Mimicking Mars: A vacuum simulation chamber for testing environmental instrumentation for Mars exploration

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We have built a Mars environmental simulation chamber, designed to test new electromechanical devices and instruments that could be used in space missions. We have developed this environmental system aiming at validating the meteorological station Rover Environment Monitoring Station of NASA's Mars Science Laboratory mission currently installed on Curiosity rover. The vacuum chamber has been built following a modular configuration and operates at pressures ranging from 1000 to 10^{-6} mbars, and it is possible to control the gas composition (the atmosphere) within this pressure range. The device (or sample) under study can be irradiated by an ultraviolet source and its temperature can be controlled in the range from 108 to 423 K. As an important improvement with respect to other simulation chambers, the atmospheric gas into the experimental chamber is cooled at the walls by the use of liquid-nitrogen heat exchangers. This chamber incorporates a dust generation mechanism designed to study Martian-dust deposition while modifying the conditions of temperature, and UV irradiated. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4868592>]

I. INTRODUCTION AND OBJECTIVE

More than 20 years after the Viking's¹ missions to study the Red planet, NASA has returned to the exploration of Mars aiming at determining the atmospheric and surface characteristics of the planet to survey possible habitability. In this sense, it has become essential to develop new instrumentation capable of detecting with higher resolution and precision the main variables that determine the atmospheric parameters on the planet's surface.² These variables are the pressure, ground and air temperature, wind direction, relative humidity, and ultraviolet radiation.

The use of planetary simulation chambers has become a common approach to prepare special missions. Vacuum experimental set-up can mimic some of the most important environmental parameters in a close environment. Among the most important applications in current and future missions are the study of DNA damage by space radiation;^{3,4} stability of crystalline phases of minerals on the surface of Mars;⁵ instrumentation validation, or survival of spores in space mission and planetary surface; or cosmic ices.⁶ These are a few examples of a long interdisciplinary list of different aspects that can be studied in these simulation chambers.

Simulation of Mars planetary conditions using vacuum chambers is not a new issue. Most of the existing experimental setups were built for specific use. Thus, some are optimized for studying biological samples in different environmental conditions.^{7,8} Others designed as large systems were testing the behavior of instrumentation and sensors on wind conditions and dust storms on the planet's surface, such as MARSWIT (Martian Surface Wind Tunnel),⁹ or the wind tunnel of the Oxford University¹⁰ and Aarhus University.¹¹ Fi-

nally, commercial systems are climatic chambers, designed to study the thermal behavior of instrumentation or to validate some protocols.

The objective of this communication is to present a new and versatile Mars simulation chamber designed primarily to test some of the environmental sensors of the meteorological station REMS (Rover Environment Monitoring Station)¹² of the mission MSL (Mars Science Laboratory)¹³ onboard the rover Curiosity, in real working conditions. The main technical characteristics and specificities of this chamber, that we have called MARTE, will be discussed along this work (see Figure 1).

There are several advantages and differences of MARTE, with respect to other simulation planetary systems: the versatility for testing different instruments or samples, the treatment of the atmospheric gases, and the possibility to include Martian dust. MARTE has been conceived in a modular concept (the total volume can be modified) and it is possible to study the behavior of instrumentation and samples of different nature and sizes in pressure ranges up to 10^{-6} mbars, with temperature control in sample holder in the range [108 K < T < 423 K]. The main body permits to simulate sun illumination at different azimuths and UV-radiation; and an extreme control on the gas composition at all total pressures using a quadrupole mass spectrometer. The atmospheric gas can be efficiently cooled down at the walls. Finally, it is possible to deposit dust by an original vibration system using gravity.

All the information is recorded by *ad hoc* developed software with LabView®, which collects the signals of different pressure sensors (Piezoresistive, Pirani, Capacitive, and Penning) to cover different pressure ranges and time response to different experimental requirements, as well as various temperature sensors and relative humidity, which we can observe in real time absorption and desorption phenomena occurring on the internal surface of the vacuum chamber, as in the

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FIG. 1. Photograph of the MARTE simulation chamber.

samples to study. This experimental set-up is open to any interested scientist or technologist.

II. TECHNICAL DESCRIPTION

Figure 2 is a schematic representation of MARTE simulation chamber indicating the position of the main pieces of equipment. MARTE is formed by two independent vacuum vessels separated by an electro-pneumatic valve. The main chamber or atmospheric chamber (AC), where the Mars atmosphere and the sample, device or instrument (from now on we will call sample) under study is introduced; and the dust chamber (DC), where we can simulate Mars dust-storms. The AC consists of two cylindrical bodies. The union between them is performed by vacuum seals LF [10^{-8} mbars]. We chose this type of design because of their versatility, pumping-speed efficiency, and simplicity of the closing protocols. Nevertheless, every one of those bodies includes ConFlat (CF) flanges so that other laboratory equipment can be easily installed. Both cylinders incorporate an inner serpentine for liquid nitrogen cooling, which allows decreasing the temperature of the atmospheric gas, and not exclusively on the sample under study. This is an important item as many other simulation setups do not cool the atmospheric gas, and therefore effects related to a rarefied atmosphere are not considered into the results.

The bottom cover of the vacuum chamber has a mechanical opening system sliding vertically and horizontally to facilitate placement of the samples. On this cover is located the sample holder bench, which allows to modify the surface temperature in the range from 108 K to 423 K by the

FIG. 2. Technical draw of MARTE, in the configuration used to test the REMS sensors of the MSL mission on board Curiosity rover.

circulation of liquid nitrogen. Also at the bottom cover a multi-pin feedthrough is located for controlling, powering, and monitoring the sample under study. In the upper ring-body several DN40CF are placed flanges pointing towards the sample that simulate the sun's position relative to the Mars surface on a tropical, at different times of the day. This design aims to help in the study of the daily response of photodiodes, as the REMS UV sensor for the NASA MSL mission. In the top cover, an electro-pneumatic valve connects the chamber AC with the dust chamber, where is the dust generator. In the AC chamber are installed the UV source, the image recording set-up and the temperature and humidity sensors.

We will consider the standard Mars atmospheric conditions to be the following:²

- **Gas composition:** Ar 1.6%; CO₂ 95%; H₂O 0.6%; N₂ 2.6%.
- **Local temperature on surface (sample holder):** 150 K < T < 280 K.
- **Pressure:** 7–20 mbars.
- **Dust:** mixture of magnetic and nonmagnetic iron oxide particles (only used for optical experiments).

A. Dust generator

The day-by-day coating of the optical rover's instruments on Mars by the atmospheric dust is one of the most intricate technological problems limiting the lifetime of many missions. One of the main advantages of this machine over any other is the ability to provide a simulation system with the

possibility of spreading dust in vacuum conditions. The free fall of a particle can describe two types of trajectories based on the resistance to progress and the interaction between the neighboring particles and the environmental gas. Ballistic trajectories, when they have no resistance to progress (high vacuum regime), and Brownian trajectories, as the particles diffuse through the fluid medium (atmosphere) in the volume of the vacuum chamber (low-vacuum regime). In the case of the Mars atmosphere, we are interested in Brownian motion to mimic the real conditions near the Mars surface. This unique set-up will allow for obtaining an estimate of the evolution of the reading at the photodiodes of the ultraviolet sensor when working in the dusty Martian atmosphere.^{1,14} As time passes, they get progressively covered and their efficiency will be progressively attenuated.

Particles used to simulate dust are composed mainly by magnetic and nonmagnetic iron oxides similar in composition to those detected on Mars. The mean particle size is less than $63\text{ }\mu\text{m}$ in diameter¹⁵ and they are placed on a dust repository compartment. This small chamber consists of two sieves, as indicated in Figure 3. Both sieves have holes of $63\text{ }\mu\text{m}$ diameter and both vibrate by using a counterweight motor shaft. The motor generates an irregular movement directly connected to the box supporting them (Fig. 3). The irregular vibration uniformly disperses the particles on the two sieves. Once the particles pass the second one, and depending on the total pressure, and the dynamic viscosity of the gas, the particles fell down by gravity. We performed our tests for REMS UV sensor with 200 mbars of Martian atmosphere, which is 95% CO_2 , at room temperature. Under these conditions we could disperse dust throughout the vacuum chamber, creating a homogeneous layer that allows us to simulate the atmosphere, temperature, and the dusty conditions of the planet.

B. Local and environmental temperature control

The sample holder consists of a copper plate ($205 \times 205 \times 6$) mm that supports the device or sample under study. The

FIG. 3. Section of dust chamber, DC, with the dust generation system.

FIG. 4. Sample holder of MARTE simulation chamber.

surface of the plate is drilled with holes M4 spaced 25 mm from each other, mimicking optical tables. This entire block is suspended by four screws M12, which allow you to adjust the height of the sample holder. The temperature of the surface of the sample holder can be controlled in the range $[108\text{ K} < T < 423\text{ K}]$. The passing of liquid nitrogen from an external dewar to the sample holder is performed by a cryogenic feedthrough. PTFE (polytetrafluoroethylene) flexible pipes lead the liquid nitrogen to the sample holder inside the steel block (Figure 4). Between the steel block and the final copper surface we have installed a resistance type Thermocoax® of 280 W that permits to regulate the temperature on surface. Screwed on the copper surface are located three types of sensors, each for different temperature ranges and response speeds: Thermocouple type K, Pt100 $[-50^\circ\text{C}, +200^\circ\text{C}]$, and Pt100 $[-200^\circ\text{C}, +800^\circ\text{C}]$. The temperature control is performed by a proportional integral differential (PID) controller (Watlow F4S®), which powers the electrical heating resistance and at the same time opens the solenoid valve controlled way in time to allow the flow of liquid nitrogen.

To cool down the gas atmosphere inside the MARTE chamber, there are two stainless steel rings (serpentine type) with an internal volume of 2.5 liters each (Figure 2). Each ring is connected to the outside by means of cryogenic feedthroughs that allow liquid nitrogen to fill the internal volume. The rings are spaced 5 mm inside the vacuum chamber to reduce thermal conduction from the wall. The filling and control method is carried out through a dewar located 1 m above the top cover of the AC and therefore acts by gravitational pressure (Figure 1). Both rings are filled simultaneously but the output of the two rings is joined, and is driving back the nitrogen to the main dewar. The control of the dewar filling is performed by passing an electrically programmed electrovalve, which is connected to another storage self-pressurized dewar of 120 l. We monitor the temperature of the inner rings by means of two type K thermocouples, each located on a cooling ring. AC is covered with neoprene isolation 1 cm thick (Figure 1). In this way the outside surface of the chamber is at the lowest and homogeneous

FIG. 5. Residual gas composition (RGA) in the Mars atmosphere at 7 mbars for three different temperatures in the sample holder, in the case of cooling the inner rings with liquid nitrogen at 77 K. Red shows an RGA at sample holder -6°C , orange at -80°C , and blue at -180°C . The vertical axis shows the ions current in ampere.

temperature as possible, minimizing the liquid nitrogen consumption.

With the system described above, we control the atmospheric temperature inside the MARTE vacuum chamber; however, this might not be straightforward. Mars atmosphere can be set, for instance, to few mbars pressure consisting in 95% CO_2 , and the remaining 5% is composed of H_2O , N_2 , and Ar_2 . However, CO_2 , the main atmospheric gas, is a poor heat transmitter and can condense on the cold walls, changing the atmospheric gas composition. This effect is shown in Figure 5, where residual gas spectra recorded at different temperatures are shown. Figure 5 shows the analog spectra or RGA measured by the mass spectrometer, through differential pumping, for the chamber between 7 mbars and 20 mbars. From room temperature to -10°C the main gas of the atmosphere is mass 44 (CO_2), as this gas only condenses on Teflon tubes in sample holder and mass corresponding to nitrogen and argon is the minority (5%). As we move down the temperature of the sample holder, the mass 44 is condensed in the cold areas (77 K, which correspond to the Teflon tubing and steel block in sample holder). The orange graph with sample holder (copper block) at -80°C indicates that the main mass in MARTE is 28, corresponding to nitrogen, following the mass 40 argon, and finally the mass 44 is CO_2 , the minority contributions are the mass 14 and 20, which correspond to the double ionization of nitrogen and argon. The blue graph which corresponds to the lowest limit surface temperature attainable in sample holder (copper block) indicates that the majority mass is 28 followed by 40 and finally 44. This indicates that as we decrease the walls' temperature in MARTE, and maintain constant pressure, CO_2 condenses and the only gases that stay in the atmosphere are nitrogen and argon, gases that are a minority in the atmosphere of Mars. This effect can be a real problem, and therefore temperatures above the condensation threshold of CO_2 have to be used. The limit of CO_2 at 7 mbars is 148 K (-125°C).¹⁶

C. Pressure control

The pressure control on MARTE is performed in dynamic mode, except the test of the pressure sensor from the Finnish Meteorological Institute (FMI), with manual pumping conductance, through a fine adjustment valve and automatic variable gas flow inlet. This mode of operation is known as STD. MARTE chamber has a rotary pump of $20\text{ m}^3/\text{h}$ pumping speed. In cases where it is necessary to reach 10^{-6} mbars, we have a Turbo pump with 60 l/s pumping speed. For the Mars simulations we only use the rotary pump.

For pressure measuring, we use different types of sensors, depending on the gas type in the atmosphere, and the response speed required in the experiment. The choice of capacitive and piezoresistive gauge is of paramount importance, because the reading is independent of gas type (direct gauge). We used in MARTE chamber four types of gauges: Pirani [$1000 < P < 5 \times 10^{-4}$] mbars, if we need a quick reading of the vacuum pressure, capacitive [$110 < P < 1 \times 10^{-2}$] mbars, and piezoresistive [$1000 < P < 1 \times 10^{-1}$] mbars, when mixed-gas atmospheres are used, and in the case of low vacuum, combined Pirani-Penning [$1000 < P < 5 \times 10^{-9}$] mbars.

We adjust the nominal pressure in mode STD, and the system automatically regulates the gas flow with respect to a reference sensor with variable gas flow. The control valve regulates the gas inlet into the vacuum system, for a specific pump speed. We regulate the conductance through a valve. For example, when decreasing the temperature at constant volume, the system is forced to increase the inflow of gas to maintain pressure constant, because the main gas (CO_2 on Mars) condenses on cool surfaces.

Condensation of water on the experimental walls is not an issue because the system has been previously pumped down to the limit, and the residual water pressure, as checked by our differentially pumped RGA, is about 3 orders of magnitude lower than the one from CO_2 or He in ATS (Air Temperature Sensor) Test.

We used two types of automatic gas flow valves. In the AC chamber we have the valve (Pfeiffer RME 005), for medium conductance and in the DC chamber we have the fine adjustment conductance (Pfeiffer EVR 116). This valve has a slower response time, because it cannot work with large flows, and the volume of the DC is much smaller than AC.

D. Measuring of gas composition

Gas composition inside the AC is determined by quadrupole mass spectrometer (Pfeiffer QMG 220) operating in two different ways depending on the total pressure. For high pressures (1 atm to 10^{-5} mbars, as it could be the case of Mars at 7 mbars) a differential pumping setup for the quadrupole is used. This allows us to measure and characterize the gas composition in our AC, even at some mbars of total pressure (Mars conditions). When AC is pumped down at pressures below 10^{-5} mbars, we introduce the quadrupole directly inside the chamber. The quadrupole is connected to a gas-manifold where several mixtures can be used to reproduce the desired atmosphere. When mimicking Mars we normally use 95% of CO_2 , 3% nitrogen, and 2% argon, at pressures from 5 to 10 mbars.

FIG. 6. Photography of the environmental temperature and humidity sensor placed on a Nylon rod at different distances from the bottom of the chamber.

E. Monitoring environmental temperature and relative humidity

We have developed two types of environmental sensors in order to characterize the ambient temperature and relative humidity, while performing simulations in MARTE chamber. Both are installed equispaced along a vertically placed Nylon rod 70 mm long and finishing in M4 threaded into a hole of the sample holder or directly on a DN40CF feedthrough (see Figures 2 and 6). On the rod we set different pairs of temperature and humidity sensors.

The Environmental Temperature Sensor (ETS) consists of RTD (Resistance Temperature Detector, type PT1000, Class A). Normally we use 5 of them distributed along the rod. These sensors have wires of equal length and thickness, so that the heat exchange through them is minimized, avoiding offset for each sensor. The sensor signals are extracted through a feedthrough in DN40CF and taken to the data acquisition system (see Figure 7).

We have tested the temperature sensor in 5 different conditions.

1. Mars gas mixture to 7 mbars with interior rings full of liquid nitrogen at 77 K.
2. Air (vacuum) at 10^{-3} mbars (maximum range of rotary vacuum pump, Pfeiffer DUO 20).
3. Air at 13 mbars.
4. Helium 5M, at 4 mbars.
5. Helium 5M, at 3 mbars with interior rings full of liquid nitrogen at 77 K.

FIG. 7. Photography of the bottom part of MARTE chamber when opened to air. Red numbers corresponding to components and instrumentation: (1) Nitrogen liquid Inner line of sample holder; (2) Thermocoax® resistance between steel and copper block in sample holder; (3) sample holder; (4) ATS engineering model (Observe the FR4 rod); (5) engineering model of pressure sensor and ICU (Integrated Circuit Unit) of REMS; (6) ETS sensor.

TABLE I. Measurement of maximum to low temperatures of the different environmental sensors registered in many types of atmospheres, measured with the ETS sensor. Temperatures are in °C. Pt5 sensor is the nearest to the sample holder, it is 70 mm. The test number 5 is necessary to test the minimum temperature inside MARTE vacuum chamber.

Sensor	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
Pt1	0	8	−4	−14.5	−16
Pt2	−5	8.5	−5	−20.5	−28
Pt3	−12	7.5	−5.5	−24.5	−46.5
Pt4	−18.2	8	−5	−33	−70
Pt5	−24.6	7	−9.5	−63.5	−90
Sample Holder	−125	−163	−161	−166	−165

The reading of the different sensors in these above mentioned conditions is summarized in Table I. Sensor Pt1 is at the higher part of the rod, and Pt5 is the closest to the sample holder table. Situation 1 is crucial for climate studies of Mars, because it is mimicking real Martian conditions (pressure and gas composition); however, it suffers from CO₂ condensation on surface sample holder. All other operating set-ups were used to evaluate different aspects of the environmental possibilities of the MARTE chamber. Helium gas was used in conditions 4 and 5 because it is an inert gas with high thermal conductivity, which promotes heat exchange on the cold surfaces and makes possible to reduce the internal temperature of the vacuum chamber, especially in the proximity of the air sensor ATS of REMS. Curiously, as it will be discussed later, the Pt1000 temperature sensor data of the ATS sensor placed at the end of the rod (Pt5) read the minimum temperature when helium gas is used (conditions 4 and 5), and we can conclude that this situation is closer to the real.

The humidity sensor is a Honeywell HIH-4000 Series, which is normally coupled with a temperature sensor. In the configuration shown in Fig. 6, we have 7 pairs of sensors. Sensor 1 is near to the bottom of the chamber and sensor 7 is near to the top. All sensors are equally distributed along the supporting rod (Nylon M8, 500 mm length).

III. REMS: TESTING SENSORS IN MARTE (AIR TEMPERATURE AND PRESSURE SENSOR)

REMS is the name of the meteorological station on board the rover MSL Curiosity of NASA's mission. It measures pressure, relative humidity, ground temperature, wind speed and direction, and ultraviolet radiation with a combination of different devices and small instruments sited on the rover case.¹² In MARTE we tested three of them at working standard conditions, particularly the atmospheric temperature, pressure, and UV sensors (the latter is not discussed in this article).

A. Air Temperature Sensor on curiosity

ATSs are located in the Curiosity “booms” (devices that contain the ATS, Wind, and Ground Temperature sensors). There are two of them on the mast of the rover. ATS¹² consists of a FR4 rod (epoxy laminate, mainly used in the construction

FIG. 8. Temperature of the RTD (Pt1000) located at the end of the rod in the ATS1 (blue) and ATS2 (green). These devices are part of the boom1 and boom2. The minimum temperatures correspond to SOL (Martian day) between 57 and 94. In these days the Rover Curiosity was still. Data from MSL Planetary Data System of NASA.

of integrated circuit boards) 35 mm long, on which are located three RTD (Resistance Temperature Detector, Pt1000 class A, with a size of 1.2×1.6 mm). Two of them are located at the extremes of the rod FR4, and the other in the middle. In the side rod, are imprinted the traces leading electrical signals to electronics following a zigzag pattern so that heat conduction is minimized through it. This sensor can calculate air temperature through the use of an algorithm previously published.¹⁷ Fig. 8 shows real data sent by the rover corresponding to the reading of the outermost external sensors.

We tested the ATS sensor at the 5 working conditions indicated previously for the ETS sensor, but it was placed at the same height with respect to the sample holder table of Pt5 (see Table I). The most favorable conditions for checking the minimum temperature of ATS on the Mars planet were made with helium as exchange gas atmosphere (see Table I in the conditions 4 and 5).

B. Pressure sensor

The REMS pressure sensor is a temperature compensated capacitive sensor developed by the FMI. It consists of two transceivers with BAROCAP® Vaisala technology for pressure and Thermocap® for temperature. One is to achieve high stability and the other high-resolution.¹² The pressure sensor is located inside the body of Curiosity rover and is connected to the outside through a chimney.

In MARTE chamber have been carried out two types of tests with respect to the pressure sensor. One of them at different temperatures and absolute pressure ranges, [0–14] hPa (mbar) with 100 Pa intervals and [−45 °C, +55 °C] with max 15 °C intervals, in an atmosphere similar to Mars, and the second one was devoted to determine the response of the sensor against sudden pressure variations. Abrupt pressure changes can be expected during wind or dust storms, and it is

important to know which is the sensor response in these conditions. The novel aspect is to verify the accuracy and response time of the pressure sensor after an abrupt change in pressure and ambient temperature.

To this goal, we used the DC as gas reservoir. When we open the pneumatic valve separating both chambers (Figure 2) the volume of the AC increases. In this way by estimating the relationship between the volumes of the two chambers, we calculate the values of initial pressure to obtain the desired total increase. The opening time of the electro-pneumatic valve is always the same, about 1 s:

$$\frac{V_2}{V_1} = \frac{P_1}{P_F} - 1 = r. \quad (1)$$

In formula (1), V_2 is the volume of atmospheric chamber AC, V_1 is the volume of dust chamber DC, the pressure P_1 is the pressure of the dust chamber, and P_F is the final pressure measured when the two chambers are connected because the valve is open. For calculating the volume ratio, r (ratio between volumes of both chambers), the atmospheric pressure in the AC or chamber 2 is considered to be 10^{-3} mbars (limit rotary pump) and the pressure in the DC is 1 atm. The value r obtained with the pressure sensor inside MARTE is 21.8 by formula (1).

In order to set a particular increase in the pressure, ΔP , we have to adjust the pressure in DC or chamber 1 before opening the valve. Formula (2) is the mathematical relationship between these two magnitudes:

$$\Delta P(r + 1) + P_2 = P_1. \quad (2)$$

The experimental results are shown in Table II. “ r ” has been calculated following formula (1), and measuring the pressure before (P_1 , P_2) and after (P_F) opening the valve. P_F is determined after using different pressure sensors from Fig. 9. In MARTE set-up, we have estimated a resolution in the determination of the absolute pressure reading of the sensor of 0.05 mbars between 1 and 4 s (time to pressure is stabilized). This value is obtained using as reference gauge Pfeiffer CMR 362 in AC chamber, with calibration ENAC (16/LC142). The second, third, and fourth rows of Table II show different ΔP for which pressure sensors were tested, following formula (2).

Thus, the MARTE chamber meets the specifications of the REMS test plan, for determining pressure (and pressure variations) in Mars conditions. However, we would like to make a point of caution. To fully understand the result of the abovementioned test, temperature variations induced in the expansion-compression process must be considered. They can affect the result of direct sensor measurements, as in the

TABLE II. Values of the pressure in the different chambers for testing the REMS pressure sensor. See text for definition of the magnitudes. Data obtained following formula (2). First row, determination of r following formula (1).

	ΔP (mbars)	P_1 (mbars)	P_2 (mbars)	P_F (mbars)	$r = \frac{V_2}{V_1}$
Calculating “ r ”	...	915.4	0	40.08	21.8
ΔP_1	1.44	42.5	6.06	7.5	...
ΔP_2	0.05	7.14	6	6.05	...
ΔP_3	0.1	8.27	6.01	6.11	...

FIG. 9. The left figure shows the time evolution of the pressure sensors at the AC chamber after opening the connection valves. The stable final result is the value of P_F required for calculating the volume ratio, r . The right figure shows the same determination using the sensors of the DC. In both cases the final reading for PF is 40.08 mbars. The different pressure readings in DC before the valve opening is due to the accuracies at low vacuum range of the different gauges used.

capacitive temperature compensated gauge of the FMI pressure sensor. The changes associated to pressure variations affect to changes in the temperature of the vacuum vessel (atmosphere). To observe this effect, we performed measurements with our temperature sensors (ETS), which indicated a maximum gradient of 0.6°C at the instant of valve opening. In Figure 10, we show the temperature change recorded at different heights with respect to the surface. At the time of opening the valve to an abrupt change in pressure with an increment of 1 atm, there is an expansion in the dust chamber and the gas compression in the atmospheric chamber. When the pressure increases in MARTE, there is also a rapid temperature increase due to gas compression. In Fig. 10 we show temperature variation of sensors located at the middle of the rod (sensors 3 and 4, see Sec. II E). At this level, the increase of temperature is about $0.17\text{--}0.23^\circ\text{C}$. This increase in temperature stabilizes at two minutes and a half, which is the minimum time of MARTE chamber stability for static pressure measurements. The uncertainty of REMS pressure sensor decreases exponentially with time with the following time constants: 2 min for high-stability Barocap® and 15 s for high-

FIG. 10. Evolution of the temperature at the moment of opening the gate valve between the two chambers. The graphs show an increase in temperature at the time of gas compression. Sensors 3 and 4 are separated by 70 mm and located at 210 mm from the bottom of the chamber.

resolution Barocap®.¹² This effect is not usually taking into account but it can be important for accurate determination of abrupt pressure variation in the electronic of the device.

IV. CONCLUSIONS

We have built a versatile vacuum system to simulate the atmospheric conditions on Mars surface. The MARTE chamber is now a unique platform for Mars environmental simulation and test of optical and electronic instrumentation, having proven its functionality in the tests of REMS environmental station on Curiosity rover.

The vacuum chamber has been built following a modular configuration and operates at pressures ranging from 1000 to 10^{-6} mbars, and it is possible to control the gas composition (the atmosphere) within this pressure range. An important improvement with respect to other simulation chambers is that the gas is cooled at the walls by the use of liquid-nitrogen heat exchangers. MARTE incorporates a dust generation mechanism.

When mimicking the typical Mars atmosphere it is very important to consider condensation effects of carbon dioxide at a pressure of few mbars on the walls of the chamber. The use of He instead of CO_2 could be a good solution to evaluate the effect of a cold atmosphere in temperature and pressure determinations.

The dual chamber configuration of MARTE is adequate to study the response of sensors towards sudden pressure variations, as the one that can be produced by storms on the Mars surface.

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