* = 0.25 mm. The conditions are: $P_0 = 3\times10^5$ Pa, W = 330 W. The SIMPLE procedure is used here.

Calculation Based On The LCP-FCT Procedure: Equilibrium Model

This calculation is based on the procedure initially developed at Laboratory for Computational Physics of Naval Research Laboratory [4]. This Flux Corrected Transport code is freely available. It is known for its robustness and versatility for many different situations. The Euler conservation equations are solved in a time dependent way. The procedure is valid for supersonic as well as subsonic conditions. The real thickness of the nozzle wall is taken into account, and extends between axial distances 0.8 and 1.3 mm, following the experimental design. The laser beam effect is introduced in the same way than in the SIMPLE calculation, but the time-dependent procedure allows an initial laser pulse to be simulated for the initiation of the plasma, as in the experimental conditions. A contour plot of the plasma temperature is shown in Fig. 3, for the same conditions as in Fig. 2.

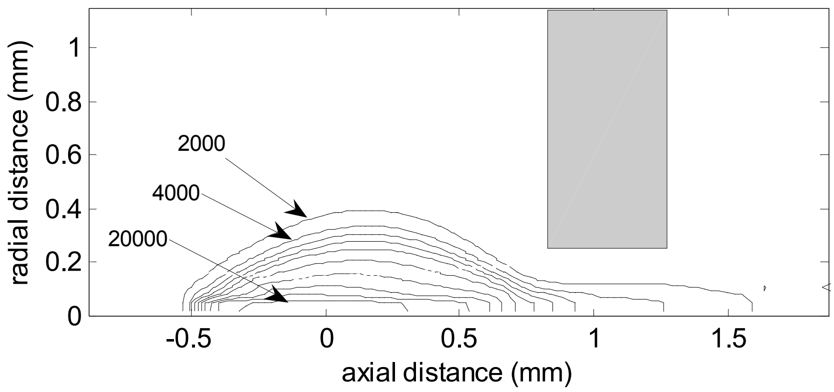

FIGURE 3. Contour plot of the plasma temperature (in K) obtained with the LCP-FCT calculation. The conditions are the same as for Fig. 2, with a nozzle thickness of 0.5 mm.

Calculation Based On The LCP-FCT Procedure: Non-Equilibrium Model

Here, the electrons are assumed to have a temperature different from the temperature of the heavy particles. Then, the energy conservation law is written separately for the electrons and the other particles (Ar, Ar^+), although the flow velocity is assumed to be the same for all particles. Ionization and three-body recombination are taken into account through the reaction:

$$Ar + e^- + E_{Ar} \rightleftarrows Ar^+ + e^- + e^-$$

The analytical forms for the direct and reverse reaction rates are taken, respectively, from Refs. 9 and 10. With these conditions, the ignition of the plasma is numerically described, step by step, provided that a small number of electrons are assumed to be present in each cell of the domain, at the beginning of the calculation. When the stationary state is achieved, it turns out that the temperature of the heavy particles remains far below the temperature of the electrons, even at the plasma core. This could be due to the assumption of the same flow velocity for electrons and heavy particles.

The main advantage of this model is that it includes, at least in a simplified form, the chemical dynamics of the plasma. Then, it should be possible to consider the case of a gas mixture, applied to the experimental situation where oxygen is added to argon in order to obtain a fast oxygen atom beam [11, 12].

COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL DATA

For each operating point (P_0, W), the best fit Maxwellian distribution, corresponding to the atom beam velocity distribution, gives the final velocity V_∞, and the equivalent stagnation temperature T_0. These values are compared with those given by the different calculation procedures. Also, by considering the points (P_0, W) for which the calculated plasma vanishes, it is possible to compare the calculated and measured threshold conditions. Finally, the mass flow rate of the nozzle is calculated by different ways: by integrating the calculated flow rate over the whole area of the nozzle, with each calculation procedure, and from the pumping speed of the vacuum system of the expansion chamber.

Equivalent Temperature T_0 and Final Velocity V_∞

The average error between calculated and experimental data is nearly the same for SIMPLE and LCP-FCT procedures, except close to the experimental threshold. This error is around 20 % for T_0, and 10 % for V_∞, for any laser power, except for W = 165 W (just above threshold), where it grows up to 25 % for SIMPLE, and 60 % for LCP (for T_0), and 13 % and 35 %, respectively (for V_∞). Fig. 4 shows a comparison for an intermediate laser power W = 330 W.

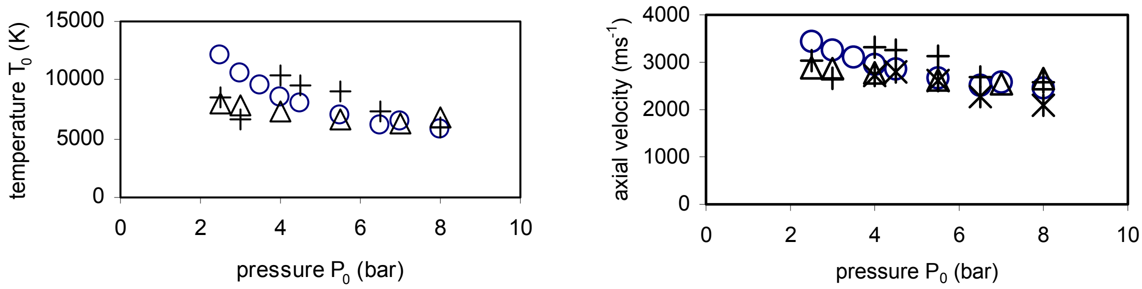

FIGURE 4. Comparison between the experimental data (○) and the calculated values for the SIMPLE procedure (Δ), and the LCP-FCT procedure (+) for laser power W = 330 W. For the velocities, the + correspond to the LCP-FCT procedure through Eq. 2, and the ж are the values of the velocity obtained at the end of the free jet expansion with LCP-FCT. It should be noticed that the error on the experimental points is smaller than the size of the symbols.

Laser Power/Gas Pressure Threshold For Plasma Maintenance

If , for a given operation point of the plasma, the gas pressure is decreased at constant laser power, the plasma vanishes at a given pressure. If the power is decreased at constant pressure, the plasma vanishes at a given laser power. The same phenomenon occurs with the calculations as well as in the experiments, and is connected to the bremsstrahlung absorption process. It appears that the threshold line obtained with the SIMPLE procedure is in fairly good agreement with the experimental values, except below 2.5 bars, where the experimental threshold increases drastically. The LCP-FCT threshold is in good agreement only above 4.5 bars. These data are reproduced in Fig. 5.

Mass Flow Rate

It is also possible to compare the mass flow rate deduced from the experimental conditions (pressure P_1 in the expansion chamber, and pumping speed), and the mass flow rate integrated over the nozzle surface with the calculation procedures. For the SIMPLE calculation, the calculated flow rates are always above the experimental values, with an average error of 44 %. With the LCP-FCT calculation (equilibrium model), the flow rates are always below the experimental values, with an average error of 37 %. It may be noticed that the number of cells along a nozzle radius is 16 for LCP, and only 6 for SIMPLE; this may influence the accuracy on the calculated flow rate through the nozzle.

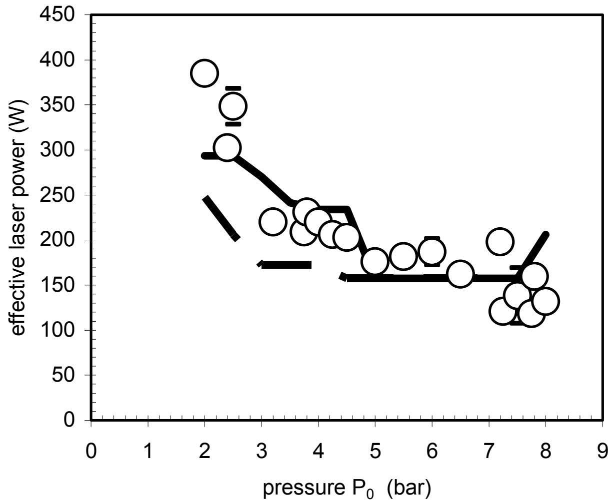

FIGURE 5. Comparison between the experimental threshold (○) and the calculated threshold for the SIMPLE procedure (full line), and the LCP-FCT procedure (dashed line). The statistic deviation on the experimental measurements is generally smaller than the symbols used, except when especially symbolized by upper and lower limits (–).

PRODUCTION OF A FAST ATOMIC OXYGEN BEAM AND TESTS ON SAMPLES

If the inlet gas is a mixture of oxygen and argon, a fast oxygen-argon atom beam is generated [11, 12]. The mean velocity of the oxygen atoms can be currently varied in the range 3000-5000 ms^{-1} with speed ratio $S_{//}$ between 7 to 15 (Fig. 6).

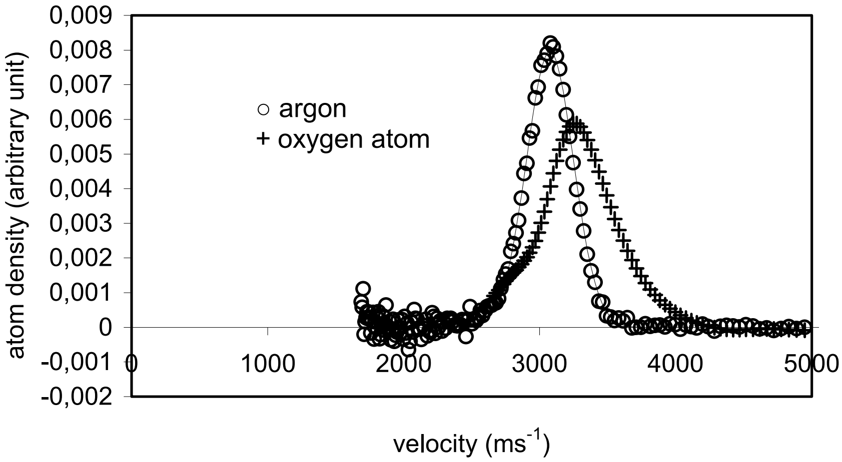

FIGURE 6. Time-of-flight velocity distributions measured for argon (○) and for oxygen atoms (+) for the conditions: inlet mixture: 33 % oxygen, 66 % argon; P_{0total} = 5 bars, W = 300 W. The best fit Maxwellian distribution for the argon velocity is given as a full line.

The atom flux in the beam is between 10^{20} and 10^{21} atoms $ster^{-1}$ s^{-1}. This corresponds to about 10^{16} atoms cm^{-2} s^{-1} at a distance of 2 m from the nozzle. In these conditions, it turns out that a sample of stainless steel, exposed to the beam flux during 1 h, presents a change of appearance (Fig. 7) which corresponds to a chemical modification of the surface, as confirmed by electron microscopy: carbon and silicon seem to be extracted up to the surface, where they appear finally as a coating. By comparing the electron microscope spectrum obtained on the exposed area with the spectrum obtained outside of exposure (see Table 1), it appears that iron and chromium are screened by the species which have grown in the spot: the decrease of iron and chromium is about 10 % while the increase of carbon is higher than 700 % and the increase of silicon is 75 %. The phenomenon is similar for a copper sample: Cu is decreased by about 8 % while carbon increases of about 100 %. Although it is not clear if such modifications concern the actual state of the material or the pollutants always present in normal conditions, it is important that an action of the oxygen atoms on the surface is clearly observed in a very short time. The same experiment, carried out with a pure argon beam operated in the same conditions, does not reveal any alteration of the surface (see Fig. 7). So, it can be expected that the argon component of the oxygen-argon beam has very little contribution in the observed phenomena. Then, the conditions encountered in the Low Earth Orbit (LEO) environment should be simulated very efficiently: 30 months at an altitude of 200 km correspond to an exposure of 24 h to the oxygen atom beam (but less than 1 h when the sample is at a distance of 30 cm from the nozzle instead of 2 m in the present case).

TABLE 1. Relative amplitudes of the main components of stainless steel and copper samples, as measured by electron microscopy out of the atom beam (reference), and in the exposed area.

	reference	**exposed area**		
Fe	123	111	-10 %	
C	6	50	+700 %	stainless steel
Si	4	7	+75 %	
Cr	18.5	16.5	-11 %	
Cu	147	136	-7 %	
C	3	6	+100 %	copper
O	4	5	+25 %	

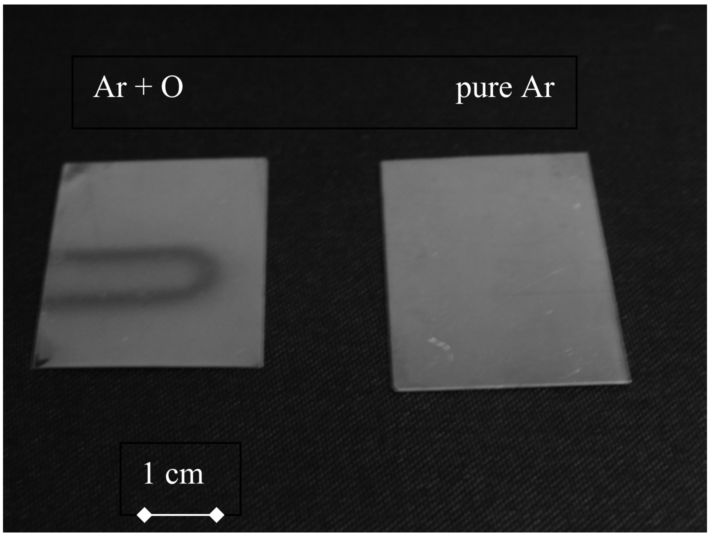

FIGURE 7. Left: sample of stainless steel after an exposure of 1 h to a beam containing 50 % of oxygen atoms and 50 % of argon atoms, at a distance of 2 m from the nozzle, with a velocity of 3200 m s^{-1} (inlet mixture: 33 % oxygen, 66 % argon; P_{0total} = 5 bars, W = 300 W). The shape of the spot is the exact projection of the beam collimator located between chambers 2 and 3, at 30 cm from the nozzle. Right: same conditions with pure argon.

CONCLUSION

The total device {laser sustained plasma/nozzle flow/free jet/atom beam} has been fully interpreted by comparing experimental data (mainly velocity distributions of the atom beam) with a calculated description of the plasma flow around the nozzle. Two different calculation procedures have been used: the SIMPLE procedure and the LCP-FCT procedure. Except for the flow rate, the results obtained with the SIMPLE procedure are generally slightly in closer agreement with the experimental data than the results obtained with the LCP procedure. Nevertheless, the LCP-FCT procedure presents important advantages: it can be operated in the supersonic as well as in the subsonic regions, and it can be extended to the case of gas mixtures.

This device can generate a fast oxygen atom beam able to simulate the conditions encountered in Low Earth Orbit environment and produce alterations of material surfaces in very short times.

ACKNOWLEDGMENTS

The authors wish to thank N. Gouillon and A. Pereira for their help in the experimental procedures, P. Echegut and E. Véron from “Centre de Recherche sur les Matériaux à Haute Température” for the analysis of the sample surfaces. They are grateful to Professors A.K. Rebrov and M.N. Ivanov for their kind support having permitted the presentation of the paper at the RGD 25 Symposium.

REFERENCES

1. D.R. Miller, “Free Jet Sources”, in *Atomic and Molecular Beam Methods*, edited by G. Scoles, Oxford University Press, New York, 1988, pp. 14-53.
2. J.M. Girard, A. Lebéhot, and R. Campargue, J. Phys. D: Appl. Phys. **26**, 1382-1393 (1993).
3. S.V. Patankar, Num. Heat Transfer **4**, 409-425 (1981).
4. J.P. Boris, A.M. Landsberg, E.S. Oran, J.H. Gardner, “LCPFCT Flux corrected transport algorithm for solving generalized continuity equations”, Laboratory for Computational Physics and Fluid Dynamics, 1993.
5. A. Lebéhot and R. Campargue, Phys. Plasmas **3**, 2502-2510 (1996).
6. R. Campargue, J. Phys. Chem. **88**, 4466-4474 (1984).
7. R. Campargue, A. Lebéhot, J.C. Lemonnier, and D. Marette, “Measured, Very Narrow Velocity Distributions for Heated, Xe and Ar-Seeded Nozzle-Type Molecular Beams of He and H_2 Skimmed from Freejet Zones of Silence; Xe Energies up to 30 eV”, in *Rarefied Gas Dynamics*, edited by S.S. Fisher, American Institute of Astronautics and Aeronautics, New York, 1981, pp. 823-843.
8. J.B. Anderson, “Molecular Beams from Nozzle Sources” in *Molecular Beams and Low Density Gas Dynamics*, edited by P.P Wegener, Marcel Dekker, New York, 1974, pp. 1-91.
9. Y.B. Zel’dovich and Yu.P. Raizer, *Physics of Shockwaves and High Temperature Hydrodynamic Phenomena*, Academic Press, New York and London, 1966.
10. J.J. Beulens, D. Milojevic, D.C. Schram, and P.M. Valinga, Phys. Fluids **B3**, 2548-2557 (1991).
11. A. Lebéhot, J. Kurzyna, V. Lago, M. Dudeck, and M. Nishida, Phys. Plasmas **6**, 4750-4758 (1999).
12. A. Lebéhot, J. Kurzyna, V. Lago, M. Dudeck, and R. Campargue, “Laser Sustained Plasma Free Jet and Energetic Atom Beam of Pure Argon or Oxygen Seeded Argon Mixture”, in *Atomic and Molecular Beams, The State of the Art 2000*, edited by R. Campargue, Springer, Berlin, 2001, pp. 237-251.