ABSTRACT

Orbiting space vehicles operating at altitudes below 1000 km (i.e. low earth orbit LEO) are subject to impact by atmospheric species. Within the altitude range ~100 to 900 km the dominant species is atomic oxygen (O1). The velocity of the vehicle through this atmosphere results in an impact velocity of 8 km/s; the flux (altitude sensitive) is typically 10^15 atoms/cm^2/s within the shuttle-orbit. Electric propulsion techniques, yielding velocities of the same order are thus appropriate for sources attempting to simulate the LEO environment. Discussion of the Southampton Arc Jet Atomic oxygen source and its performance are covered, with particular relevance to improving Atomic Oxygen flux and Velocity.

1. INTRODUCTION

Generation of intense high velocity atomic oxygen beams has been the objective of the space community since the early space missions. It was noticed that atomic oxygen gas-surface interactions played a significant role in both aerodynamic drag on a satellite and in surface degradation; however it is only since the advent of shuttle flights that the particularly damaging effects caused by atomic oxygen have been apparent.

Atomic oxygen provides the dominant species for momentum exchange (hence drag and attitude torques) up to an altitude of 900 km; significant mass from the central core of an isentropic expansion (altitude sensitive) is typically 10^15 atoms/cm^2/s within the shuttle orbit. Electric propulsion techniques, yielding velocities of the same order are thus appropriate for sources attempting to simulate the LEO environment. Discussion of the Southampton Arc Jet Atomic oxygen source and its performance are covered, with particular relevance to improving Atomic Oxygen flux and Velocity.

Erosion of space vehicles surfaces and payloads is of prime concern, causing such effects as degradation and failure of thermal control surfaces, optical glow and contamination of the near space-craft environment(1). Preliminary testing of materials non-resistant to high fluxes of O1 is already underway for many planned missions. For instance science payloads, such as ROSAT(2) may be particularly sensitive. Indeed impact by reaction products on some surfaces may be crucial. With the planned operation of the International Space Station and the incumbent long term use of Low Earth Orbit for manned and unmanned operations, the ability to predict the behaviour of vehicle surfaces in this highly reactive and corrosive atmosphere has to be undertaken.

It is evident that from a review of the literature associated with the effects of atomic oxygen that both velocity and flux are important parameters in the determination of gas-surface reactions. The work of Giani et al(3) shows that flux can have a significant influence if chemically enhanced sputtering occurs. Further the velocity of impacting species plays a crucial role with regard to the dynamics of the gas-surface interaction, as can be seen from the laboratory based results on shuttle glow. Thus far only a few laboratories have been able to promote these radiative effects associated with atomic oxygen.

This report discusses Southampton's experience in operating an Arc heated source. Results will be presented for the source's performance with respect to O1 production efficiency and acceleration. Discussion on the source's limitations in performance will also be covered. In addition a brief review of other methods will enable conclusions to be drawn on future prospects for better O1 simulation.

2. EXPERIMENTAL APPARATUS

The experimental facility generates atomic oxygen by the use of a continuum beam source. This is derived from the central core of an isentropic expansion exhausted from a high pressure source into vacuum to form the molecular beam.

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tungsten rod welding stock and is silver soldered to the same size copper pipe for electrical and cooling services. The Body houses a copper anode of annular space charge effects). The Body is connected to the positive terminal of a conventional 8kw welding supply via water cooled power cables. The arc is sustained internally (non-transferred mode) so as to optimise production of neutral, ground state species, via expansion from a nozzle. Normal residence times of heated gas prior to expansion are about 5ms, so as to remove inadequate quenching out of ionic and excited species.

High energy heavy specie particle generation is accomplished via the 'seeding' technique. Section 2.1.7 uses a light carrier gas (He) to provide the necessary high velocity free jet expansion for beam formation. The heavy gas is introduced as a minor constituent downstream of the arc (so as not to oxidize the electrodes). The heavy gas expands close to the light gas velocity, with some velocity slippage occurring. With beam enrichment, a high percentage of beam flow can consist of the heavy specie.

2.1 Atomic Oxygen Generation Techniques

The conventional method of generating atomic oxygen in Arc heaters utilises molecular oxygen as the minor constituent injected downstream of a high temperature Helium flow. This method has been used in the Southampton source but recently other seed gases have been investigated with a view to increasing the O$_1$ yield in the source and hence the resultant molecular beam. The injection of O$_2$ as source gas for O$_1$ has been used in various Arc heated facilities(6,7), and although producing high flux levels, is seen not to be fully dissociated in a pure Helium flow. In fact Silver et al(7), added Argon gas at very high arc power levels to realise full dissociation. This is by virtue of Argon’s lower thermal diffusivity and hence higher nozzle exit temperatures. The disadvantages of operating with even a small percentage of Argon is the resultant increase in the bulk mixture molecular weight and hence decrease in attainable exit speed. This effect can clearly be seen in reference 7. This is where the direct molecular oxygen route may suffer in comparison to other chemical routes such as the Nitrous Oxide/Nitrogen reactions detailed below.

2.2 Instrumentation - Flow Characterisation

The necessary information needed to adequately characterise a molecular beam requires both knowledge of individual specie concentration and velocities. Absolute values of Flow velocity, although desirable are hard to achieve with any certainty, due to the extensive calibration procedures needed in the number density measuring device. With Mass Spectroscopy, care has to be taken in subtracting the contribution of O$_1$ signal from cracked parent ions. Furthermore, the corrections used to account for differing collision cross sections in an electron bombardment detector will also contribute to the overall error(8). Other effects such as O$_1$ recombination on the ioniser inlet will add to the problem. Thus extreme care has to be taken when basing flux measurements solely on mass spectroscopic measurements, and indeed an accurate citation for spacecraft borne mass spectrometers confirms these fears(9).

Measurements of the molecular beam were accomplished by two methods. In the first instance, flux values were based on mass spectroscopic measurements, accompanied by the standard correction formula due to Sibener et al(10). An alternative approach involved the use of velocity discrimination to decrease the uncertainty in discriminating between beam and thermal background. This made use of a Cylindrical Mirror Analyser (CMA) (VG Quadrupoles) electrostatic energy filter located on the front end of the mass spectrometer with a low emission ioniser (to minimise space charge effects). A schematic of both can be seen in figure 3. The CMA is able to scan energy with intensity at a constant filter transmission, irrespective of filter energy. The resultant scans will be a convolution of the measured energy distribution and CMA response. Typical results for the CMA/Mass analyser combination provide both mass and energy filtering, with a typical overall transmission shown in figure 4, with beam flag on and off. This particular scan shows the nitrogen molecules accelerated in a Helium beam. Note the large thermal background peak in comparison to the 1.7 eV beam peak. Of interest is the difference in thermal background in both blocked and unblocked cases. This would cause an under estimation of beam dissociation with just using the Mass Spectrometer.

3. SOURCE PERFORMANCE

The Arc heater in Southampton differs from earlier Arc heated O$_1$ generation techniques, in both gas flow rate and arc power. Helium is used as the working gas in the South Hampton source, operating at approximately 10 mb/s, or about 0.6 g/min mass flow. This scales as a factor of 1/30 the flow speed of the other sources with a consequent drop in necessary pumping speeds to maintain an adequate background vacuum. Arc power is in the range of 1.5 to 3 Kw and thus reduces the costs of DC a power supply.

With both the gas flow speeds and arc power scaled down it is still possible to produce Helium average nozzle exit temperatures in the 1500 K range. This produces a beam velocity of 3 to 4 kms depending on arc power (current); this relationship can clearly be seen in figure 5, which shows Helium energy versus arc current. A typical CMA energy scan of the Helium beam is shown in figure 6.

A thermal breakdown of heat losses to the various components can be seen in figure 7, this particular operating point yielding a thermal efficiency of 17.5%. The relatively low efficiency is due in main to the high thermal diffusivity of Helium gas and the long residence time in the nozzle. This limits the maximum attainable expansion velocity to no greater than about 5 kms for Helium unless either the nozzle is shortened or a lighter carrier gas is used. In both cases this would be impractical, due to the necessity for neutral, ground state specie and the reactivity of a lighter gas (Hydrogen) to oxygen.

Intensities of a pure Helium beam 0.5 metre downstream of the source have been estimated at 1017 at/cm$^2$/sec. Production of atomic oxygen via molecular oxygen provides approximate values of O$_1$ fluxes of 0.5 x 1014 at 0.1 ms/sec and 0.1 ms downstream of the source. This has been estimated by a combination of both mass spectroscopic/CMA measurements and by the rate of degradation of Carbon in the beam compared to orbital and other experimental data.

An alternative seed gas N$_2$O was also utilized. Collisional dissociation of this species produces, N$_2$, O, O$_2$ and NO at the source temperature. All of these species are evident to some extent in the earth’s upper atmosphere.

Typical relative percentages and average species energies of the seeded N$_2$O and O$_2$ route are provided in table 1 with the raw data from the CMA/Mass spectrometer combination seen in figure 4.

Additional gains in O$_1$ production with the Nitrous Oxide method have also been acheived by injection of Molecular Nitrogen through the 1.7 eV arc. Atomic Nitrogen is produced, which when mixed with the N$_2$O reactive
ionised gas is accelerated by electrostatic means.

Ion acceleration devices are widely used, but suffer from several problems. The main problem is providing an intense enough ion beam at low ion energies. Acceleration to 5eV (O\(_1\) at 8 km/s) provides space charge limitations on available beam intensity. In addition, neutralisation of the ion beam further reduces intensity. With all these factors, a typical charge exchanged ion beam of O\(_1\) at 5eV and probably not exceed much in excess of 10\(^{13}\) at/cm\(^2\)/s, a flux much lower than needed to adequately model typical space station altitudes. However, the advantages include a lower gas load on a vacuum system than a nozzle source and a large beam area.

Nozzle type sources, use the random thermal motion of a heated gas to provide the kinetic energy for the O\(_1\) beam. In addition the high temperatures generated in the source provide the O\(_1\) usually by dissociation of O\(_2\). However, acceleration to 8 km/s requires very high gas temperatures in the source, and for pure oxygen would require temperatures of 8000 K, not readily obtainable with most means. Thus the seeding technique is widely used, primarily using Helium as the carrier gas. Most improvement in this area of beam generation has concentrated on raising source temperatures and hence O\(_1\) velocity. Fluxes of O\(_1\) generated are high and comparable to or in excess of those encountered at LEO altitudes. Types varying from Arc heaters, RF/Microwave heating, Resistance heating to Laser discharge heating all provide varying degrees of O\(_1\) velocity range. Most recently, the Laser discharge sources have demonstrated the capability of achieving 8 km/s\(^2\). Disadvantages include the need generally for high pumping speeds unless the system is pulsed and the lower than orbital velocities for most of the methods. The pulsed laser source of Caledonia meets the twin requirements of velocity and flux, but uncertainties as to the effect of having peak fluxes greatly in excess of orbit may be a problem.

5. CONCLUDING REMARKS

The development of a low power, high fluence Arc heated source of atomic oxygen has been undertaken. Two routes to produce O\(_1\) have been investigated: Direct dissociation of molecular oxygen and through the chemical dissociation of N\(_2\)O both by Arc Heated Helium. Both produce high fluxes of O\(_1\) comparable to that of low earth orbit, but there are limitations on available beam energy with this route as experienced with our system. Other sources provide alternative methods of beam production, with only a couple of sources adequately meeting the twin requirements of beam flux and velocity. It can be seen that future attempts to produce more reliable and easier methods generating of O\(_1\) and other high energy specie production will encompass much of the electric propulsion technology used primarily for spacecraft applications.

ACKNOWLEDGEMENTS

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4. ALTERNATIVE SOURCES OF O\(_1\)

Various other methods of producing O\(_1\) beams have been used. The source discussed here are confined to those that produce O\(_1\) above thermal energies, thus ruling out such types as effusive sources.

There are basically two ways to approach the problem of high energy O\(_1\) production. The first uses a gas's random thermal energy and converts this into directed kinetic energy via nozzle expansion. Alternatively an
REFERENCES


2. Pye J.P. "The XUV Wide Field Camera ROSAT" COSPAR XXVI, Symp no. 7 on UV Space Astronomy.


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Figure 1: Molecular beam facility

Figure 2: Arc Heater

Figure 3: CMA - Quadrupole Mass/Energy filter

Figure 4: Nitrogen Blocked/Unblocked beam signal
Figure 5: Arc Current V Beam Energy (He)

Figure 6: Helium beam energy distribution measured by CMA/Mass filter combination

Figure 7: Arc Heater Thermal Losses

Figure 8: Optical photograph at 100X magnification of Lexan film exposed to O₂ beam. (Courtesy of RAL, UK)
Figure 9: Nitrous Oxide seeded in Helium, with and without added Nitrogen.