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ROAR -- A Ground-Based Experimental Facility for Orbital Aerodynamics Research

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Abstract

DISCOVERER is a European Commission funded project aiming to revolutionise satellite applications in Very Low Earth Orbits (VLEO). The project encompasses many different aspects of the requirements for sustainable operation, including developments on geometric designs, aerodynamic attitude and orbital control, improvement of intake designs for atmosphere breathing electric propulsion, commercial viability, and development of novel materials. This paper is focused solely on the description of the experimental facility designed and constructed to perform ground testing of materials, characterising their behaviour in conditions similar to those found in VLEO. ROAR, Rarefied Orbital Aerodynamics Research facility, is an experiment designed to provide a controlled environment with free molecular flow and atomic oxygen flux comparable to the real orbital environment. ROAR is a novel experiment, with the objective of providing better and deeper understanding of the gas-surface interactions between the material and the atmosphere, rather than other atomic oxygen exposure facilities which are mainly focused on erosion studies. The system is comprised of three major parts, (i) ultrahigh vacuum setup, (ii) hyperthermal oxygen atom generator (HOAG) and (iii) ion-neutral mass spectrometers (INMS). Each individual part will be considered, their performance analysed based on experimental data acquired during the characterisation and commissioning, thus leading to a complete description of ROAR's capabilities. Among the key parameters to be discussed are operational pressure, atomic oxygen flux, beam shape and energy spread, mass resolution, signal-to-noise ratio and experimental methodology.

Keywords: Atomic oxygen, very low Earth Orbit, gas-surface interactions, free molecular flow, vacuum, mass spectrometry.

1. Introduction

The DISCOVERER project is a complex enterprise aiming to study and generate novel knowledge, technologies and ultimately capabilities by addressing the different challenges of satellite applications at very low Earth orbit (VLEO). The consortium comprising the project includes a variety of institutions, from different sectors, each exploring distinct aspects of the questions surrounding the exploitation of VLEO for a number of applications, independent of their nature: scientific, technologic or economic. The wide scientific scope of DISCOVERER can be better understood when considering the three research questions [1] encompassing the project:

How can we improve our understanding of, and make best use of, the orbital aerodynamics of the space platform and its ability to perform attitude and orbit control manoeuvres?

Are there propulsion methods which use the residual atmospheric gas as a propellant, providing drag compensation whilst removing the lifetime limits caused by carrying a limited amount of propellant?

Are there materials or processes which reduce the induced drag on spacecraft surfaces?

In order to properly engage with these questions an experimental facility has been envisioned to provide original insight into the mechanisms governing the interactions between the surface of the spacecraft and the environment surrounding it. Atomic oxygen is the most abundant component in the atmosphere between 100 km and 450 km of altitude, resultant from the dissociation of molecular oxygen by ultraviolet radiation, the oxygen atoms are predominantly on their ground state O(3P) and extremely reactive. The interactions with the spacecraft surfaces will lead to material degradation and increased drag, reducing lifetime and potentially hindering satellite applications in VLEO. The search for new and better suited materials becomes even more compelling when considering that Earth observation data and services markets are expected to reach $8.5 billion by 2026 following the current growth [2].

The Rarefied Orbital Aerodynamics Research (ROAR) facility is a ground-based experiment designed to simulate the free molecular flow and flux of oxygen atoms found in VLEO conditions. It is aimed to investigate novel materials that might reduce the induced drag by specularly reflecting the atoms and its outcomes are of interest to all three scientific questions cited above. The experimental results are expected to bring new light to the current understanding of gas-surface interaction mechanisms governing the material's behaviour [3-6], which would be proven invaluable for the prediction and consequently discovery of other novel materials and applications.

Two different approaches are currently followed to perform materials investigations, either through on-ground experimental facilities or via direct in-orbit tests [7-14]. Whilst the latter provides results to the real environment, it is an expensive process and limited in terms of opportunities. On the other hand, ground-based facilities studies have been focused mostly on evaluating how resistant the materials are to atomic oxygen erosion and not necessarily on the physical and chemical processes involved. Therein lies one of the main features that distinct ROAR from the other facilities as the investigation of such process played a fundamental role in its design conception. In this paper this will be addressed jointly by a discussion of the facility's current status and developments.

2. Rarefied Orbital Aerodynamics Research (ROAR) Facility

2.1. Vacuum system

When considering free molecular flow (FMF) the fundamental physical quantity it relates to is mean free path (λ), which corresponds to the average distance travelled by a particle between two consecutive collisions. It is related to the pressure (P), the gas under consideration and its temperature.

$$\lambda = \frac{k_B T}{\sqrt{2}\pi d_0^2 P} \quad (1)$$

where k_B is the Boltzmann constant, T the gas temperature and the effective cross-section of the gas particles, d_0. FMF is attained when λ is much greater than the system's typical dimensions.

Figure 1 depicts the mean free path for a flux of 10^{19} atoms·m^{-2}·s^{-1} at the sample (maximum expected flux of AO) considering two different emission profiles, a collimated beam and cosine emission. The operation region of interest was defined for a λ larger than 10^2 m (four orders of magnitude larger than the sample's dimension) and determined 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. As will be considered further in the section, ROAR expected pumping capacity will initially be approximately 23.5 m^3/s which means that experiments are expected to be performed with a minimum mean free path close to 200 m. Pumping capacity is expected to be increased to 37 m^3/s on a second development phase.

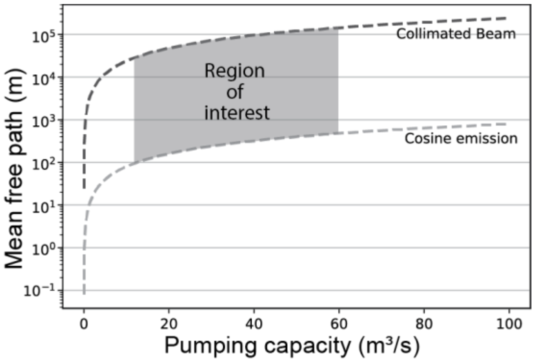

Figure 1: Graph of mean free path as function of pumping capacity for ROAR. Region of interested was defined based on a minimum mean free path of 100m and maximum pumping capacity of 60m³/s.

Because of the high pumping capacities (tens of cubic metres per second) and the expected high amount of oxygen and other reactive species in the residual atmosphere inside the chamber, cryopumps and non-evaporable getter pumps are the choice for the main vacuum system. Primary pumping stages are performed with multistage Roots pumps, thus keeping the vacuum system completely oil free, reducing the contamination of hydrocarbons from the pumps while also being safer given the oxygen-rich environment that will comprise the experiment [15-18]. The experiment was designed following a two-chamber configuration typical in ultrahigh vacuum systems with a load lock chamber for sample exchanges and a main chamber where the scattering measurements are performed.

Chamber geometry and pressure distribution across it were tested for different pumping capacities using Monte Carlo simulations [19]. Figure 2 depicts the results for the main chamber with nominal pumping capacity (37 m^3/s) and maximum AO flux (10^{19} atoms·m^{-2}·s^{-1}), for such parameters pressures are expected to vary between 10^{-8} and 10^{-7} mbar as indicated by the gradient seen in the figure. However, as mentioned, the first tests are going to be performed in less demanding conditions, with lower AO fluxes and lower pumping capacities whilst still maintaining free molecular flow and pressures are expected to still be around 10^{-7} mbar.

This concludes the description of the vacuum system main characteristics. Experimental validation is currently missing as the system assembly is still being performed. The final section of this paper will address current status and short-term updates expected to be in place at the time of the conference.

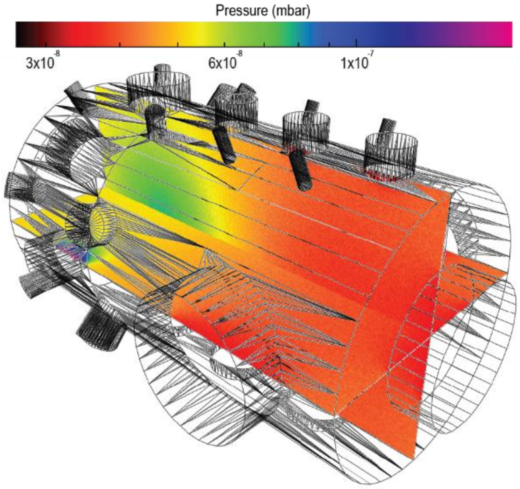

Figure 2: Pressure profile of the main chamber calculated via direct simulation Monte Carlo [19] considering ROAR's nominal performance (maximum pumping capacity and maximum flux of oxygen atoms).

2.2. Atomic oxygen source

Amongst the different techniques to produce a hyperthermal beam of oxygen atoms [20] the only one producing 100% of neutral atoms with kinetic energy varying around 4-6 eV is based on electron stimulated desorption (ESD) developed by G. B. Hoflund et al. [21-23]. The principles upon which the Hyperthermal Oxygen Atoms Generator (HOAG) is built can be described in simple steps. A silver membrane is used as interface between the oxygen supply and the vacuum inside the chamber. The species providing the oxygen atoms, either molecular oxygen or carbon dioxide, dissociate at the upstream side of the membrane. The O atoms then permeate the silver membrane and emerge at the downstream (vacuum) side and are exposed to an electron beam. This beam will induce the O atoms to desorb (via ESD) generating the beam of oxygen atoms.

The reported flux of O atoms dates from the mid-1990's and is around 10^{17} atoms·m^{-2}·s^{-1}. In order to increase it to 10^{19} atoms·m^{-2}·s^{-1} new technologies are being developed and going to be tested, therefore besides of being a unique experimental facility for materials characterisation, ROAR also represents a singular test bed for the production of oxygen atoms. ROAR will allow the investigation of different parameters affecting the permeation and desorption of O atoms, like the effects of the membrane temperature and thickness, electron beam current and energy, system's geometry and the interplay between them.

A diagram of the atomic oxygen production process is seen in figure 3 (top right) together with schematics of an atomic oxygen source (bottom). The HOAG unit is mounted on to a DN40 conflat flange, the oxygen supply port is seen at the back of the flange. At the other extremity the silver membrane is shown surrounded by a heating jacket. The model seen in figure 3 correspond to the test unit designed and built for preliminary studies, used for the development and optimisation of the source.

The atomic oxygen beam characterisation will consist of determining not only the flux of atoms but energy distribution, beam shape, ratio of ions to neutrals, and stability over time. These measurements are going to be performed by ROAR's detection system composed of mass spectrometers, which are the topic of the next section.

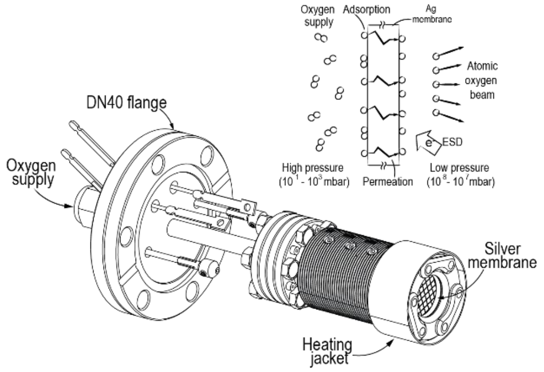

Figure 3: Diagram illustrating the physical process through which the hyperthermal atomic oxygen beam is produced (top right). Schematics of the HOAG is also seen in the figure (bottom) showing a model similar to a test unit used for preliminary studies. It is also indicated the connection for the oxygen supply, together with the mounting flange (DN40CF), heating sleeve and the silver membrane.

2.3. Detection system

The detectors used for the atomic oxygen beam and sample characterisation are ion-neutral mass spectrometers (INMS) with time-of-flight capability. They measure particle's energy and velocity for both ions and neutrals and are mounted on a moving stage that circumscribes the sample, allowing them to change their location during the experiments, thus creating a 3D map of the scattered particles. The fact that they are not fixed also allows for determining the atomic oxygen beam shape and energy distribution as a function of position. The latter when combined with the other measurements will provide characterisation levels that are unprecedented in atomic oxygen beam experiments.

The particles enter the detector via a small aperture (<5°) and go through an ion filter that selects the charge state being detected, neutral or ionised. If the particles being measured are neutral, the ion filter will deflect the ions and only the uncharged particles go through. The next stage consists of an ioniser that is followed by a time-of-flight and a detector that measures the mass/charge ratio. If, however, the particles of interest are the charged ones, the neutrals aren't ionised and can no longer reach the detector. A diagram of these stages is provided in the figure 4 below.

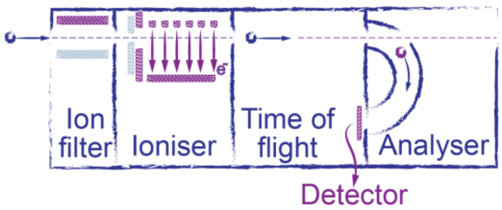

Figure 4: Schematics of the ion-neutral mass spectrometers that comprise the detection system for ROAR.

Besides the INMS, ROAR will also have a residual gas analyser that will monitor the background's composition. The background measurement's relevance is twofold, determining the residual atmosphere inside the chamber before, during and after the experiments is of fundamental importance for comparison reasons and also as a reference for the INMS. The mass spectrometers are going to be calibrated against the background.

3. Methodology

ROAR's experimental methodology and commissioning are addressed in more details in this section. Once all the previously described parts are mounted the system must be fully characterised before the material analysis experiments commence. System's characterisation starts with assessing the vacuum system's performance accompanied by the conditioning of the atomic oxygen source, which can be done simultaneously with the calibration of the spectrometers.

Considering the choice of pumps for ROAR there are a few possible ways of performing the pumping down of the system. The simplest procedure is to pump the main chamber with the primary system, once the crossover pressure for the cryopumps (10^{-1} mbar) is achieved the gate valves isolating them are open and they are responsible for bringing the chamber's pressure down to near ultrahigh vacuum pressure (10^{-9} mbar). An alternative would be to reduce the chamber's pressure with a turbomolecular pump to values considerably lower than the crossover threshold (10^{-6} - 10^{-7} mbar) and then switch to the cryopumps. This procedure reduces the amount of water adsorbed onto the cryopanels and in principle would allow for longer operation before regeneration of the pumps is required. Once pressures are low enough, below 10^{-8} mbar, the getter pump is started.

When stable conditions are achieved, the conditioning of the HOAG can be performed. As explained previously, the atomic oxygen source operation is based on the dissociation of oxygen atoms into a silver membrane. The O atoms then permeate the membrane and are desorbed on the vacuum side creating the hyperthermal oxygen beam. For this mechanism to work it is required the silver membrane to be almost completely clean of any contaminants that could cause the O atoms to desorb as other species, e.g. carbon that would lead to the formation of CO. The conditioning of the atomic source consists in heating up the membrane to temperatures between 300°C - 500°C to speed the permeation while keeping an oxygen supply on the upstream side. This will initially produce mainly CO and to a lesser extent molecular oxygen, until the amounts of carbon in the membrane are significantly reduced and the amount of carbon monoxide is negligible compared with the O_2 from the recombination of O atoms. Once this point is achieved the conditioning is concluded and the production and characterisation of the oxygen beam can be performed. The INMS calibration can be performed during conditioning of the atomic source and once it is concluded the facility is ready for its first tests.

To assess stability of the atomic oxygen beam and the performance of the mass spectrometers quartz samples are going to be used. These parameters are fundamental for the facility's operation as they will determine exposure times, angular steps for the INMS displacement, integration time for the measurements and other determining factors of experimental relevance. Following the quartz samples other standard materials are going to be tested and their results compared with literature: Kapton (polyimide tape), gold, HOPG (highly oriented pyrolytic graphite), amongst others [24-26]. These tests will allow the comparison between the observations made in ROAR with the literature and other facilities and will serve as reference for the analysis of novel materials. Establishing how the facility behaves with already known materials provides a baseline for the material analysis.

The entire procedure described here is expected to last for 4 to 8 weeks, once the system is assembled and all parts are in place. Commissioning of the atomic oxygen source itself is a process that may take up to two weeks. Optimal operation parameters aren't determined yet and defining those can be rather time consuming considering the number of variables and uncertainties involved in an experiment of such complexity. An update on the current status of the facility is provided in the next section.

4. System's current status

ROAR's current state of development isn't as far advanced as expected when the abstract was submitted (February 2019). Due to an 18-week delay on the manufacture of the vacuum chambers the assembly and testing has been heavily compromised. The chambers arrived on early September and therefore system assembly is still incipient.

Figure 5 (a) shows the main chamber and its support in the laboratory, they have been assembled together with the DN500 gate valves (b) and the cryopumps as shown in figure 5 (c). Schematics of the complete assembled system is also provided for reference (d). Next steps are focused on finishing the assembly of the heaviest flanges (the main chamber has one extra DN500 port for a third cryopump and a DN800 door) to move to the assembly of sample holder, moving stage for the detectors, mounting of commercial parts (residual gas analyser, pressure gauges, turbomolecular pumps, getter pump, etc) and start the commissioning as described in section 3 – Methodology. These developments are ongoing and will be updated for the conference.

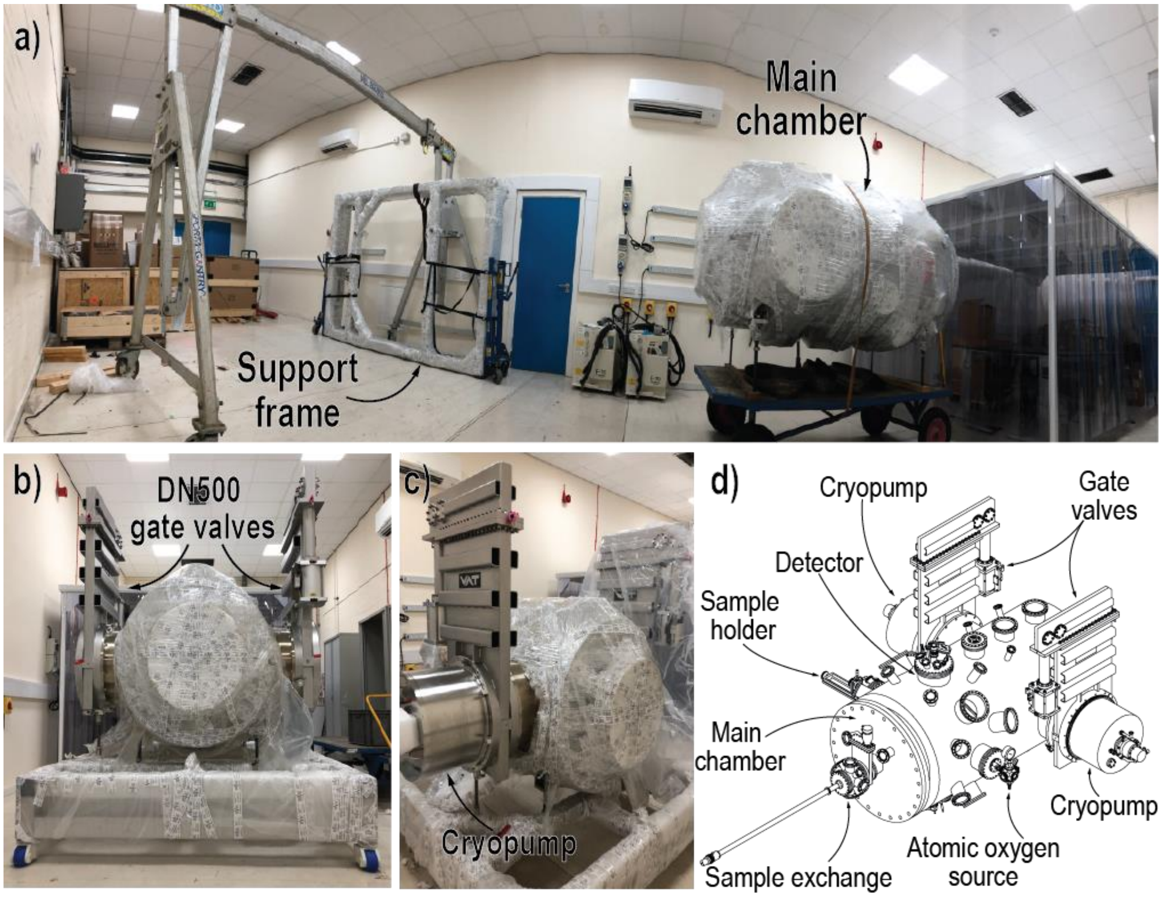

Figure 5: Pictures of the assembly of ROAR in the laboratory, showing the main chamber and the support frame initially separated (a), with the DN500 gate valves (b) and cryopump (c) attached. A full system schematics is provided in (d) for reference.

5. Conclusions

DISCOVERER is a project that tackles the challenges to make sustainable operation of satellites in VLEO a reality. As described in this paper a new experimental facility was designed and is being assembled, the Rarefied Orbital Aerodynamics Research (ROAR) facility and is expected to be operation by the end of the 2019. ROAR will reproduce the atomic oxygen flux experienced by spacecraft in very low Earth orbits to investigate the gas-surface interactions between the O atoms and the surfaces. The goal is to deepen the knowledge of the mechanisms governing the interactions and to identify new materials that would promote specular reflection.

Besides providing a beam of hyperthermal oxygen atoms, ROAR also ensures that free molecular flow conditions are kept during the experiment via a combination of vacuum pumps, cryopump and non-evaporable getter pump. The other components of the vacuum system were described and a profile of the pressure gradients during the experiments provided. The atomic oxygen beam is produced via electron stimulated desorption, a process that is based on the dissociation of oxygen through a silver membrane and flux of 10^{17} - 10^{19} atoms $m^{-2} s^{-1}$ are expected. The detection system is briefly considered, the ion-neutral mass spectrometers are combined with a residual gas analyser to provide a map of the particles scattered by the sample. They are also responsible for characterising the atomic oxygen beam providing beam shape, energy distribution in addition to flux.

Due to delays on the manufacture of the chambers (18 weeks) the methodology is discussed only on descriptive terms as the system is currently being assembled. Once the vacuum system is in place the atomic oxygen source will be commissioned and the mass spectrometers calibrated against the chamber's background. To characterise ROAR's performance the first set of samples will consist of materials whose response to atomic oxygen is well characterised, *e.g.* quartz, polyimide tape (Kapton), gold, etc. Finally the current status of the facility is provided which will be updated until the date of the conference.

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