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ORIGINAL PAPER

Autonomous Thermal Simulator for EXOMARS-MicroMED Calibration

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Abstract

The paper presents the process innovation introduced by the Autonomous Thermal Simulator (ATS), in the development test campaign loop of space scientific equipment and devices. ATS is a special thermal simulator equipment originally designed to support the ground calibration of "MicroMED", a scientific instrument for the study of Martian environment that will be integrated on the lander of the ExoMars 2020 mission led by the European and Russian space agencies. The development activities of MicroMED before the flight require numerous tests in the laboratory both to calibrate the instrument and to verify its operations and performances under the same operating conditions foreseen during the operations on Mars. The ATS not only meets the specific functional and operational requirements of the development/calibration/set up tests of equipment destined for space missions similar to that of MicroMED but introduces a significant change of the overall testing process: for setting up the instruments, for its calibration, and finally for the qualification and validation. The rationale for introducing this change arises from the observation that the development of MicroMED-like equipment (being sensors, experiments or devices) to be installed on board space platforms, has testing requirements less stringent than the ones related to the spacecraft itself, since the operative environment is not the same. In addition, the execution of tests campaigns for development and qualification of space apparatus, using the conventional equipment/process, results to be money and time consuming, and—utmost important—not so flexible and manageable as the experimenter wishes it to be; one for all, the use of thermal vacuum chambers, which typically simulate the operative s/c external environment, is not always within everyone's reach and their reduced flexibility in any case impacts the rapid development times often necessary for the development of complex space systems. There is also a second aspect to be considered. The very delicate design of some experiments such as MicroMED, which is highly sensitive to temperature values, gradients and time-variations, especially around its inlet components used to collect Mars atmosphere and dust samples, requires its precise calibration. More specifically, the calibration must be carried out both at fixed temperature set points and along specified temperature time-profiles, with homogeneous temperature values at each instant. Well, if the fixed temperature set point can be easily simulated in most of thermo-vacuum chambers, the particularly demanding dynamic requirement cannot be reproduced in traditional test equipment because of their thermal inertial characteristics. ATS represents a unique apparatus that has the main advantage to closely surround the test hardware as a glove, thus guaranteeing suitable reach of abovementioned strict conditions. ATS leads to a significant change and process innovation in this context.

Keywords ExoMars · Mars · Simulation · Calibration · Thermo-chamber · Space

1 Introduction: ExoMars 2020 and Mars environment

The ExoMars 2020 mission will deliver a European rover and a Russian surface platform to the surface of Mars, after a launch by means of a Proton rocket and a nine-month journey. The ExoMars rover will travel across the Martian surface to search for signs of life. It will collect samples with a drill and analyse them with next-generation instruments.

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ExoMars will be the first mission to combine the capability to move across the surface and to study Mars in depth.

During launch and cruise phases, a carrier module (provided by ESA) will transport the surface platform and the rover within a single aeroshell. A descent module (provided by Roscosmos with contributions by ESA) will separate from the carrier shortly before reaching the Martian atmosphere. During the descent phase, a heat shield will protect the payload from the severe heat flux. Parachutes, thrusters, and damping systems will reduce the speed, allowing a controlled landing on the surface of Mars.

After landing, the rover will exit the platform to start its science mission. The primary objective is to find well-preserved organic material, particularly from the very early history of the planet. The rover will determine the physical and chemical properties of Martian samples, mainly from the subsurface. Underground samples are more likely to include biomarkers, since the tenuous Martian atmosphere offers little protection from radiation and photochemistry at the surface.

After the rover egress, the instruments on the Surface Platform will start their operations. The on-board payload is mainly devoted to image the landing site context, to monitor long-term climate, and perform atmospheric investigations. It is planned to operate for 2 terrestrial years (one Martian year).

Among the several on-board instruments, the Surface Platform includes a meteorological station and a suite of sensors, the Dust Complex, devoted to the study of the dynamics and characteristics of sand and atmospheric dust and of their impact on the characteristics of the atmosphere, its circulation and the global Martian climate.

2 MicroMED Experiment

MicroMED, is a miniaturized evolution of the MEDUSA instrument [7, 8], whose main characteristics are compared in Table 1. It was conceived by INAF Astronomical Observatory of Capodimonte (OAC) for the measurement of characteristics of the dust suspended in the Martian atmosphere near the planet surface, both in terms of particle size and abundance in the size range 0.4–20 µm. It is part of the Dust Complex on board the Russian Surface Platform of the ExoMars 2020 mission.

Martian dust comes from clastic alteration, chemical weathering and erosion (wind/water/ice) of rock beds, as well as regolith (impacts of all sizes). It is permanently present in the atmosphere with variable abundance and has a key role in the dynamic and thermodynamic evolution of the atmosphere (large scale circulation at diurnal-seasonal-annual time-scales) and on the climate. The dust cycle, dust storms and dust devils are typical phenomena involving wind and atmospheric dust.

The dust cycle is characterized by lifting, transport in the atmosphere, deposition and eventual scavenging by clouds and precipitation. As on Earth, on Mars wind is supposed to cause grains (hundreds of nanometres to centimetres) to lift off from surface. Large grains (> 70 µm) are lifted but do not go into suspension and are carried down by winds to surface, where they bounce back into flight (saltation). Saltation trajectories are expected to reach several meters both in length and height [1]. Saltating sand and grains may strike larger grains ($d_p < 1$ cm) and push them along the surface (creep). Saltation may also impact much smaller particles, allowing them break the interparticle forces and go into suspension. Finally, surface volatile outgassing, dust storms and

Table 1 MEDUSA vs MicroMED

	MEDUSA	MicroMED
Total mass	2243 g	500 g
Total maximum power consumption	21.44 W	5 W (average)
Sampling head	Nozzle	Minimized tube
Collecting mirrors aperture	± 33° in FW direction ± 47° in BW direction	± 65° at 90° direction
Sampling volume	1.2 mm × 0.32 mm × 3 mm	1 mm × 1 mm × 0.03 mm
Laser diode	Wavelength: 808 nm, optical power: 1000 mW	Wavelength: 830 nm, optical power: 150 mW
Pump maximum flow rate	5.5 l/min	1.0 l/min
Microbalance for dust	Mass sensitivity: 5.09·108 Hz/g/cm^2	No
Microbalance for water vapour	Mass sensitivity: 2.47·109 Hz/g/cm^2	No
Proximity electronics	4 channels (2 for forward scattering + 2 for backward scattering)	1 channel with 2 outputs: low gain ~ 10^5, high gain ~ 10^7

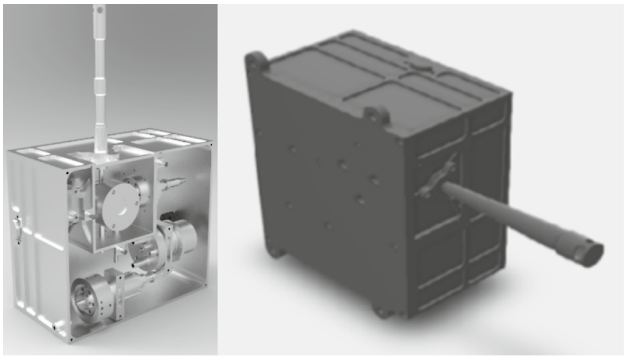


Fig. 1 MicroMED apparatus

dust devils, are also responsible of injection and transport of particles in the atmosphere.

During saltation and suspension processes, impacts cause the grains to acquire electrical charge. On Earth, this process causes the generation of large atmospheric electrical fields [2–6]. This process is believed to be active also on Mars but no instruments have been sent up to now on the Red Planet to measure the electric field, or to monitor the saltation and suspension processes. The Dust Complex, will measure, for the first time and simultaneously, the saltation rate (through an Impact Sensor), the induced suspended dust (MicroMED sensor), the atmospheric electric conductivity and electric field. This will allow to shed light, for the first time, on the dust lifting process on Mars and on its impact on the characteristics of the atmosphere and on the Martian climate.

The MicroMED experiment is the result of the collaboration between INAF, Milan Polytechnic, INTA of Madrid, IKI of Moscow with the support of the Italian Space Agency, and is funded by the Campania Region/ASI.

The concept of MicroMED [9–11] was developed when ESA established to move the ExoMars lander mission into the Entry, Descent and Landing Demonstrator Module (EDM) mission. MicroMED was conceived to satisfy the imposed stringent limitations in terms of mass, accommodation and power consumption.

The MicroMED system is basically a parallelepiped of approximately $70 \times 126 \times 110$ ($L \times W \times H$) mm, with an approximately 88 mm high and a 14 mm max diameter intake inlet (see Fig. 1).

A proper fluid-dynamic system (pump and a sampling head) allows the sampling of Martian atmosphere. Dust grains are detected by an Optical System, based on light scattering, and then ejected into the atmosphere. Inside the container there is a laser, a laser beam absorber, a static light-scattering system composed of a collecting mirror and a photodiode-detector whose signal is amplified–acquired–processed by the electronic board of the device. The latter performs the functions of control and communication from/to the S/C (in reality another sensor of the Dust Complex in which MicroMED is integrated).

The measurement of the dimensional distribution of the sampled grains will allow the characterization of dust in Mars atmosphere and the understanding of its impact on the climate.

The MicroMED apparatus will be placed on one side of the Martian surface platforms (Fig. 2) and protected by a thermal blanket from which the inlet emerges by about 20 mm, to be able to inhale dust from the Martian environment.

Such installation determines the thermal excursion the experiment will be subjected to.

3 Development, Calibration and Qualification Test Requirements for MicroMED-Like Instruments

The preparation of Martian missions presents, in addition to several technological problems, a challenge for the experimenters who prepare the platforms and the experimental modules. Indeed, it is necessary to reproduce and simulate the conditions in which the instrument will operate, i.e. temperature and pressure to properly test the instrumentation. As far as MicroMED is concerned, it is very sensitive to the operating temperature given the very low density of the Martian atmosphere, therefore, it is necessary to properly and finely calibrate the instrument in the operating temperature range conditions envisaged under the thermal cover on the Surface Platform.

The environmental conditions in which the instrument will operate are:

Operational temperature range	− 20° to + 40 °C
Non-operational temperature range	− 40° to + 50 °C
Operational pressure	6–8 mbar

On top of this, the calibration temperature set up point need to be varied with the following characteristics:

Regulation step	0.5 °C
Accuracy	± 0.5 °C

The need to reproduce these conditions is recurrent in the activities of setting up the experimental equipment and must take into account the mandatory sterilization prophylaxis to which every object aimed to touch the Martian soil must comply with (Planetary Protection). To make these recurring operations simple, repetitive and time-effective, it is necessary to have equipment that can be used with extreme flexibility, practicality and reliability.

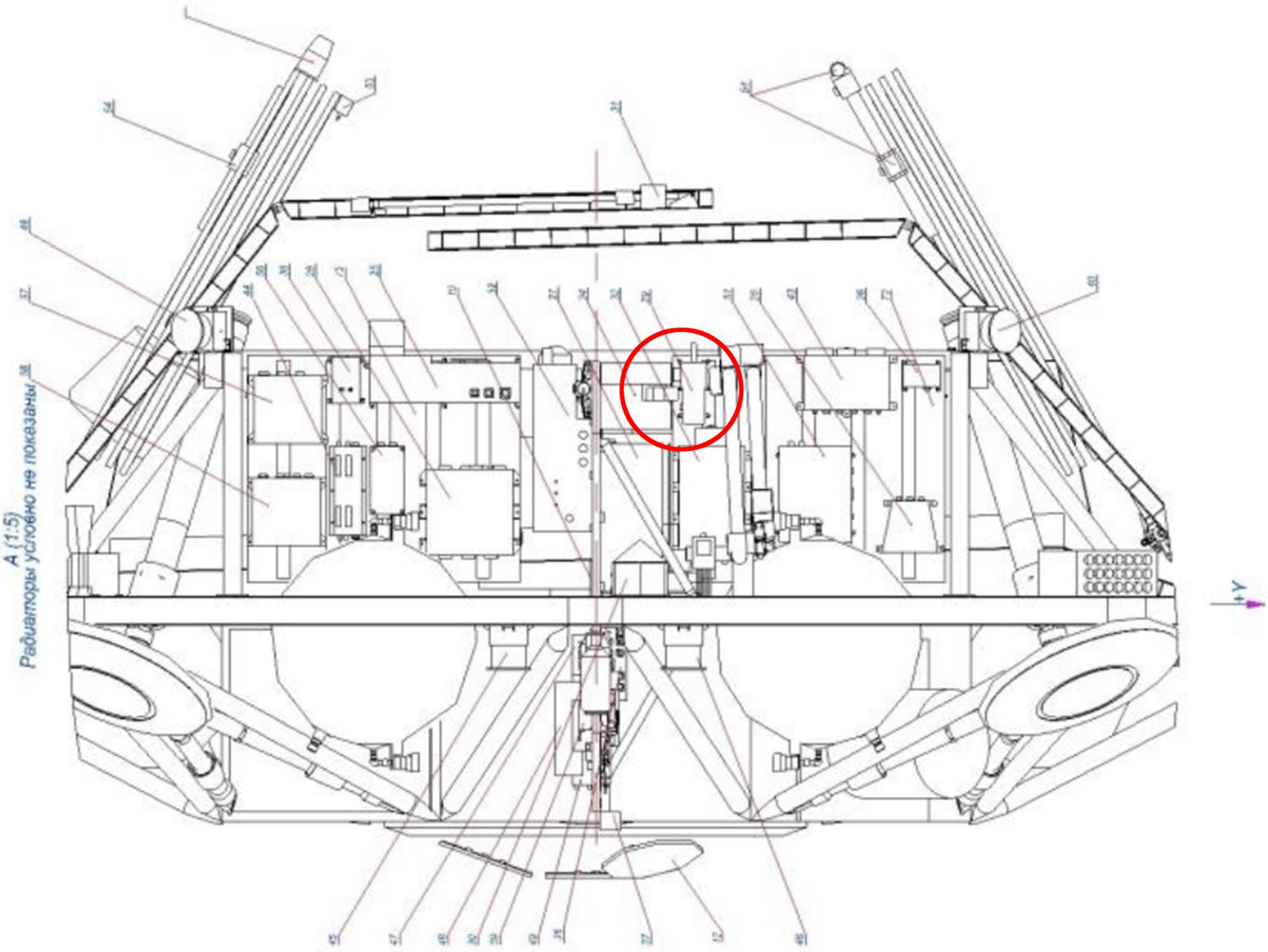


Fig. 2 Position of MicroMED onboard the surface platform of the ExoMars mission 2020

3.1 Test Equipment Requirements

The test setup has to be able to realistically represent the Martian conditions in terms of ambient pressure, ambient temperature and atmospheric composition to allow a realistic simulation of the operations of the planet. The presence of a sterile cleanroom is also mandatory because of the planetary protection constraints that preserve every system outside of Earth from contamination by terrestrial organisms (bacteria and spores).

So, the main features needed for a test equipment dedicated to this specific class of systems are:

- Simulation of pressure in the 6–8 mbar range
- Simulation of temperatures in the range − 20 °C and + 40 °C
- Sterile conditions in accordance with the planetary protection constraints
- Atmosphere made mostly of CO_2 (on Mars the percentage of CO_2 in the atmosphere is 95.3%).

Thermo-vacuum chambers are the most widely diffused equipment to reproduce space environments (in terms of pressure and temperature), however, their dimensions, operating cost and a limited-dynamics do not make them the best solution. Currently the developers have two possibilities:

1. Buy and install a standard vacuum chamber in their laboratory and equip it with all the necessary installations (huge vacuum pump, liquid nitrogen hardware and so on); then provide the chamber with the installations for powder production/ignition, and finally create a surrounding sterile environment.
2. Carry out development activities in another laboratory (which must in any case be equipped with the powder injection system and must be placed in a sterile environment). Continuously transfer the system under test form a laboratory to another (often in a very far location).

It was immediately realized that both the above solutions are expensive, complex and not flexible, consequently they

Fig. 3 The vacuum chamber at INAF-OAC premises in Naples

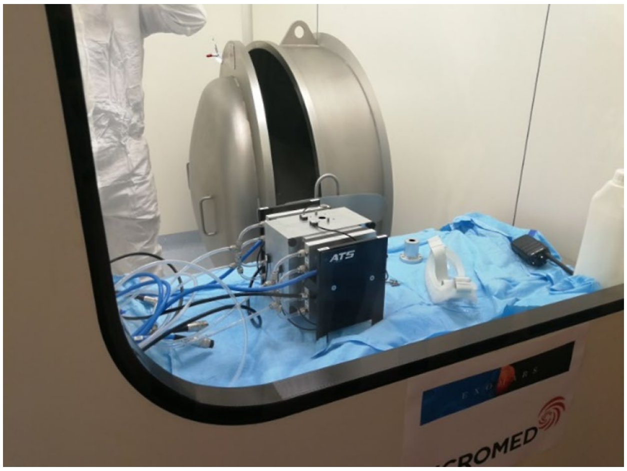


Fig. 4 The clean/sterile chamber at INAF-OAC with ATS ready to be set up

increase the costs and slow-down the development time of the system under investigation/calibration/tuning. It is, therefore, important to have a manageable and performing test equipment, cheap and easy to use, such as to make sterilization operations less demanding.

In the following paragraphs it is shown how the solution used in OAC allows to efficiently and effectively solve the problem.

The problem of low pressure has been solved with a vacuum chamber whose access is possible only from a clean and above all sterile airlock, but the problem of simulating simultaneously the thermal excursions foreseen during the mission remains.

Many of the systems hypothesized proved to be difficult to operate, did not guarantee compatibility with the needs to keep the operating environment sterile and also provided complex and expensive systems and whose operational security would have created other obstacles in the already complicated operations routine.

3.2 INAF-OAC Martian Atmosphere Simulation Set Up

OAC is provided with a small vacuum chamber (a cylindrical stainless-steel vessel, 1300 mm in diameter and 2296 mm in length—see Fig. 3) equipped with a complex injection apparatus which allows to reproduce Martian conditions also in terms of composition and dust loading. The chamber is able to reproduce vacuum conditions up to 10^{-4} mbar, so it is perfectly suitable for the reproduction of Martian pressure conditions (6–8 mbar).

Dust can be injected directly in the chamber through a dedicated device. Dust is embedded in an ethanol solution that is vaporized inside the chamber through a dedicated aerosol generator.

3.3 Clean and Sterile Room

To guarantee the cleaning and the sterile requirements, INAF-OAC is provided with a cleanroom with ISO-7 and ISO-5 conditions that allows to maintain a low level of particulates in the air. Indeed, every tool, instrument or component introduced inside the cleanroom has to be sterilized by means of Isopropyl Alcohol or by means of a dry heat process inside a Binder© oven, and the cleanliness condition helps to keep the elements sterile.

MicroMED integration has been completely executed in such clean conditions, in accordance with the ISO 14644 standards, as well as ATS usage (Fig. 4).

3.4 Test Set Up Finalization with ATS

The thermal environment needs to be simulated and this last is of utmost importance for the instrument calibration being the dust measurement very sensitive to the temperature changes.

INAF-OAC facility was already able to fulfil most of the requirements needed for MicroMED integration and testing. However, MicroMED has to be tested in different temperature conditions, in particular to the limit temperature values to be met during the mission (− 20 °C, + 40 °C). Such aspect is key as the instrument temperature influences the instrument efficiency from a fluid dynamic point of view [9], plus both the laser and the pump ability to work properly throughout the temperature range of the instrument has to be checked.

To by-pass the problems mentioned at the beginning of this paragraph, the INAF-OAC team has renounced the solution of setting up a standard thermal-vacuum chamber in its laboratories. Both the larger dimensions required and

Fig. 5 The ATS "Glove-Box"

the installation of liquid nitrogen plants would have taken away economic and time resources (as well as space in an already overcrowded site of equipment and plants).

Furthermore, the uncertainty persisted that systems based on shroud (radiating panels) or cold plate (conductive bases) would have not satisfied the requirements of uniformity of the thermal field on the system and the performance of thermal cycles in reasonable times.

Last but not least, the need to be able to carry out the development, tuning and calibration of the MicroMED apparatus with sufficient flexibility in its laboratories in close contact with the entire team of scientists and technicians.

The choice of the team consists therefore in completing their test set up with an equipment that overcomes the problems already mentioned at the beginning of this chapter.

The solution was proposed and implemented by Trans-Tech; it is a special autonomous thermal simulator—called ATS, Fig. 5—to be installed inside small vacuum chambers, which embraces MicroMED like a "glove" with no necessity of special plants for its installation and operation and, last but not least, very handy and easy to use in the mounting-dismounting operations.

4 The Autonomous Thermal Simulator ATS

The design of the ATS was conceived to solve both the functional and operational requirements (and scientist's undisclosed wishes) and allows a complete verification of the instrument. The ATS equipment achieves the different temperature conditions needed for the tests. The specific requirements for the ExoMars mission payloads are:

- temperature range: min $< -20°$ max $> +40$ °C (when operative)
- operational pressure: 1 mbar.

And the scientist needs:

- regulation step: 0.5 °C
- accuracy: ±0.2 °C
- thermalization time: < 1 min/ °C.

The operations required on ground to carry out a complete and comprehensive set of calibrations/characterizations of the MicroMED instrument are rather complex due to the simultaneous set up of the functionality of the apparatus (optical system, laser, pump, etc.) and the need to operate in a sterile environment. All of these aspects, together with the need to carry out multiple repetitions of the same operations, produce not only the classic functional requirements (pressure, temperature, etc.) but also non-negligible operational requirements.

To match functional and operational requirements it has become essential to develop an ad-hoc support equipment for ground thermal simulation tests which allows the reproduction of the thermal conditions when MicroMED is placed inside the sterile vacuum chamber. Such specific equipment was not available on the market thus requiring a tailored-design testing apparatus in accordance with the specific functional and operational requirements of the tests as well as the dimensional, electrical and mechanical interface of the MicroMED experimental apparatus.

The System developed by Trans-Tech is based on the use of thermoelectrical actuators (Peltier), overpassing their functional limit (low efficiency at high temperature differences between the two sides) coupling the Peltier "hot" sides with a "water-blocks" thermal exchange devices acting as heat sinks. The combined control of the Peltier and the cooling device for the heat sinks, acting on a mini-thermal-chamber (the "Glove-Box") in which MicroMED is enclosed, allows to obtain the requested performances in terms of temperature and its distribution.

The schematic layout of the ATS system is shown in Fig. 6.

Such system overcome the use of solutions such as Liquid Plate cooled with liquid nitrogen, allowing a more flexible management of the test operations, as well as a better distribution of temperatures to the advantage of greater safety and simplicity of the system.

ATS is also easily transportable and mechanically reconfigurable for applications with different mechanical interfaces.

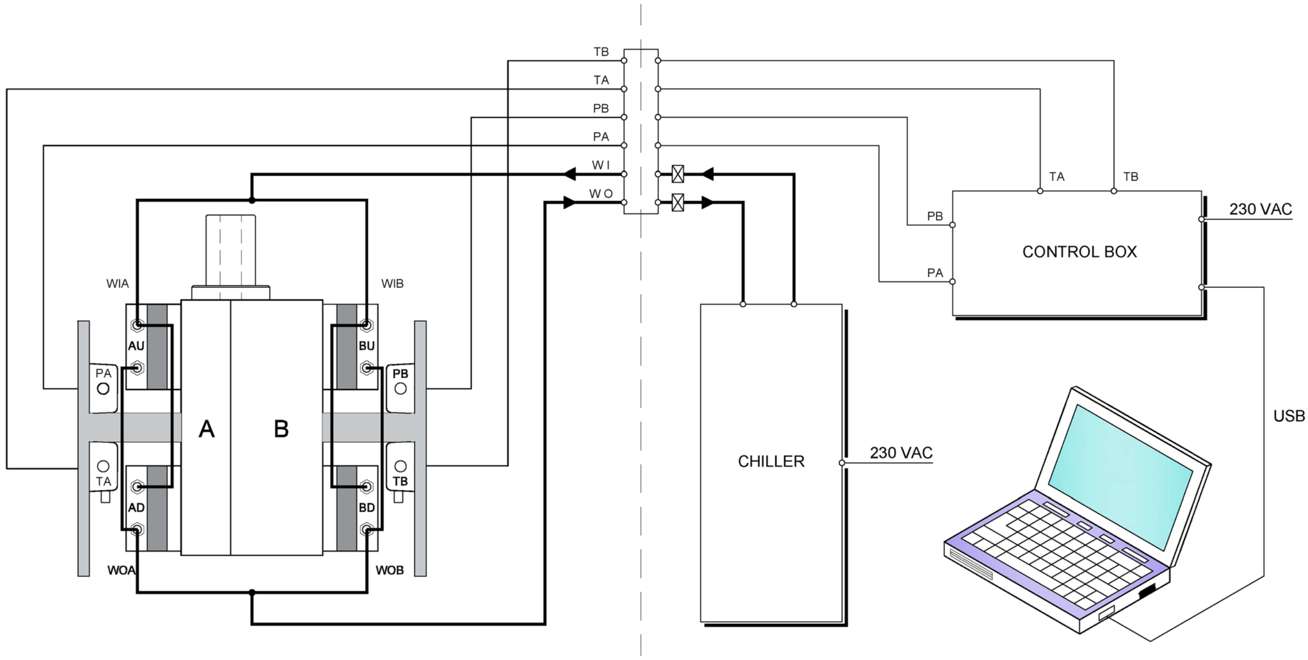


Fig. 6 ATS system layout

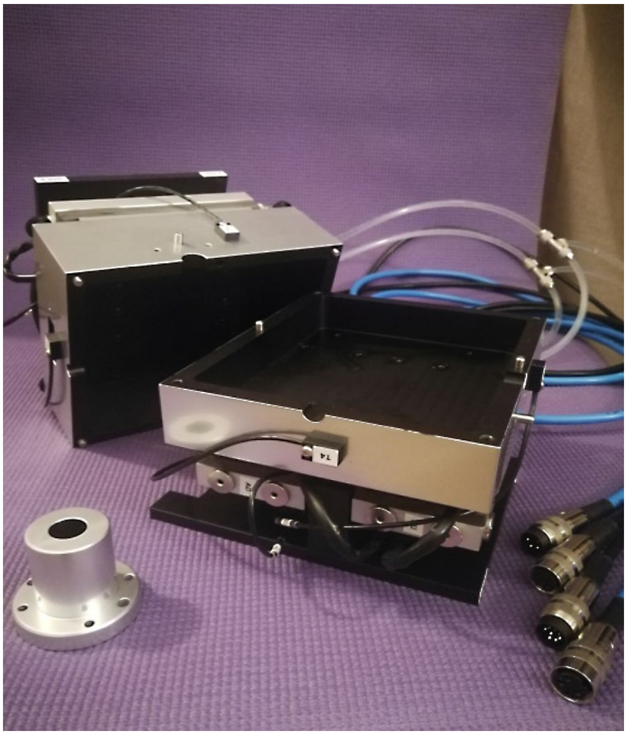


Fig. 7 The ATS "Glove-Box" open

4.1 ATS System Description

The ATS equipment consists of an aluminium container (the "Glove-Box") inside which MicroMED is installed using the same mechanical and E/E interfaces as for its installation on the Lander.

The "Glove-Box" consists of two separable shells for an easy installation of MicroMED (Fig. 7). The sequence of Fig. 8a–c shows MicroMED installation in the thermal box shells.

Each shell is equipped with Peltier actuators, for temperature conditioning, and 10 temperature sensors arranged on its surface (2 of which are dedicated to the control function). The aluminium structure of the "Glove-Box" is black anodized inside (to maximize the heat exchange with its contents) and is polished outside (to minimize heat exchange with the external environment).

The "Glove-Box" is equipped with two insulating supports that allow it to be placed on the floor of the test chamber while maintaining a high level of insulation from it.

The thermal analyses carried out in the design phase show that this configuration ensures a temperature excursion over the whole surface limited within 0.5 °C in the condition of radiation with infinite environment (Fig. 9).

The "Glove-Box" is the only component of the ATS system to be placed inside the vacuum test chamber (Fig. 10). When installed in the test chamber, the Thermal Box is protected by a light Mylar® blanket whose purpose is to further reduce radiative heat exchange with the vacuum test chamber and above all to protect the system from the contamination of the Mars simulant dust grains used during the tests of MicroMED.

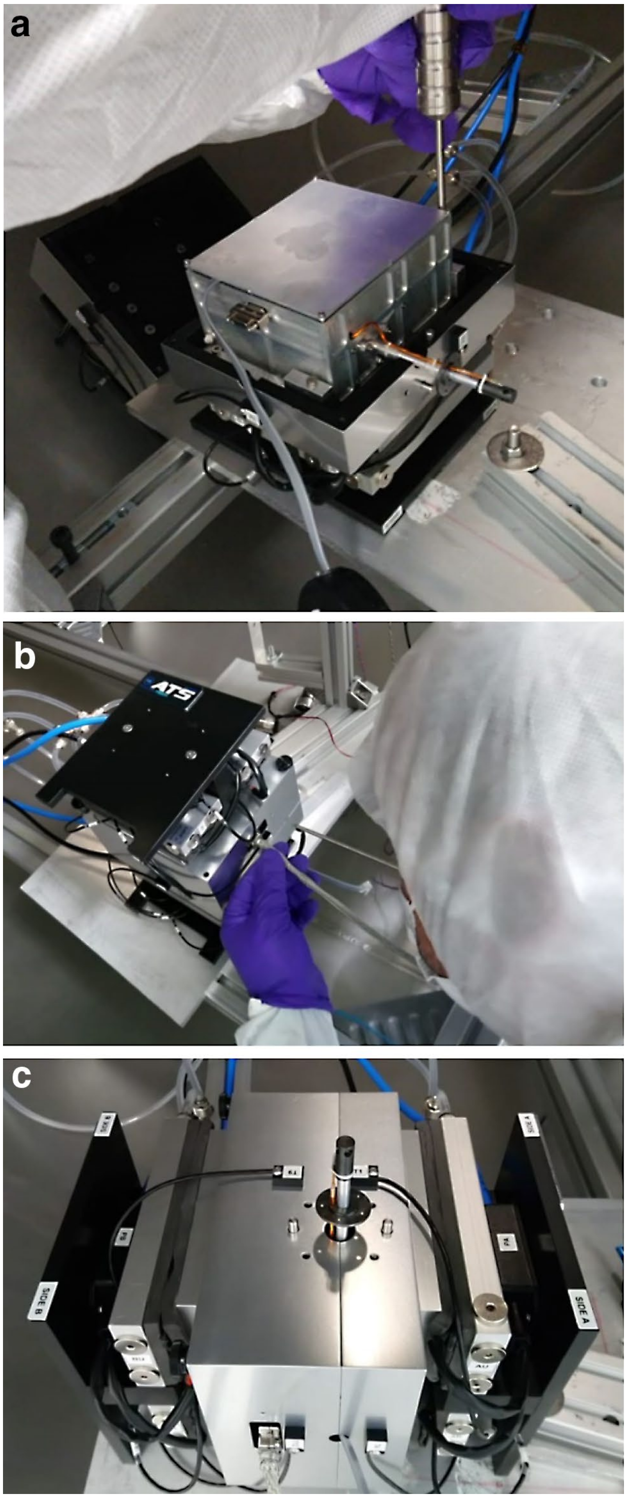


Fig. 8 **a** MicroMED being fixed inside one of the shells of the ATS "Glove-Box". **b** MicroMED installation inside ATS at OAC. **c** "Glove-Box" closed embracing MicroMED

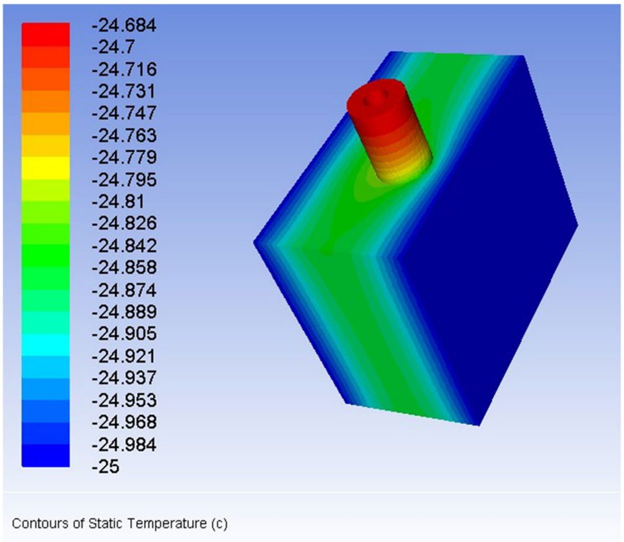


Fig. 9 Temperature distribution inside the "Glove-Box"

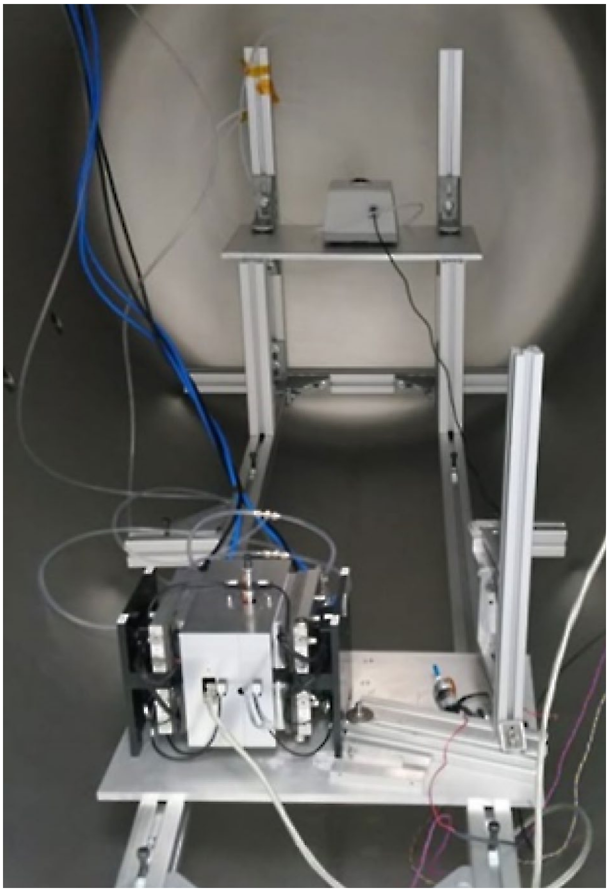


Fig. 10 ATS inside the vacuum chamber

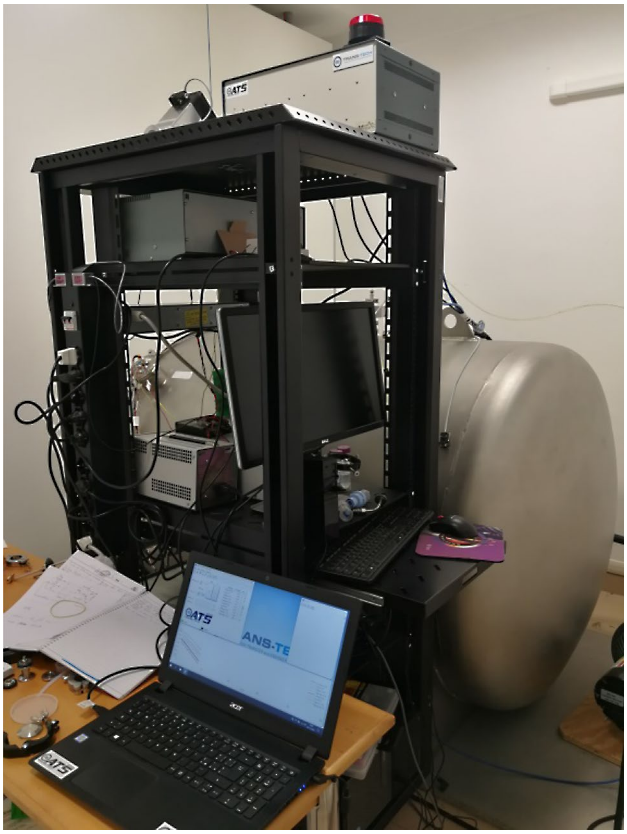


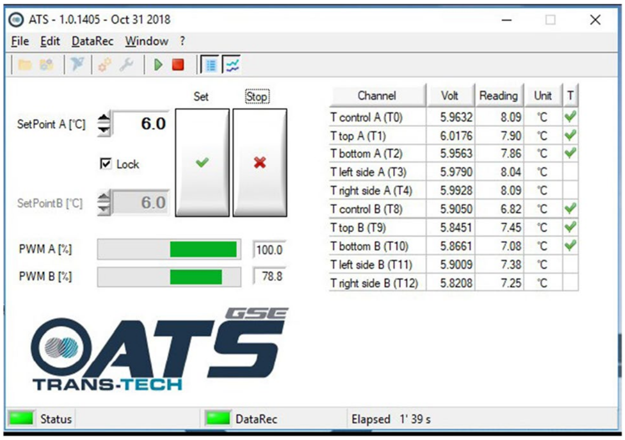
Fig. 11 The Control Computer

Fig. 12 The control box

The “Glove-Box” is connected to the other components of ATS through wiring and piping equipped with E/E connectors and hydraulic through the through-flange specially developed for ATS that guarantees its own seal and the one of the chambers.

Outside the vacuum chamber, the other components of the ATS GSE system are allocated. These components are:

- A Computer equipped with an integrated dedicated SW that operates the settings, control and data acquisition functions as well as their representation and registration (Fig. 11).
- A Control Box, which is the electronic unit that operates the driving of the actuators, the monitoring of sensor signals, data communication and commands to/from the control computer, as well as security functions (Fig. 12).



SetPoint A [°C] 6.0

☑ Lock

SetPoint B [°C] 6.0

PWM A [%] 100.0

PWM B [%] 78.8

Channel	Volt	Reading	Unit	T
T control A (T0)	5.9632	8.09	°C	✓
T top A (T1)	6.0176	7.90	°C	✓
T bottom A (T2)	5.9563	7.86	°C	✓
T left side A (T3)	5.9790	8.04	°C	
T right side A (T4)	5.9928	8.09	°C	
T control B (T8)	5.9050	6.82	°C	✓
T top B (T9)	5.8451	7.45	°C	✓
T bottom B (T10)	5.8661	7.08	°C	✓
T left side B (T11)	5.9009	7.38	°C	
T right side B (T12)	5.8208	7.25	°C	

🟩 Status 🟩 DataRec Elapsed 1' 39 s

Fig. 13 The ATS SW and GUI

A stand-alone chiller (i.e. outside the main control loop) supplies the flow of coolant (water and glycol at 20%) at required pressure for the operation of the thermal actuators.

A largely customizable SW is running on the control computer to allow the monitoring and control of the ATS functions. The screenshot shown in Fig. 13 illustrates the main GUIs available to the operator to manage the system.

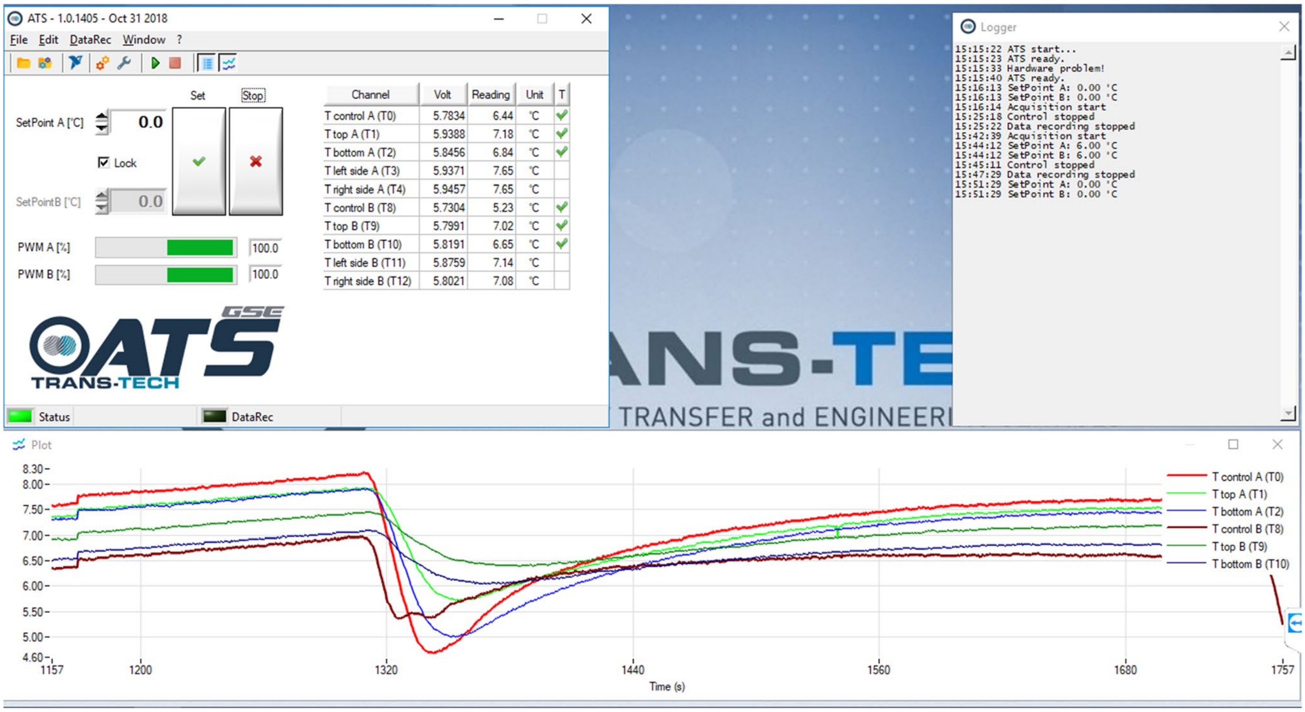
The SW offers the capability to continuously record the temperature historical evolution of the ATS operation during MicroMED test campaigns (Fig. 14).

4.2 ATS Performances

During the qualification and delivery test, performances curves were recorder and stored. The data refers to the ATS functioning without MicroMED inside and in ambient pressure (1 bar), that is a worst condition (presence of thermal exchange by convection and ice formation at low temperature). Figure 15 shows all the temperature monitored on the ATS surfaces during a warm-up (the figure does not show the steady-state condition since the test was performed “in air” and not in vacuum that allow a uniform temperature distribution on the whole ATS surface).

The system achieves the temperature gradient of about > 10 °C/min. It can be noted that the heat sink temperature remains almost constant demonstrating the good design of the overall system.

The curves in Fig. 16 show the warming up of the ATS by 5 °C steps, up to 50 °C. The water temperature flowing inside the heat sink was set at 25 °C. In this case, the average gradient achieved is about 5 °C/min. The heat sink temperature remains almost constant also in this case.



Channel	Volt	Reading	Unit	T
T control A (T0)	5.7834	6.44	°C	✓
T top A (T1)	5.9388	7.18	°C	✓
T bottom A (T2)	5.8456	6.84	°C	✓
T left side A (T3)	5.9371	7.65	°C	
T right side A (T4)	5.9457	7.65	°C	
T control B (T8)	5.7304	5.23	°C	✓
T top B (T9)	5.7991	7.02	°C	✓
T bottom B (T10)	5.8191	6.65	°C	✓
T left side B (T11)	5.8759	7.14	°C	
T right side B (T12)	5.8021	7.08	°C	

```
15:15:22 ATS start...
15:15:23 ATS ready.
15:15:33 Hardware problem!
15:15:40 ATS ready.
15:16:13 SetPoint A: 0.00 'C
15:16:13 SetPoint B: 0.00 'C
15:16:14 Acquisition start
15:25:18 Control stopped
15:25:22 Data recording stopped
15:42:39 Acquisition start
15:44:12 SetPoint A: 6.00 'C
15:44:12 SetPoint B: 6.00 'C
15:45:11 Control stopped
15:47:29 Data recording stopped
15:51:29 SetPoint A: 0.00 'C
15:51:29 SetPoint B: 0.00 'C
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Fig. 14 The ATS SW monitoring panel and logs

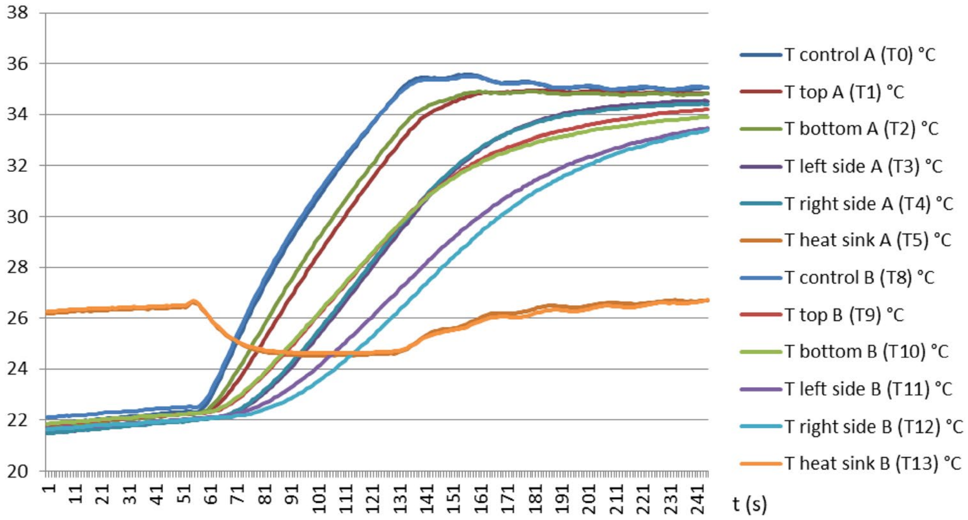


Fig. 15 ATS warming from ambient temp up to 35 °C

Finally, a cooling down test was performed and the results are shown in Fig. 17. In this case, the temperature gradients vary as the temperature decrease; it must be noted that, as said, the test was performed at ambient 1 bar pressure, with significant effect of convection. The temperature gradients are 10 °C/min, then 5 °C/min and finally 2 °C/min as the temperature of the ATS system approaches the – 20 °C. Again, the heat sink temperature (with the water-cooling set at 5 °C) remains almost stable. As far as the functional performances during real MicroMED tests, specifically during the pump and optical subsystems calibration tests, data coming from the temperature sensors installed on MicroMED have been analysed to check the quality of the thermalization process and of the variation of temperature.

As Fig. 18 shows, the instrument temperature uniformly changes and the temperature gradients for the various parts of the instrument appear both linear and uniform throughout the instrument. The ATS system demonstrates to be fast and affordable, with 40-degree temperature variations and uniform temperature field obtained in about 20–30 min.

Fig. 16 ATS warming up to 50 °C by steps

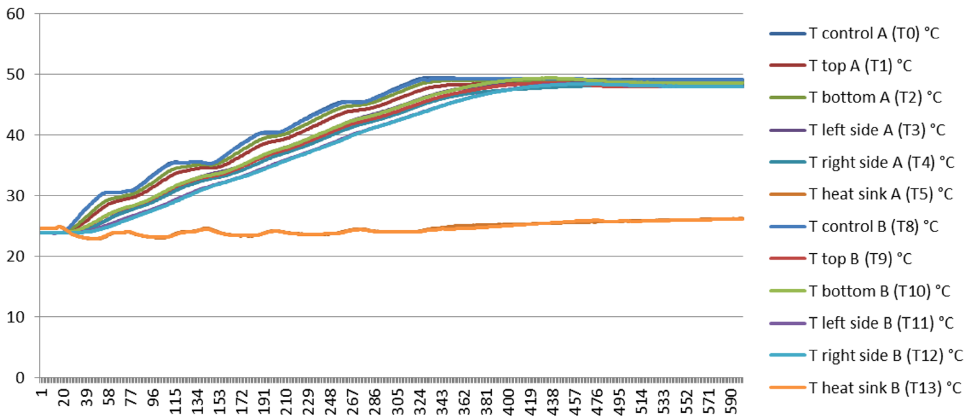
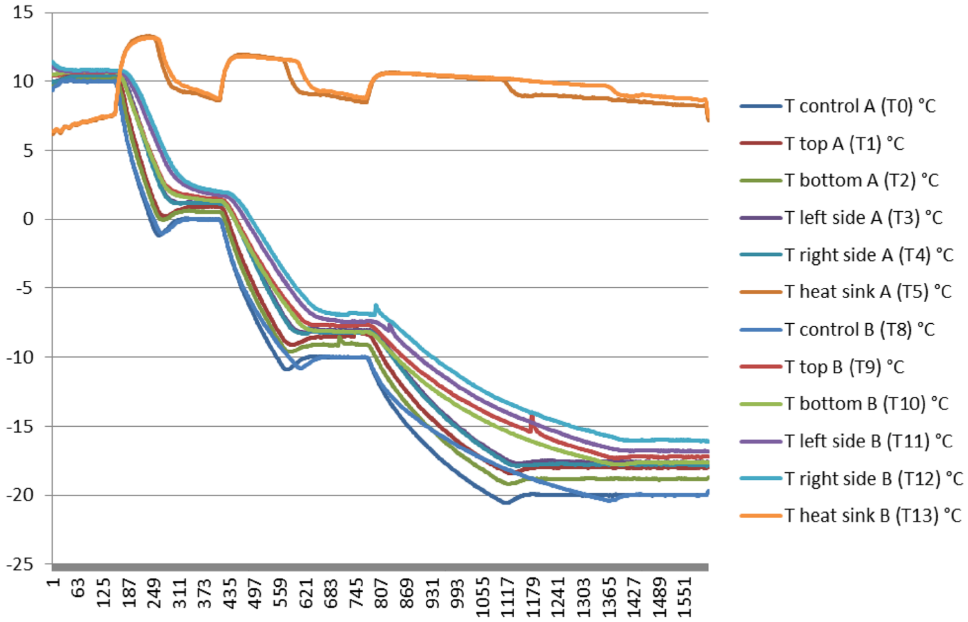


Fig. 17 ATS cooling down at −20 °C by steps



MicroMED test campaigns have been performed both at the Martian Simulation Chamber at the INAF-OAC, and at the AWTS facility (Martian Wind Tunnel) [12] at the University of Aarhus, Denmark.

Given that the two facilities use different temperature control systems (OAC uses the ATS system, meanwhile a cold plate system is installed at the AWTS facility) it was possible to compare the results of tests from the two campaigns to understand which system provides the better performances in terms of stability of the set temperature value, time needed to reach such temperature, uniformity of temperature inside the instrument (among the various subsystems).

During tests performed at the Martian Simulation Chamber in Capodimonte in Naples, MicroMED was placed into the ATS system with only the inlet head outside of the box (by means of the custom-made hole conceived for the inlet head). The ATS is perfectly suited for the installation of MicroMED, which can be fixed using screws on one of the ATS shells. Inside the Chamber, Martian conditions in terms of atmospheric pressure (6 mbar) and composition (CO2) were set.

At the AWTS facility in Denmark, instead, MicroMED was installed on a cold plate, while inside the chamber. Martian conditions were then set.

Comparison of the test results in both facilities are described in Table 2.

Table 2 shows that the ATS allows a more uniform temperature distribution among the different MicroMED subsystems. Indeed, temperature differences range between 6.5 and 8.5 °C when using the Cold Plate, and between 1.5 and 1.7 °C with the ATS. Moreover, the difference between the set temperature value for the tests and the average temperature of the subsystems is significantly lower with the ATS, allowing average differences of less than 2 °C.

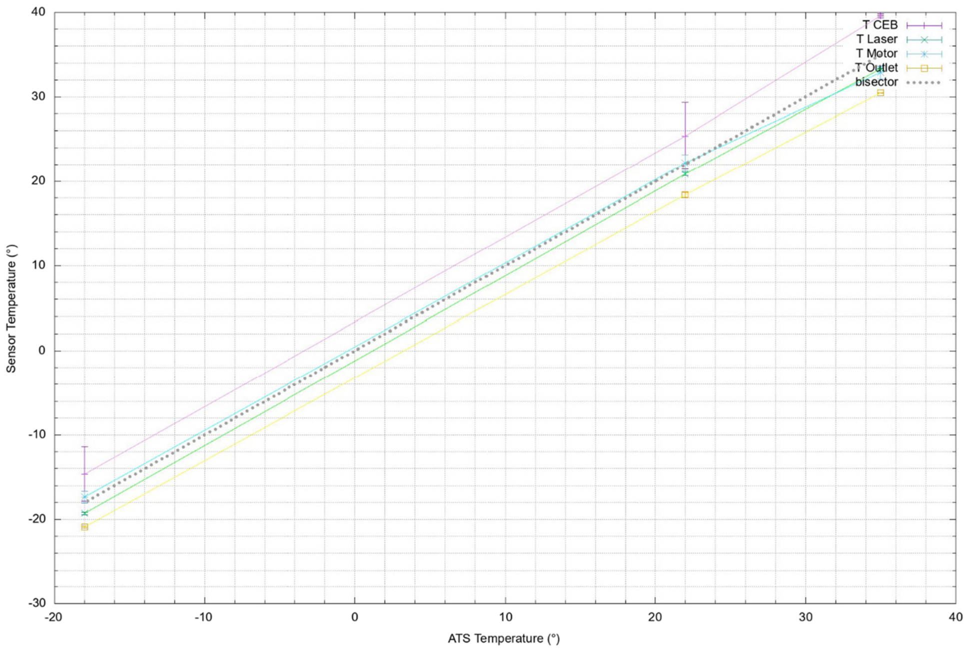


Fig. 18 Evolution of the values of the temperature sensors present on MicroMED vs ATS temperature

Table 2 Temperature difference among MicroMED subsystems for various measurement runs performed with MicroMED set up on the AWTS cooling plate and on the ATS

Run ID	Duration (s)	T_{set}	$T_{\text{in\_laser}}$	$T_{\text{fin\_laser}}$	$T_{\text{in\_outlet}}$	$T_{\text{fin\_outlet}}$	$T_{\text{in\_motor}}$	$T_{\text{fin\_motor}}$	Max_diff	Avg_diff
Cold plate (all temperatures are in °C)										
62	180	− 15	− 11	− 8	− 7.5	− 6.2	− 4.5	− 2.3	6.5	7.33
63	79	− 15	− 10	− 8	− 5.8	− 5.3	− 2.7	− 2.1	7.3	8.83
63b	176	− 15	− 9	− 7	− 5.5	− 5	− 2	0	7	9.50
64	180	− 15	− 9	− 7	− 4.7	− 5	− 0.5	− 2	8.5	10.27
65	104	− 15	− 14.5	− 12.5	− 11	− 11.5	− 8	− 7	6.5	3.83
65b	80	− 15	− 14	− 12.5	− 11.7	− 12	− 7	− 6.5	7	4.10
65c	133	− 15	− 14	− 12.5	− 11.8	− 12	− 6.3	− 5.7	7.7	4.30
ATS (all temperatures are in °C)										
0150	37	− 15	− 15.3	− 15	− 16.1	− 16.1	− 17	− 16.3	1.7	1.13
0160	47	− 15	− 15.1	− 14.8	− 16	− 15.8	− 16.6	− 16.6	1.5	0.90

Table 3 Temperature gradient measured on different MicroMED subsystems during operation runs with MicroMED set up on a cold plate and on the ATS

Run ID	Duration (s)	Grad_laser (K/min)	Grad_outlet (K/min)	Grad_motor (K/min)
Cold plate				
62	180	1.00	0.43	0.73
63	79	1.52	0.38	0.46
63b	176	0.68	0.17	0.68
64	180	0.67	0.10	0.50
65	104	1.15	0.29	0.58
65b	80	1.13	0.23	0.38
65c	133	0.68	0.09	0.27
ATS				
0150	37	0.49	0.00	1.14
0160	47	0.38	0.26	0.00

Table 4 Comparison of ATS vs conventional thermo-vacuum chambers

Pro and con's		
	Thermo vacuum chambers	ATS—autonomous thermal simulator
General	They are massive and highly integrated systems and the actuators for thermal control inserted inside the vacuum but require non-negligible external plants	ATS can be easily integrated in existing vacuum chamber with a minimal effort and the only external devices are a PC and ECU (electronic control unit) and an industrial chiller (water/glycol)
Temperature ranges	− 70 °C/+ 100 °C Up to − 195 °C/+ 150 °C	Nominal − 20 °C/+ 40 °C Max − 30 °C/+ 60 °C
Sterilization	Possible only by integrating all or part of the chamber in clean and sterile laboratories (of considerable size)	Using small vacuum chambers, it is possible to create more clean and sterile environments with reduced costs and easier usage
Costs	Order of 100/1000 thousand euro	Order of 10 thousand euro
Dimensions	Significant (meters)	Can be easily integrated into a small vacuum chamber (< 1 m in diameter) Furthermore, it is possible to make ATS vacuum tight (which would make the use of vacuum chambers no longer necessary)
Thermal control system:	Cooling Liquid nitrogen flooding (boiling mode) Liquid nitrogen partial flooding (boiling mode) Liquid nitrogen pressurized circuit Pressurized gaseous nitrogen circuit Combined liquid and gaseous nitrogen modes Mechanical cooling with intermediate fluid Heating: Lamps or IR emitters	Peltier cells with controlled heat sink, both for cooling and heating
Others	Require the installation of fixed plant with nitrogen circulation at very low temperature and high pressure	No fixed installation is required to carry water and glycol inside the chamber at normal temperatures (min − 15 °C) and pressure (max 6 bar) The circulation is ensured by conventional industrial chillers (transportable)
Heat transfer	Radiation by shroud: greater uniformity in the thermal field but slow dynamics Conduction by cold plate: faster dynamics but very strong temperature gradient	By conduction and radiation since all the system under test is enclosed inside the "ATS "Glove-Box": superior temperature uniformity and faster dynamics

Even during the tests, the ATS guarantees a more uniform temperature for the subsystems. The ATS is thus able to very quickly counteract the natural temperature increase due to the powering of MicroMED subsystems (e.g. when the laser is switched on and dissipates heat).

ATS is also able to reach the set temperature value faster than the cold plate system.

As can be observed in Table 3, the temperature gradients registered at the different MicroMED subsystems are lower using ATS with respect to the cold plate.

5 Conclusions

The primary (and qualifying) characteristic of the ATS system consists in "embracing" the sample with the test field rather than creating a more or less regular environment (cube, parallelepiped, etc.) where to place the experimental or production object. This allows a much more precise control (in space and time) of the conditions to be guaranteed on the experimental or production object.

The ATS system is extensively scalable:

- in size—the thermal box can have dimensions adapted to the specific use.
- in layout—the thermal box can be easily scaled in a "plate" or in a box with all the sides controlled by Peltier elements. Furthermore, parts of the structure can also be made with transparent surfaces according to specific needs
- in performance—temperature range, control accuracy and dynamics can be adapted to specific requirements
- in equipment—the number of Peltier cells, sensors and above all the presence or type of chiller, can be modified according to needs

Furthermore, ATS presents a number of advantages with respect to conventional solutions, as shown in Table 4.

The ATS system can be used in multiple fields:

- Medicine—keeping temperature of cultures/organisms during under control during examination/analysis procedures
- Engineering—any need for thermal tests on small objects (max 500 × 500 × 500 mm envelope) in the absence of thermal chambers or for flexible operation
- Biology—keeping temperature of biological samples under control during examination/analysis procedures
- In various research fields where strict environmental thermal control is required both in terms of set point and temperature time profiles. For example: fluid physics, material physics, biophysics, hydroponic cultivation, etc.

ATS is a versatile system, designed specifically to reproduce the thermal environment in which the instrument MicroMED will operate. It allows precise and fast tests of the instrument in its whole operating range, from −20 to +40 °C. The produced thermal environment has proven to be highly stable and reproducible. ATS can be sterilized so it can be placed in clean environment and in contact with flight hardware and is able to work also in the low-pressure CO_2 environment needed to simulate Martian conditions.

The system can be easily adapted to be used in different environments and for different applications.

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References

1. Almeida et al (2008) Giant saltation on Mars. PNAS 105(17):6222–6226. https://doi.org/10.1073/pnas.0800202105
2. Esposito F, Molinaro R, Popa CI, Molfese C, Cozzolino F, Marty L, Taj-Eddine K, Di Achille G, Franzese G, Silvestro S, Ori GG (2016) The role of the atmospheric electric field in the dust-lifting process. Geophys Res Lett. https://doi.org/10.1002/2016gl068463
3. Franzese G, Esposito F, Lorenz R, Silvestro S, Pop CI, Molinaro R, Cozzolino F, Molfese C, Marty L, Deniskina N (2018) Electric properties of dust devils. Earth Planet Sci Lett 493:71–81. https://doi.org/10.1016/j.epsl.2018.04.023
4. Harrison RG, Barth E, Esposito F, Merrison J, Montmessin F, Aplin KL, Borlina C, Berthelier JJ, Déprez G, Farell W, Houghton IMP, Renno NO, Nicoll KA, Tripathi SN, Zimmerman M (2016) Applications of electrified dust and dust devil electrodynamics to Martian atmospheric electricity. Space Sci Rev. https://doi.org/10.1007/s11214-016-0241-8
5. Neakrase LDV, Balme MR, Esposito F, Kelling T, Klose M, Kok JF, Marticorena B, Merrison J, Patel M, Wurm G (2016) Particle lifting processes in dust devils, Space Science Review, 203. Iss. 1–4:347–376. https://doi.org/10.1007/s11214-016-0296-6
6. Murphy J, Steakley K, Balme M, Deprez G, Esposito F, Kahanpää H, Lemmon M, Lorenz R, Murdoch N, Neakrase L, Patel M, Whelley P (2016) Field measurements of terrestrial and martian dust devils. Space Sci Rev 203(1–4):39–87. https://doi.org/10.1007/s11214-016-0283-y
7. Colangeli L, Lopez-Moreno JJ, Nørnberg P, Della Corte V, Esposito F, Mazzotta Epifani E, Merrison J, Molfese C, Palumbo P, Rodriguez-Gomez JF, Rotundi A, Visconti G, Zarnecki JC, MEDUSA: the ExoMars experiment for in situ monitoring of dust and water vapour (2009) MEDUSA: the ExoMars experiment for in situ monitoring of dust and water vapour. Planet Space Sci 57:1043–1049. https://doi.org/10.1016/j.pss.2008.07.013
8. Esposito F, Colangeli L, Della Corte V, Molfese C, Palumbo P, Ventura S, Merrison J, Nørnberg P, Rodriguez-Gomez JF, Lopez Moreno JJ, Battistelli E, Gueli S, Paolinetti R, The International MEDUSA Team (2011) MEDUSA: observation of atmospheric dust and water vapor close to the surface of Mars. Int J Mars Sci Explor 6:1–12. https://doi.org/10.1555/mars.2011.0001
9. Mongelluzzo G, Esposito F, Cozzolino F, Molfese C, Silvestro S, Popa CI, Dall'Ora M, Lubieniecki M, Cortecchia F, Saggin

B, Scaccabarozzi D, Zakharov A (2018) Optimization of the fluid dynamic design of the dust suite-MicroMED sensor for the ExoMars 2020 mission. In: 2018 5th IEEE international workshop on metrology for aerospace (MetroAeroSpace), 2018. https://doi.org/10.1109/metroaerospace.2018.8453505

10. Scaccabarozzi D, Saggin B, Pagliara C, Magni M, Tarabini M, Esposito F, Molfese C, Cozzolino F, Cortecchia F, Dolnikov G, Kuznetsov I, Lyash A, Zakharov A (2018) MicroMED, design of a particle analyzer for Mars. Measurement 122:466–472
11. Scaccabarozzi D, Saggin B, Pagliara C, Magni M, Tarabini M, Esposito F, Molfese C, Dolnikov G (2017) Thermo-mechanical design of a particle analyzer for Mars. In: 2017 IEEE international workshop on metrology for aerospace (MetroAeroSpace), 2017. https://doi.org/10.1109/metroaerospace.2017.7999571
12. Holstein-Rathlou C, Merrison J, Iversen JJ, Jakobsen AB, Nicolajsen R, Nørnberg P, Rasmussen K, Merlone A, Lopardo G, Hudson T, Banfield D, Portyankina G (2017) An environmental wind tunnel facility for testing meteorological sensor systems. J Atmos Ocean Technol 31(2):447–457. https://doi.org/10.1175/jtech-d-13-00141.1