O-ZONE: affordable stratospheric air dynamic sampling device

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Abstract

The current situation regarding air pollution, global warming and the world approaching the point of no return have led the United Nations to focus on improving the environmental situation through the SDGs [1]. In line with these ambitions, O-ZONE team, was born in 2019 with the clear objective of taking concrete action against climate change [2].

The team's goal is to build a compact, low-cost, and reusable device to sample stratospheric pollutants, at various altitudes and thus provide air quality indications in mid-range areas for monitoring, prevention, and rapid intervention in case of unpredictable events.

The O-ZONE team was therefore born as an idea of some students from the Aerospace Engineering course at the same University. The students took part in the REXUS/BEXUS project by Swedish National Space Agency (SNSA), Deutsches Zentrum für Luft- und Raumfahrt (DLR) and European Space Agency (ESA) [3]. As in each of these projects, the team tackled the various steps of space missions but, in this case, with extra constraints. They had to work during the lockdown with various complications due to the pandemic. Although the launch was delayed, the students carried on with their motivation and then launched their device on board the BEXUS 30.

The prototype launched in Kiruna - Sweden (at the Esrange base), and which reached an altitude of 27.8 km, is a sampling system for Volatile Organic Compounds (VOCs), such as NO_X and SO_X, Particulate Matter (PM) and Chlorofluorocarbons (CFCs) responsible for the depletion of the Ozone layer [4].

These types of samplers [2] fill the technological gap in atmospheric analysis; the current state of the art allows air to be monitored only statically from ground stations or by satellite analysis [5], while O-ZONE presents an accessible, easy-to-use and rapid in situ sampling method.

This paper describes the technical specifications and design aspects of the device and the experience that has allowed the students to grow as a team, especially in terms of personal skills and the ability to work with concurrent engineering and interdisciplinarity.

Finally, the experiment results will be shown.

Keywords

Atmospheric Pollution, SDGs, Sampling, CFCs, BEXUS30.

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Acronyms/Abbreviations

CFCs	*Chlorofluorocarbons*
DLR	*Deutsches Zentrum für Luft- und Raumfahrt*
DMAC	*Dimethylacetamide*
DPPO	*Diphenyl-p-phenylene oxide*
EDX	*Energy Dispersive X-Ray Analysis*
ESA	*European Space Agency*
ESEM	*Environmental Scanning Electron Microscopy*
FT-IR	*Fourier-Transform InfraRed*
GC-MS	*Gas chromatography coupled to a mass spectroscopic detector*
IAC	*International Astronautical Congress*
LCA	*Life Cycle Assessment*
LQM	*Limit of quantification*
LOD	*limit of detection*
PM	*Particulate Matter*
PVDF	*Polyvinylidene fluoride*
SDGs	*Sustainable Development Goals*
SNSA	*Swedish National Space Agency*
SSC	*Sweden Space Corporation*
SSEA	*Symposium on Space Educational Activities*
TVAC	*Thermal vacuum chamber*
VOCs	*Volatile Organic Compounds*
UV-VS	*Ultra Violet Visible Spectroscpy*

1. Introduction

The point of no return on global warming highlighted by the United Nations and environmentalists is leading, perhaps too slowly, to an unprecedented social and economic revolution [1]. To accelerate the process of change, institutions and governments need to give a stronger push. They should use appropriate legislation to encourage companies to update their production cycle through the now increasingly widespread Life Cycle Assessment (LCA). Obviously, this intervention must have a technological and scientific basis that allows for the intensification of controls and the subsequent tightening of penalties for those who violate what has been sanctioned.

Starting from the current problems related to pollution and especially regarding the emission of pollutants into the atmosphere [4], the O-ZONE project was born to act concretely in the fight against climate change [6] [7].

In 2019, a group of students from the aerospace engineering course at the University of Padova, supported by Alessandro Francesconi, Professor of Aerospace Systems and Systems, and Roberta Bertani, Professor of Chemistry for Aerospace Engineering, came up with cheap and easily deployable alternative technologies for atmospheric monitoring [2]. After officially becoming part of the innovative projects of the University of Padova and then obtaining economic support, their adventure to build a pollutant sampling device began [6].

In October 2019, the application was then submitted for the BEXUS project of SNSA, DLR, and ESA [3]. This project allows a student team to place their innovative experiment on board the "Gondola" (support structure) of a stratospheric balloon, together with other teams from all over Europe. The balloon reaches an altitude of around 25 km and allows a variety of instrumentation and tests to be carried out. This opportunity immediately interested the O-ZONE team, who wanted to analyse atmospheric air at different altitudes in order to understand how pollutants such as VOCs, PM, and CFCs, are distributed and stratified in the various atmospheric levels up to 25 km.

The submitted application was accepted and plunged the team into a real space mission with phases of verification, review, design, and development of their device. O-ZONE then expanded to 17 operational members who oversaw developing the testing subsystems and disseminating their extraordinary experience [7]. There were a few complications along the way, the most obvious being the Coronavirus pandemic, which tested the team's perseverance and resulted in the launch being postponed for a year. The O-ZONE team did not give up and, taking advantage of the "extra" time, decided to design a second version of the prototype, with even better performance and even more compactness.

In October 2021, the O-ZONE experiment flew aboard the BEXUS 30 successfully completing all assigned tasks, landed safely and ready for recovery.

This paper will therefore describe what was designed, developed, and tested during the three years of the project, with a focus on the launch, the technologies used, and a hint of the results obtained.

2. Design of the experiment

The experiment consists of a set of filters that use a pneumatic system and a pump to suck the atmospheric air and trap air pollutants. Thanks to the on-board computer, valves are activated to differentiate the samples collected at different altitudes and to understand, after landing and subsequent analysis, the distribution of PM, VOCs and CFCs over the 25 km or so covered by the stratospheric balloon [8].
The components necessary for its proper operation of the experiment are installed inside a box made up of aluminium plates. Going into details, the skeleton of the structure is made of aluminium profiles on which the plates protecting the device during the landing phase are fixed while 40mm thick polystyrene panels complete the external design to ensure proper thermal insulation. Considering the internal structure, this is characterized by 3 different levels (aluminium plates, see Figure 1), each of which is dedicated to host a different subassembly; from the bottom to the top level there is the pneumatic subsystem (Figure 2), the electrical subsystem, and the sampling bag. This final design has been chosen after several iteration and allows an easy and quick access to all the components since it considers the main *design for assembly* principles. To conclude, rubber bumpers are used to connect the experiment box to the Gondola system preventing damages to the internal components during the landing phase.

Figure 1. O-ZONE experiment exploded view.

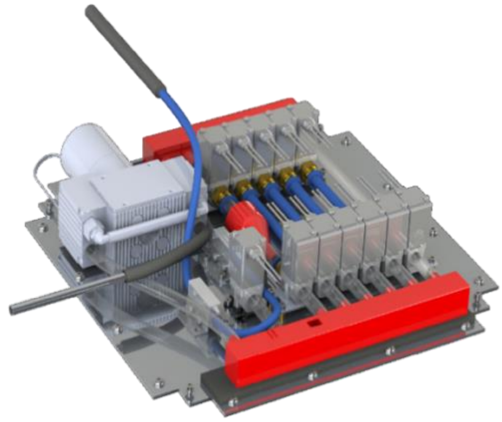

Figure 2. O-ZONE base level (CAD view of the pneumatic subsystem plate).

The external box protects the central system, the core of the experiment. The pneumatic system's functionality is guaranteed by a diaphragm pump, which is needed to suck the air the device rises into the atmosphere. The diaphragm avoids possible contamination of the air with the oil of the gears. Moreover, this model can work at low pressures because it has a minimum pressure limit of 25 mbar.
The air that flows inside the circuit was regulated by 2 flowmeters to obtain an accurate reading. Once through the pump, the air is conveyed into the various tubes through the opening and closing of solenoid valves.
In order not to compromise the samples and to safeguard the mechanical and electronic components, thermal solutions were adopted.
An external insulating shield, made of aluminium and panels of Polystyrene, protects the experiment from the thermal flows that can heat or cool down overly the device. Furthermore, thanks to continuous temperature control, the system can switch on and off the active thermal system made of heaters.

2.1. Pneumatic subsystem

The heart of the project is the pneumatic system (Figure 3): it is responsible for the suction and distribution of air within the pneumatic circuit. The system is essential and compact, this to be contained in small spaces, and thanks to this feature it can be easily scaled and reproduced. Going into details, as mentioned above, the main component of this subsystem is a diaphragm pump which aim is to suck the external air at different altitudes. With the membrane technology, contamination between the air (to be analysed) and the oil used for the lubrication of the rotary mechanisms is avoided; furthermore, the pump must be able to work at low pressures, indeed it has a minimum pressure limit of 25 mbar. The power supply to the pump is adjusted according to the flow of air that passes through the pneumatic circuit: 2 different flowmeters are used to obtain an accurate reading of the flow, placed at the beginning and at the end of the circuit respectively. The airflow is then led inside the pneumatic circuit thanks to 12 solenoid valves which are opened by an Arduino Due at different intervals based on the altitude reached by the experiment [6]. This allows a dynamic sampling and a complete isolation of the air between the different phases.

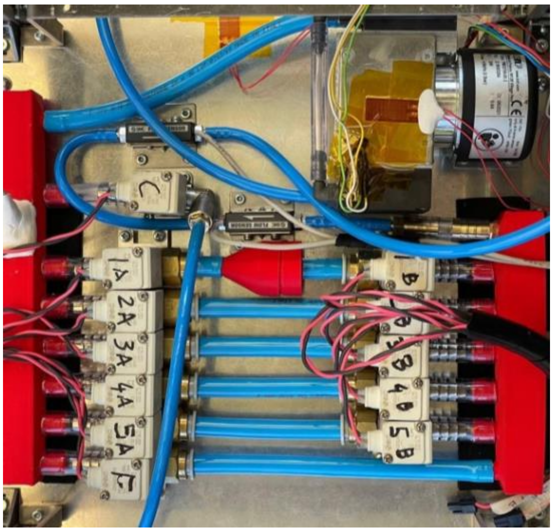

Figure 3. Top view of the pneumatic subsystem.

The pump model is particularly suitable for the experiment because it is light and small and at the same time it guarantees excellent performance for our requirements even at low pressures and temperatures as it was verified in the thermal vacuum chamber (TVAC). The self-imposed constraint of the device's overall cost influenced some key decisions during the design phase. It was chosen to adopt 4 pollutants filters, each responsible for sampling the air in an interval of 4.5 km of altitude during the ascending phase. During the first interval, a PM filter is used, capable of trapping organic and inorganic molecules. In addition to this first chemical system, the device contains a sampling bag that will be filled during the last part of the ascent and the floating phase (expected between 22.5 and 25 km).
As mentioned above, the air is collected at different intervals based on the reached altitude; the complete sampling sequence is therefore explained in Table 1.

2.2. Sampling subsystem

The aim of the experiment is to sample air at different altitudes, from 0 km to 25 km, using a system consisting of a sampling bag and three different kinds of filters. Therefore, the sampling system is namely composed by three different technologies.

2.2.1. Adsorption filters

Stainless steel thermal desorption tubes composed of a three-layered system made of Tenax TA/Graphitized Carbon Black/Carbonex 1000. The first layer consists of Tenax ® TA (35/60 mesh), a macro-porous semicrystalline diphenyl-p-phenylene oxide (DPPO) polymer [6]. The second one is made of Graphitized Carbon Black (40/60 mesh), a nonporous adsorbent which interacts through Van der Waals' forces [7] [8]. The third layer is Carboxen 1000 (60/80 mesh), a Carbon Molecular Sieve. With only one tube it is possible to sample compounds with different volatilities in such a way that the least volatile compounds get trapped in the weakest material (the third layer, Carbonex 1000) and the most volatile ones get trapped in the strongest compound (Tenax TA). The analytes can then be extracted via thermal desorption or solvent extraction, using CS2. The flow rate is kept constant at 0.05 L/min during the sampling phase [7] [8].

2.2.2. PM filters

The second sampling system is made of particulate matter filters consisting of a Whatman® QM-A quartz filter, with a pore size of about 2.2 μm and a diameter of 25 mm, and an ATTP microporous hydrophilic polycarbonate filter, with a constant pore size of 0.8 μm and a diameter of 25 mm. These filters are capable of sampling organic and inorganic particles [8]. The filters are placed into a custom-made 3D printed support. The arrangement of the filters is such that both can be used in the same pipe. The polycarbonate membrane is cut in half and one portion of the two is placed onto the intact quartz filter. The flow rate is kept constant at a known flow rate of 3 L/min.

2.2.3. Sampling bag

A 3 litres polyvinylidene fluoride (PVDF) sampling bag is the last sampling system adopted in the experiment. Its purpose is to collect and store the air during the last phase of the flight. PVDF sampling bag has previously been proved to be excellent at storing VOCs, to be resistant to abrasion and chemicals and to do not produce background levels of Dimethylacetamide (DMAC) or phenol [7] [8].

3. Launch Campaign

The launch campaign took place at the Esrange base in Kiruna between 24 September and 4 October 2021. Initially, flight preparation tests were carried out, and these included verifying the experiment's correct mechanical and electrical connections with the gondola and communication with the ground station. After the pre-flight tests, the experiment was placed aboard the gondola at the Sweden Space Corporation (SSC) space base. The balloon, hosting four other experiments, began its ascent that lasted about an hour and a half and then remained floating for another four hours. The gondola reached an altitude of 27 km, where the external temperature was below −60°C and a pressure of 17 mbar. Before the launch campaign, several tests were carried out in a vacuum chamber to verify the correct functioning of the experiment under these critical conditions. Vacuum and thermo-vacuum tests were carried out using dry ice to simultaneously simulate temperature and pressure at high altitudes. During the tests, the flowrate through the filters was monitored, and an automatic and a manual adjustment method was created for the flowrate based on the altitude (therefore the pressure). In the same way, the thermal control system was tested, and the power consumption was checked [8].
The experiment followed the various phases planned (Table 1), filtering the air with all the available filters and filling the sampling bag. The behaviour of the experiment was nominal in all phases; the times were respected, as were the airflow rates and temperatures. Communication with the ground station was optimal and allowed the experiment to be guided through the entire flight without considerable signal losses that could compromise the device's functionality.
Recovery took place promptly (24 hours later) to minimize the time between sampling and analysis.

Table 1. Process flow table.

	Altitude [km]	Sampling method
I phase	0-4.5	PM filter
II phase	4.5-9	1st VOCs filter
III phase	9-13.5	2nd VOCs filter
IV phase	13.5-18	3rd VOCs filter
V phase	18-22.5	4th VOCs filter
VI phase	22.5-25	Sampling bag
Last phase	0	Analysis

4. Results

Various analytical techniques can be used to study the samples collected, such as Fourier-Transform InfraRed (FT-IR) or UV Visible spectroscopy (UV-VS), gas chromatography coupled to a mass spectroscopic detector (GC-MS), and electrochemiluminescence devices. The latter are common analytical methods used to directly quantify chemical pollutants in the air, such as VOCs and CFCs in air samples [9]. Therefore, the results obtained can be compared with those reported in literature if additional validations confirm the reliability of these techniques at high altitudes. These analyses are performed in a laboratory, indeed if the analyses are carried out on-site an accurate calibration is needed to ensure the correlation between the instrumental response and the concentration of target molecules. Thus, after the sampling the filters and the sampling bag undergo different tests which comply with several methods. The adsorption filters are analysed by GC-MS with a thermal desorption program to detect very low concentrations, in the order of magnitude of ppb, expected for many of the examined analytes. The method employed is NIOSH 2549 1996 [10] [11]. The particulate matter filters are studied qualitatively and examined by Environmental Scanning Electron Microscopy (ESEM) [8]. The sampling bag is analysed by gas GC-MS with the methods EPA 3C 2017 and EPA TO 15 1999) [8]. The latter are commonly used for the characterization of environmental samples containing mixtures of volatile organic compounds. Many VOCs are revealed in a concentration below the limit of quantification (LOQ) only qualitative considerations can be made.
However, from a qualitative point of view, their presence in the collected sample is ascertained since their concentrations were higher than the limit of detection (LOD) of the analytical method involved. The polycarbonate filter collects scattered particles, both organic and inorganic with dimensions ranging from 5 to 10 μm. Their composition is identified by using the Energy Dispersive X-Ray Analysis (EDX) analysis.
This prototype is proved to be operating, but the data extracted so far are not enough to either validate the method or to estimate the sampling error. Thus, further tests need to be performed to verify the reliability and integrity of this promising and low-cost sampling tool [12].

5. Discussion

During the three-year project, the students not only had the opportunity to build a device and improve its design from a 1.0 prototype to a second 2.0 version, but also to develop personal skills, soft-skills and to enter the world of research and work. The testing phases engaged them the most and proved to be the winning strategy for the operation of the device in flight. In particular, the thermal vacuum test was an example of the team's commitment to thoroughly testing an experiment under realistic flight conditions for the first time in the history of BEXUS. The team also had the opportunity to present their achievements at major international conferences, the most important of which was the International Astronautical Congress (IAC) [7].

6. Conclusions

After two years of development and improvement, the experiment took part in the BEXUS 30/31 launch campaign in Kiruna (Esrange base) at the end of September 2021.
The experiment worked as planned during the flight despite a minor problem with the GPS, but thanks to the implementation of both an autonomous and manual mode the device was able to sample the air in all the filters and collect enough air on the sampling bag.
The analyses of the filter and the air conducted in Italy were successful. During the whole BEXUS program period the team experienced a very effective growth in both teamwork skills and interdisciplinary knowledge.
The results demonstrated the functionality of the experiment and enabled the team to achieve the objectives initially set. The work carried out by the team can be found in the Student Experiment Documentation (SED), which is available online [8].

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