DESIGN AND DEVELOPMENT OF A HYPER-THERMAL ATOMIC OXYGEN WIND TUNNEL FACILITY

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ABSTRACT

A hyper-thermal orbital aerodynamics test facility is described. The Rarefied Orbital Aerodynamics Research facility (ROAR) is a dedicated apparatus designed to simulate the atmospheric flow in very low Earth orbits (VLEO) to investigate the impact different material properties have on gas-surface interactions, and determine the aerodynamic properties of materials from the reemitted gas distribution. The main characteristics observed in VLEO to be reproduced are the free molecular flow regime and the flux of oxygen atoms at orbital velocities impinging on the spacecraft surface. This is accomplished by combining an ultra-high vacuum system with a hyper-thermal oxygen atoms generator. Materials performance will be assessed via a scattering experiment in which an atomic oxygen beam is incident on the surface of a test sample and the scattered species are recorded by mass spectrometers. The design of the experiment is discussed, from the specification of the vacuum components to the generation of oxygen atoms and their detection.

INTRODUCTION

Atomic oxygen is the predominant atmospheric constituent between 200 km and 450 km altitude. This region is defined as very low Earth orbit (VLEO), where aerodynamic effects have a significant impact on the design of space systems. Resultant from the dissociation of oxygen molecules by ultra-violet radiation, the oxygen atoms, usually on their ground state $O(^3P)$, are extremely reactive and represent a challenge for spacecraft due to material degradation through etching and erosion. Material resistance to atomic oxygen (AO) has been an active research area with both on-ground [1]–[3] and in-orbit tests being performed specially in polymers and composite materials [4]–[8].

At altitudes around 300 km, the AO flux on ram surfaces is around 10^{19} atoms m^{-2} s^{-1} with an average kinetic energy of 4-6 eV, considering thermal energy of the O atoms and their relative velocity to the spacecraft. The material's response to this environment is governed by the gas-surface interactions (GSI), the mechanisms through which one reacts to the other, and how they are influenced by exposure conditions [9]–[12]. A clear understanding of these mechanisms would be proven invaluable to the search of novel, better suited materials, contributing significantly to development of new technologies and applications in the VLEO region.

The materials investigation is currently done following two different approaches, either through on-ground experimental facilities or via in-orbit tests. Although the latter provides real response to the environment, it is still rather expensive and limited in terms of access to it. On-ground facilities, on the other hand, are more cost effective and can provide quicker feedback on the material's suitability to VLEO conditions. However, a great majority of the efforts are still focused on evaluating the material's resistance to erosion, not considering specifically the physical and chemical processes leading to observed behaviour, or the flux distribution of the reemitted flow.

It is in this scenario that DISCOVERER looks to bring its major contributions by exploring this gap, and as part of such project a new experimental ground facility is being developed. In this paper we will describe the general design of such apparatus, its role within the project and its contributions to field.

DISCOVERER PROJECT

DISCOVERER is a €5.7M, 4¼ year Horizon 2020 funded project which aims to revolutionize Earth observation (EO) by operating satellites at much lower altitudes than usual [13], [14]. EO data and service market is estimated to reach \$8.5 billion by 2026 [15] according to Euroconsult and is comprised of different strategic sectors, like maritime surveillance, intelligence and security, food security and land management, among others.

Orbiting closer to the Earth allows satellites to be smaller, lighter and less expensive without compromising data throughput or image resolution[16]–[18]. However, at reduced orbital altitudes drag forces become significant, thus reducing considerably orbital lifetimes. DISCOVERER's main objective is to address this issue through fundamental research in three key fronts, (i) aerodynamic characterization of materials with the aim to identify alternatives that minimise drag, (ii) active aerodynamic control methods and (iii) atmosphere breathing propulsion for drag-compensation.

To address these subjects, the University of Manchester is building this unique experimental facility for orbital aerodynamics tests of materials. ROAR is an ultra-high vacuum hyper-thermal atomic oxygen experiment dedicated to identifying novel materials with more attractive properties for applications in very low Earth orbits, like promoting specular reflection of the atomic oxygen (AO) beam. This will be achieved through a better understanding of the gas-surface interactions between the test samples and the atomic oxygen beam that simulates the natural orbital environment conditions. This experimental apparatus plays a key role in the DISCOVERER project as it contributes directly to the three scientific motivations. It is the main tool for material identification and its findings will be validated in real orbital environment by a Satellite for Orbital Aerodynamics Research (SOAR) to be launched in 2020 as part of the DISCOVERER project[13][14][19]. The data provided by SOAR will be interpreted and correlated to those acquired by ROAR and used to improve the experiment's reliability, and understand any differences caused by other environmental factors not reproduced by ROAR. Furthermore, the facility will be used to test different intake geometries for the atmosphere breathing electrical propulsion [20], [21], thus supporting the scientific development of DISCOVERER as a whole.

ROAR is truly a singular experiment, the first of its kind in the UK and the one of the very few in the world designed to provide detailed data on the gas-surface interactions (GSI) governing the material behaviour when exposed to a hyper-thermal atomic oxygen beam. ROAR features and technical specifications also represent a special platform where further developments will bring orbital aerodynamics tests to unparalleled levels. This paper discusses the design of such facility, including the vacuum system, the AO generator and detection.

RAREFIED ORBITAL AERODYNAMICS RESEARCH (ROAR) FACILITY

As previously stated, ROAR's objective is to *simulate environmental conditions at very low Earth orbits* to *characterise the gas-surface interactions*. Although there are a few atomic oxygen facilities investigating the erosion of materials caused by AO[22]–[25], not many of them are actually interested in understanding the mechanisms behind the gas-surface interactions. In that sense ROAR represents quite a singular experiment focused on characterising the AO interaction with the sample by providing an angle-resolved map of the scattered/emitted particles.

A fundamental characteristic of ROAR is its concern in guaranteeing that the GSI will take place in similar flow regime of that found in VLEO, *i.e.* free molecular flow (FMF). Different flow regimes will directly affect the interactions between the AO beam and the sample, which could possibly compromise the experiment results and their interpretation. Therefore, in order to correctly simulate the environment two features are required, (i) the correct flow regime, in this case FMF and (ii) AO beam properties similar to those experienced by the spacecraft when in orbit. The next sections will describe the system design, starting from the vacuum system responsible for attaining free molecular flow, then the atomic oxygen generator and the detection system for GSI characterisation.

2.1 Vacuum system

One of the main characteristics of ROAR is the concern to keep FMF during the entire experiment. When considering flow regimes the basic physical quantity of interest is the mean free path (λ), which corresponds to the average distance travelled by a moving particle between two consecutive collisions. It is related to the pressure (P) and the gas under consideration (via its effective cross-section, πd_0^2), and is given by the following equation:

$$\lambda = \frac{k_B T}{\sqrt{2}\pi d_0^2 P}$$

where k_B is the Boltzmann constant and T the gas temperature. FMF is attained when λ is much greater than the particle's typical dimensions.

Another way of characterising flow is via the Knudsen number, K_n, a dimensionless parameter defined as the ratio of λ to the system's typical dimension (l). In this case free molecular flow is commonly defined by $K_n>10$. In the case of orbital aerodynamics it has been demonstrated though that the concentration of particles near the surface can be considerably higher than that found further away (freestream) due to the largely thermally reemitted flow at lower velocities from the surface. Therefore a local Knudsen number can be defined that employs a local mean free path instead. Direct simulation Monte Carlo has demonstrated that due to local changes in particle density, higher Knudsen numbers (>1000) should be considered when FMF conditions are required [26].

The graph in figure 1 depicts the system's pressure and mean free path for a flux of 10^{19} atoms m^{-2} s^{-1} at the sample considering two different emission profiles, a collimated beam and cosine emission. The region of interest was defined for a K_n larger than 10^4 and determines a minimum pumping capacity of 12.5 m^3/s. The upper limit of 60 m^3/s was adopted taking into consideration the range of pumps available, their costs and dimensions. The experiments are expected to be operated at pressures around 10^{-7} Pa (for a collimated beam), which gives a K_n varying from $2.5 \cdot 10^4 – 8 \cdot 10^6$.

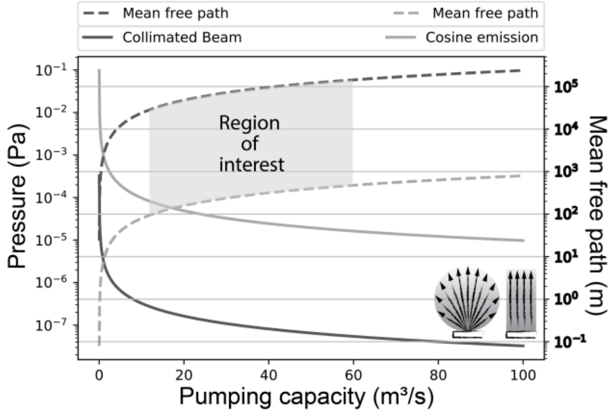

Fig. 1. Pressure and mean free path as a function of pumping capacity for two different emission profiles, cosine emission (inset left) and collimated (inset right). The region of interest is obtained for a minimum K_n of 10^4, defining a lower limit for the pumping of 12.5 m^3/s.

Another important feature when designing the vacuum system is the residual atmosphere desired in the chamber and the gases to be pumped during the experiments. For aerospace applications it is important to have what is considered a clean vacuum, *i.e.* free of hydrocarbons and therefore oil free pumps are preferred[27]–[30]. Such requirements are satisfied by a combination of turbomolecular and cryopumps. However, due to the possible reactions between the sample and the AO beam it is important also to consider vacuum pumps more suitable for pumping reactive gases. Non-evaporable getter (NEG) pumps are the choice to conclude the ultra-high vacuum system. For primary pumps Roots are the most adequate option as they are oil free and provide good pumping capacities.

As for the chamber design, it was opted to have a two chamber configuration, one for sample exchange/storage (loadlock chamber) and a main chamber where the experiments will take place, housing the UHV vacuum pumps and the detectors. This concept is to secure a more practical procedure when loading/unloading samples, therefore minimising the UHV chamber exposure to contaminants. A simplified overview of the system can be seen in figure 2.

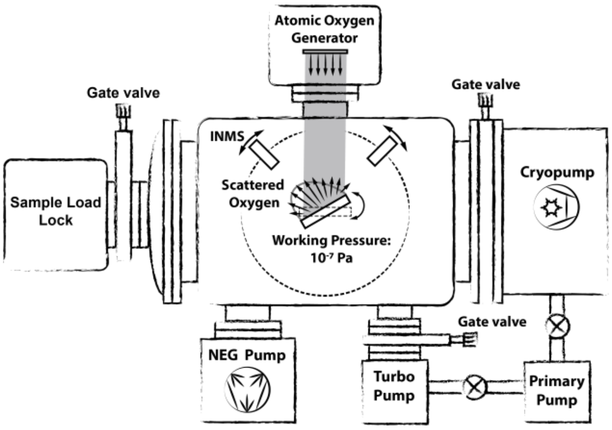

Fig.2. Simplified scheme of the Rarefied Orbital Aerodynamics Research (ROAR) Facility depicting the vacuum system and the experiment's main components like the AO generator and the detector (INMS).

The chamber's geometry and pump locations are tested using Monte Carlo simulations [31]. Figure 3 illustrates the simulation results for the main chamber, with a pumping capacity of 37 m^3/s (given by 3 cryopumps, $10 m^3/s$ each and two NEG pumps 3.5 m^3/s each) and a flux of 10^{19} atoms m^{-2} s^{-1}. It depicts the pressure change along the chamber and can be used to corroborate the pressures range from figure 1.

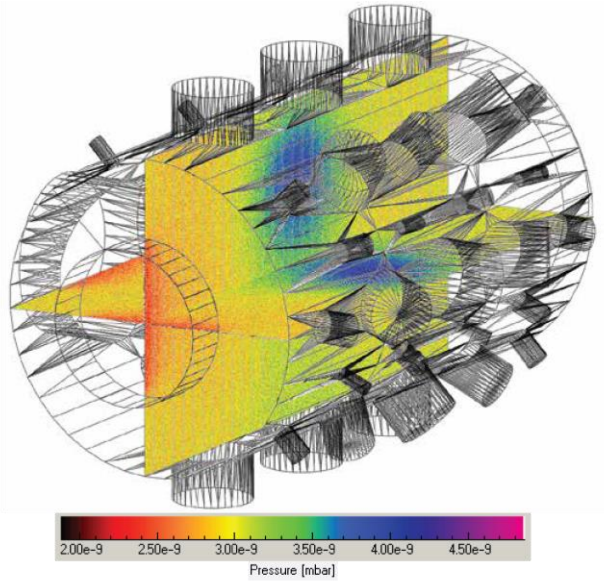

Fig.3. Example of pressure profile of the main chamber calculated via direct simulation Monte Carlo [31]. These simulations are used to evaluate chamber geometry and pressure gradients for different configurations of vacuum pumps.

2.2 Hyper-thermal atomic oxygen generator

There are many different techniques to produce a beam of oxygen atoms with energy distribution varying from thermal to hyper-thermal velocities. Each method is more suitable depending the energy of interest, for instance hyper-thermal velocities are usually obtained from ionisation of the species, followed by an acceleration stage and then production of neutrals by charge exchange with a target gas. On the other hand, when lower velocities are desired, supersonic nozzle expansion or freejet are mostly applied. A review of different AO sources is provided by J. Kleiman *et al.*[25].

Each different source has its own limitations, either on the average kinetic energy of the produced atoms, percentage of neutrals to ions or flux. Among the sources discussed, the only source producing a beam of 100% neutral O atoms with kinetic energy between 4-6 eV is one based on electron stimulated desorption (ESD). This source was developed by G. B. Hoflund *et al.* [32]–[34] and will be described in more details as it will be applied in ROAR.

The hyper-thermal oxygen atoms generator (HOAG) basic principle can be described in five steps (figure 4 inset). A silver membrane is used to separate the ultrahigh vacuum region from the oxygen supply. Oxygen molecules adsorb and dissociate at the silver membrane surface and through permeation reach the UHV side. An electron beam is then used to stimulate the oxygen atoms to desorb from the surface, thus creating an AO beam.

The reported flux of O atoms from this source based on mid-1990's designs is around 10^{17} atoms m^{-2} s^{-1}. The source has been redesigned and will be optimised to provide an increased flux of upto10^{19} atoms m^{-2} s^{-1}. A scheme of the new design is shown in figure 4. The produced beam will be fully characterised using the detection system designed for experiments in ROAR (section 2.3). Parameters like beam profile, energy distribution, composition, ion to neutrals ratio, stability and flux will be quantitatively determined.

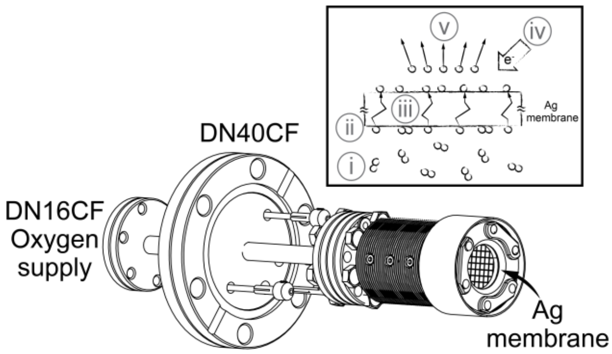

Fig. 4. Schematics of the hyper-thermal oxygen atoms generator (HOAG), the chosen AO source for the project. Inset figure shows the physical concepts involved in the production of AO, an oxygen supply is provided to one side of the silver membrane (i). The molecules adsorb and dissociate at the membrane's surface (ii) and through permeation (iii) reaches the ultra-high vacuum side of the membrane. An electron beam is used to promote the desorption of the atoms form the surface (iv) thus creating an AO beam (v).

2.3 Detection system

ROAR's detection system is comprised of two ion-neutral mass spectrometers (INMS) and a residual gas analyser (RGA). These mass spectrometers are similar to those installed on SOAR and are responsible for characterising the incoming AO beam and the scattered particles.

Figure 5 provides a simple schematic of the INMS main components. Particles enter the detector through an aperture of collection angle <5 degrees and go to an ion filter responsible for selecting the type of particles being measured, neutrals or ions. The next stage is an ioniser where an electron shower ionises the neutral particles and the particles follow to the time-of-flight and the detector and their energy and velocity are measured.

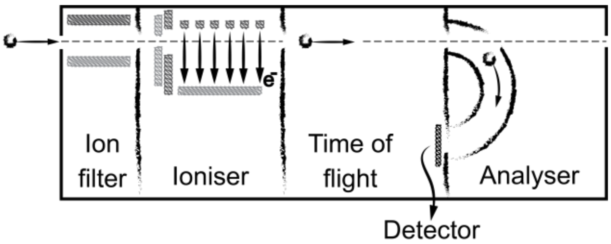

Fig.5. Schematics of the sections composing the ion-neutral mass spectrometers (INMS) applied in ROAR. They are the main tool for the characterisation of the gas-surface interactions.

The INMS will be calibrated against the RGA using the background. Differently from the model employed in the SOAR satellite, the mass spectrometers for ROAR will have a wider dynamic range of energy, going from around 10 meV (room temperature kinetic energy) to 4-6 eV (hyper-thermal kinetic energy), which will require a pulsed mode of operation.

The sensors will be mounted on a moving stage that will cover the entire hemisphere above the sample surface, providing a full map of the scattered particles. This setup will also be used to characterise the incoming AO beam.

2.4 Experimental facility

As described in section 2.1, ROAR is comprised of two different vacuum chambers, the main chamber where experiments are performed and is kept under UHV pressures, and the load lock chamber used for sample exchange and storage, being kept in high vacuum pressures only. As explained, this is to make the whole operation more efficient, minimising the UHV chamber exposure to higher pressures and contaminants.

To ensure that samples and payloads are manipulated in a proper environment, an ISO-7 cleanroom will be installed in the laboratory. The ROAR load lock chamber is situated inside the cleanroom while the UHV chamber will be in a normal laboratory area (figure 6). This ensures that normal operation during experiments are performed in a less restricted area while keeping the manipulation of more sensitive material to the controlled environment provided by the cleanroom.

The cleanroom extends ROAR's application to payload tests and considering the chamber's versatility for future upgrades, as it is expected ROAR will be further upgraded maintaining it as a unique test facility.

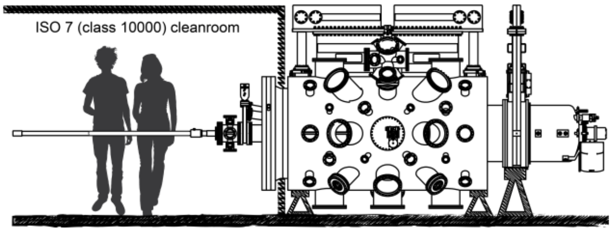

Fig.6. Schematic of the ROAR facility depicting the system's interface with an ISO-7 cleanroom for manipulation of samples and payloads.

CONCLUSIONS

DISCOVERER is an ambitious project that intends to transform satellite design concepts in VLEO. It will identify, characterise and develop new materials for low drag satellites, design and test aerodynamic orbital manoeuvres and propulsion methods for drag compensation. As part of the project a new experimental setup is being designed, the Rarefied Orbital Aerodynamics Research (ROAR) Facility and will be operational in 2019. ROAR will reproduce the atomic oxygen conditions found in VLEO while keeping free molecular flow regime to investigate gas-surface interactions. The system is comprised of ultra-high vacuum chambers, an atomic oxygen source based on electron stimulated desorption and mass spectrometers. Fluxes of the order of 10^{19} atoms m^{-2} s^{-1} are expected and experimental results will consist of angle-resolved maps of the particles scattered by the sample.

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