Testing material's orbital aerodynamic properties: ground-based and on-orbit experiments.

Vitor T. A. Oiko, Peter C. E. Roberts, Stephen Edmondson, Dhiren Kataria, and the DISCOVERER team.

Abstract: Very low Earth orbits (VLEO) consist of a portion of the atmosphere comprised usually between 150-450 km of altitude. In this region the aerodynamic properties of spacecrafts are governed by the interactions between the particles comprising the residual atmosphere, i.e. atoms and molecules, and the external surfaces of the spacecrafts. Because neutral oxygen atoms (O^3P) are the most abundant element found at these altitudes, VLEO is a very aggressive environment with erosion of the external surfaces and drag generation being the common issues faced by spacecrafts. In order to make satellite operation more sustainable, it is therefore necessary to develop new materials that overcome these problems. In this context, we at The University of Manchester have been working on the development of such materials and also of new techniques/methodologies to more effectively assess their performance. The work has been divided on two different fronts, firstly with the construction of a new atomic oxygen exposure, the Rarefied Orbital Aerodynamics Research (ROAR) Facility, and secondly through on-orbit tests by exposing materials at the International Space Station (ISS) as part of the Materials International Space Station Experiment (MISSE). In this talk we will present the latest results on both fronts, including the current developments of ROAR and the preliminary analysis of material samples that recently returned from the ISS after being exposed to the space environment for one year.

1. Introduction

Very low Earth orbit (VLEO) corresponds to the portion of the atmosphere defined between 150-450 km and provides a challenging environment with atomic oxygen (AO), O(3P), as the predominant species with a number density that is dependent on altitude and other factors like solar activity, latitude, variation on Earth's magnetic field, among others [1]. At 300 km of altitude the AO number density is around 10^9 cm^3 [2], the average orbital velocity of the spacecraft in relation to the oxygen atoms is approximately 7.7 km/s [3], which is equivalent to kinetic energy of 4.9 eV and yields a flux of the order of 10^{15} atom cm^{-2} s^{-1}at ram direction. The collisions between the oxygen atoms and the surfaces of the spacecraft lead to a series physical-chemical interactions that result in surface degradation through oxidation and erosion [4-8]. They are also responsible for increase of drag that can be translated into reduction of mission's lifetime.

A better understanding of the mechanisms governing these interactions allows the development of novel materials and coatings that are better suited to the aggressive environment of VLEO with the possibility of having their properties tailored to specific applications. Currently, these studies are conducted either via on-orbit tests [9, 10] or using ground-based facilities that simulate some features of the real space environment [11-14]. Whilst the former is becoming more accessible specially through the Materials International Space Station Experiment (MISSE) [15], ground-based atomic oxygen exposure facilities are still fundamental tools for the study of materials.

The majority of the atomic oxygen exposure facilities operational today are focused on investigating the induced erosion, which is a serious concern as its effects can compromise different systems like optical and electronics with the potential of compromising whole missions [16,17]. Identifying materials that are resistant to AO erosion has been a key interest of these facilities [18, 19], however, in order to expedite the effects to AO exposure, many have increased AO flux to levels that are a few orders of magnitude above those experienced by spacecrafts when in VLEO [20]. This undoubtedly is a helpful capability that allows the observation of what equivalently long exposure would cause to the materials, nevertheless it also carries the risk of becoming unrepresentative of the actual gas-surface interactions experienced on orbit.

Describing the gas-surface interactions is a complex task that involves a great number of variables and uncertainties affecting both the gas particles and the surface, like composition, morphology, energy of the gas, flux intensity, flow regime, etc, with different models applied to describe the results observed in the laboratory tests [21-24]. To properly characterise the dynamics, reactions and processes involved, a facility that provides similar values of AO flux and energy distribution of those of VLEO and equipped with the appropriate detectors is required. Because of this, the DISCOVERER project [25] has proposed the construction of a novel experiment that is designed to investigate the gas-surface interactions between materials samples and a beam of AO [26]. Among the study developed in the project, samples of different materials were sent to the International Space Station (ISS) as part of the Materials International Space Station Experiment (MISSE) to be exposed to the space environment and be retrieved for post-exposure analysis. This paper provides a brief description and an update on the current developments of the ground-based facility and the on-orbit tests.

2. Rarefied Orbital Aerodynamics Research (ROAR) Facility

The Rarefied Orbital Aerodynamics Research (ROAR) facility is the experiment being commissioned at The University of Manchester that is designed to investigate the gas-surface interactions between a beam of 4.5 eV neutral oxygen atoms and samples of different coatings and materials. To guarantee that the interactions observed are in good agreement when compared to those of the real environment the system has an ultrahigh vacuum (UHV) system composed of two crypumps (Sumitomo CP-20) and a non-evaporable getter, NEG, (SAES, CapaciTorr D3500) that together provide 23.5 m^3s^{-1} of pumping capacity. Working pressures are estimated to vary between $2x10^{-7}$ and $2x10^{-9}$ mbar depending on the emission profile of the atomic oxygen source, with the upper limit given to a cosine emission and the lower one to a collimated beam for a flux of 10^{15} atom cm^{-2} s^{-1} measured at the sample. This range of pressures ensures that free molecular flow regime is kept throughout the experiments, with mean free paths that are four orders of magnitude longer than the system's characteristic length. The UHV system is installed and once the cryopumps are commissioned it will be fully operational. Currently, ROAR's base pressure is of $4.5x10^{-8}$ mbar without any gas loads.

The combination of cryopumps with a different type of vacuum pump like sputter-ion or turbo is commonly seen in space simulation chambers for thermal cycling tests, specially driven by the high pumping capacity and the need for a clean vacuum, free of hydrocarbons [27-29]. However, the combination of cryopumps with the NEG is one of the innovations seen in ROAR. Non-evaporable getters are very efficient to pump out active gases like H2, CO, CO2, N2, and so on [30], which for an AO exposure facility are gases expected to be present due to possible reactions with the testing samples. System performance hasn't been assessed yet as the ultrahigh vacuum system is still being commissioned, but these results will provide a good reference for the design of future facilities or the update of the currently operational ones.

The atomic oxygen source (AOS) applied in ROAR is an advance of the source developed initially by Hoflund and Outlaw that is based on the electron stimulated desorption of oxygen atoms from a silver membrane [31, 32]. A silver membrane acts as interface between two regions, a high pressure one where O2 is provided, and a low pressure one given by the ultrahigh vacuum environment of the experiment's chamber. The oxygen molecules adsorb on to the membrane and dissociate, the atoms then permeate through it, reaching the UHV side, where an electron beam impinging on the surface causes them to desorb creating the beam of oxygen atoms. O beam with kinetic energy of 4.5-5.0 eV and a flux of 10^{13} atom cm^{-2} s^{-1} has been achieved [32].

Increasing the AO flux to the expected level of 10^{15} atom cm^{-2} s^{-1} requires both the permeation and desorption processes to be optimised. Permeation can be increased through a number of measures, either by increasing the temperature of the silver membrane, making it thinner or by increasing the concentration of atoms near it. Desorption on the other hand can only be increased by applying an electron gun that provides higher currents. The source applied in ROAR has some modifications on the upstream side of the membrane that allows for a glow discharge to be formed on the high-pressure side of the membrane. The presence of a plasma near the surface causes both the temperature and the gas concentration to be increased near the surface, leading to an increase in permeation. For this improvement to be translated into AO flux, it must be accompanied by an increase in desorption, which is achieved by applying a high current electron gun that provides between 5-50 mA with electron energies varying between 100 eV and 10 keV (Kimball Physics, EGG-3103). This configuration of AO source is another innovative characteristic of ROAR. The independent control of both electron current and energy gives the possibility of isolating and analysing a parameter that has not been explored, and therefore optimised, so far in the production of AO, the effect of the electron's energy on the desorption process. Studies of the effect of electron's current, energy, surface's temperature and thickness are going to be carried once the source is operational. The AOS is still being commissioned as part of ROAR, with all subsystems already installed and leak tested.

The detection system of ROAR is also another area where a novel approach has been taken. It comprises two different sensors, an Ion-Neutral Mass Spectrometer (INMS) and a residual gas analyser (RGA, Pfeiffer, PrismaPro QMG250). The latter is a standard tool for monitoring the conditions of the vacuum inside the chamber, its cleanliness and the composition of the residual atmosphere. For studying gas-surface interactions it is of fundamental importance to be able to monitor the conditions in which the experiments are performed. Contaminants can potentially interfere with the interactions between the AO beam and the samples and therefore every precaution to avoid and detect them has been taken.

The INMS is a mass spectrometer built at Mullard Space Science Laboratory at University College London that is composed of four sections: ion filter, ioniser, time-of-flight (TOF), and finally the analyser. The first two stages are used to select if either neutrals or ions are being detected, the TOF is used to determine the particle's velocity, and the analyser measures the particle's mass. It is mounted on a moving stage that allows it to rotate around the sample so it can measure the angular distribution of the scattered particles on the range of 5-90 degrees in relation to the normal of the sample. It is currently installed in ROAR's main chamber and in-air tests are being performed. The INMS unit mounted in ROAR is very similar to the one installed in the test satellite that is part of the DISCOVERER project, the Satellite for Orbital Aerodynamics Research (SOAR) [33].

Figure 1 shows a schematic of ROAR and the systems just described together with the sample holder and sample exchange chamber, thus providing an overview of the facility and how its components are distributed along the main chamber. This concludes the description of the ground-based facility and its condition. Next section will be dedicated to the efforts made regarding on-orbit tests.

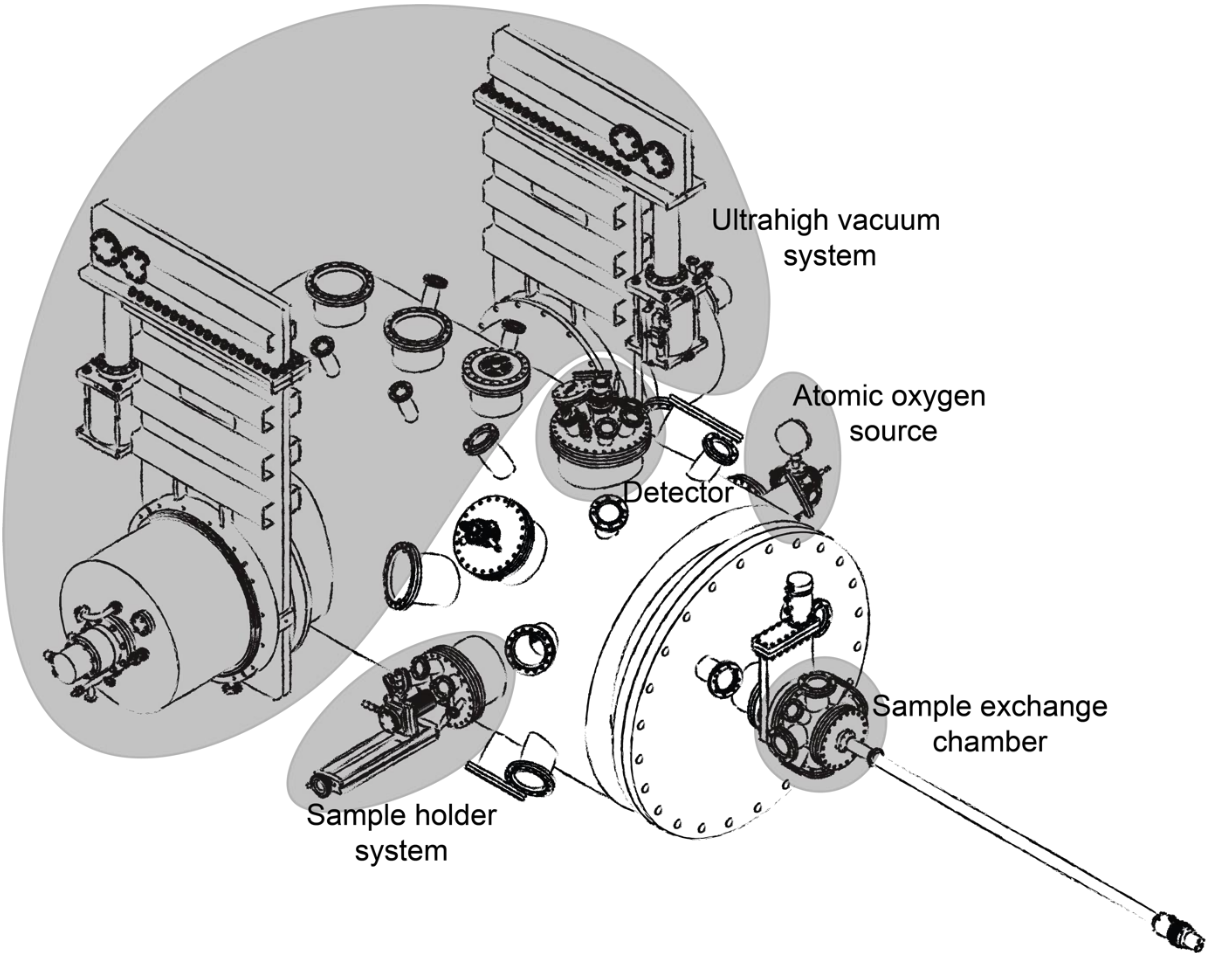

Figure 1: Schematics of ROAR depicting the main systems described, ultrahigh vacuum, atomic oxygen source and detection. Sample holder and sample exchange chamber are also indicated in the figure, giving an overview of the facility's geometry.

3. On-orbit tests

On-orbit tests are a very important tool for the development of new technologies and has been applied in several cases related to the research of novel materials. Missions like the Long Duration Exposure Facility (LDEF) [34,36] and the Materials International Space Station (MISSE) at the ISS [37-39], among many others. As part of the study of novel materials for VLEO applications, two different on-orbit experiments are being performed. The results of these experiments are going to be compared with those obtained on the ground-based tests and will allow for a more refined interpretation of the data. The first on-orbit experiment corresponds to a test satellite that has been developed and launched on the 3rd of June 2021 with two payloads, one INMS and a set of fins where the new materials are deposited onto [33]. The second test is comprised of to two samples that were launched to the ISS as part of MISSE-12 mission to be exposed on ram and wake. The samples are made of 6 different materials, 4 novel ones and 2 references and were exposed for approximately 12 months to the space environment. These samples were retrieved and are now being analysed.

Atomic force microscopy (AFM) images show an average roughness between 2-4 nm for pre-exposure samples. Images also show that the substrate, ITO/PET (Sigma-Aldrich, 639303-1EA), presents some cracks on the surface once it undergoes heat treatment in vacuum for temperatures above 373 K. These are due the different thermal properties of ITO and PET that result in an anisotropic shrink that causes the ITO to crack [40]. These cracks are around 200-300 nm height. The AFM images also show that on the plateaus the roughness is between 3-7 nm, which gives an aspect ratio of 100 for these samples. These are preliminary data, and the effects these have on the gas-surface interactions are yet to be determined.

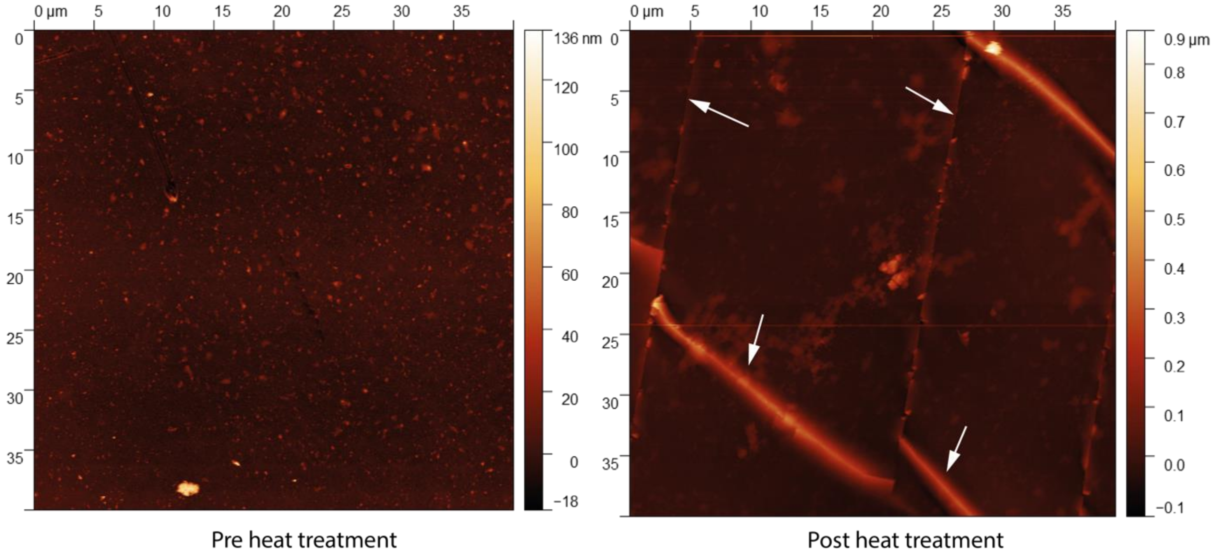

Figure 2: AFM images showing the substrate of pre-exposure samples before undergoing heat treatment (left) and after where the cracks due to the anisotropic shrinkage of ITO/PET are indicated by white arrows (right).

4. Conclusions and perspectives

This article presents a brief update on the developments of the Rarefied Orbital Aerodynamics Research (ROAR) facility, currently in commissioning stage at The University of Manchester. ROAR is an AO exposure facility designed to investigate the gas-surface interactions between a hyperthermal beam of neutral oxygen atoms and a sample. A general description of ROAR's main system, ultrahigh vacuum, atomic oxygen production and detection, is provided with all systems installed and being commissioned. Because of ROAR's objectives, its design has innovative characteristics that are not seen in other AO exposure facilities, like the combination of cryopumps with non-evaporable getter, the newly developed atomic oxygen source with a glow discharge and high-current electron gun, and the ion-neutral mass spectrometer being applied for ground-based studies.

Another aspect of the research focused on the development of new materials are the on-orbit tests. This is approached in two different fronts, the first one is with the Satellite for Orbital Aerodynamics Research (SOAR), which hasn't been considered in detail in this article, and the tests that were part of the MISSE-12 mission. The samples were retrieved and are yet to be analysed. Meanwhile, preliminary analysis of samples prior to the exposure to the space environment has shown that despite of changes in the sample's morphology due to anisotropic shrinkage of the substrate, samples are still considerably flat with a surface roughness varying between 3-7 nm. How these features influence the gas-surface interactions are going to be studied once the facility is fully operational.

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