COMSOL thermal simulations of a Mars environment facility

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Abstract

This work describes the implementation with COMSOL Multiphysics® of a thermal simulation of a space environmental chamber, the SpaceQ chamber [1]. Space environment facilities are needed to test and simulate on Earth the expected performance of hardware and instrumentation that shall operate in space. The main goal of this work is to demonstrate the potential of COMSOL to simulate the thermal gradients within the chamber and use this to design future tests of space instrumentation in simulating facilities and to decide where to install thermal control sensors. We validate the model against the experimental measurements in the chamber used under Martian and vacuum conditions. Here, we use the 'Heat transfer module' software package, we model the properties of the chamber walls, the injected, pressurized atmosphere and the refrigerating table, and consider conduction, convection and radiation in solids and gases and surface-surface radiation. For studies under Martian surface conditions, to test the operation of instrumentation of the ExoMars 2022 mission to Mars [2], the chamber is filled-in with CO_2 at about seven mbar, and the base is refrigerated down to 250K. This produces unavoidable, strong, thermal gradients within the chamber, as the walls are in contact with the laboratory ambient. For future vacuum tests, the chamber shall be used to bake components out and test degassing during the cruise phase in space or to validate the operation of instruments for the Moon when they are exposed to direct solar illumination. For this purpose, the chamber has an external heating blanket, and the chamber is vacuumed to down to 10^{-3} mbar.

Keywords: *simulation, Mars, vacuum, Heat transfer*

1. Introduction

The simulation chambers have played a major role in space and interplanetary missions from the 1960s [3]. They have been used to recreate as close as possible the environmental conditions that an instrument or a spacecraft experience. This allows qualifying specific components and materials for space instrumentation. Simulation chambers can be used for simulating planetary environment [4,5] and to perform Thermal Vacuum Tests (TVT), outgassing and sterilization through the Dry Heat Microbial reduction (DHMR) tests as defined in the standards (ECSS-Q-ST-70-02C and ECSS-Q-ST-70-57C). These tests play a significant role in validating the integrity and thermal performance of the components. The main environmental conditions in space are high vacuum, radiation exposure and varying temperatures. Thus, before launching any spacecraft platform to space, every component or scientific instrument must be tested to demonstrate that it survives through this thermal dynamic process and, when applicable, its functionality must be shown through different thermal ranges.

Our simulating facility, the SpaceQ chamber, has an operating temperature in the range of 163–423 K and the pressure range from $< 10^{-5}$ mbar (high vacuum) to ambient pressure. The cooling of the chamber is performed by passing liquid nitrogen through the working plate. This is controlled by a PID which is in feedback through a temperature sensor. On the other hand, heating is performed by an external jacket that can operate up to 423 K. Though this chamber can be used to qualify components for space operations by performing TVT, outgassing, and sterilization through DHMR tests, the SpaceQ is mainly used for (i) simulating Martian conditions and (ii) to test and qualify instrumentation for space with varying thermal, water content and/or pressure changes.

As the chamber is subjected to a temperature difference created either by cooling or heating locally, this process will produce unavoidably a thermal gradient. So, it is essential to understand the temperature profiles inside the chamber. In particular, in the case of water injection to simulate the water cycle under Martian conditions, the thermal gradients affect the local relative humidity (RH %). Since the RH % is only monitored at one point with a dedicated probe, its extrapolation to the rest of the chamber environment must be inferred through the local temperature (T) and pressure (P) field. Pressure equilibrates within the full chamber, and thus a single point measurement is sufficient. However, the temperature can be only measured at a few spots within the chamber due to the natural room limitations of this closed facility. The purpose of this work is to implement, as a first approach, a 2D COMSOL heat transfer model of the chamber to simulate the thermal gradients inside. Future studies will simulate the 3D behaviour and incorporate the simulation of other elements like the nitrogen pipe, which have strong thermal inertia. The results of the 2D simulations shall be compared with the measurements taken within our Martian environment experimental measurements. The model shall thus provide an overview of the existing thermal gradients for the duration of the tests. These results can be used in the future to plan and perform experiments at different conditions but also to calculate, for each grid point the RH % as a function of the measured RH % and P, and the derived COMSOL temperature field T.

1.1 SpaceQ chamber

An experimental chamber (Figure 1) has been built which can operate at temperatures between 163K to 423K and pressures from < 10^{-5}mbar to ambient. This chamber allows for the injection of different gaseous compositions. The facility is a cubical stainless-steel chamber with 30 cm long edges and an aluminum door. It has various utility ports including two viewports, thermocouple feedthroughs, a relative humidity sensor, Pirani gauges for pressure monitoring, gas inlets, ports for a rotary and a molecular turbo pump, connections of USB, and DB25 to read the data from the instrumentation while being tested inside as well as ports for an infrared spectrometer. Within the chamber, at its base, the facility has a plate that can be cooled down to 163K using liquid nitrogen. Instruments can be mounted directly on this plate, to test their functionality at low temperatures. The chamber walls can be warmed up with an external heating jacket up to 423K, for outgassing, thermal vacuum cycle or other tests. To create a Martian atmosphere, we vacuum the chamber to 10^{-3} mbar and then CO_2 gas is injected from a cylinder (we use 100% CO_2) until the atmospheric pressure inside reaches 7 mbar (average pressure range on Mars).

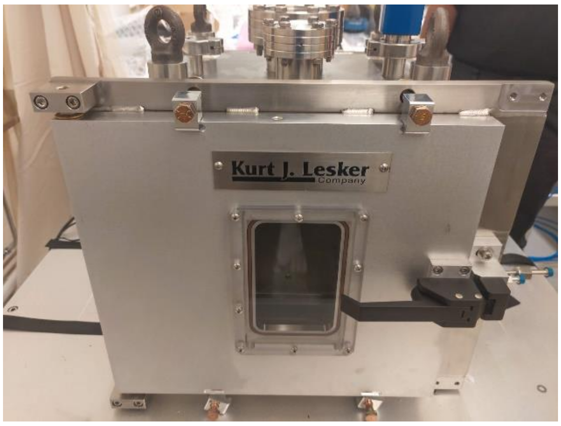

Figure 1. View of the SpaceQ chamber facility.

2. Heat Transfer Theory

Heat transfer is the physical process that describes the interchanges of thermal energy between different environments or bodies. Heat can be transferred by conduction, convection and radiation. There needs to be a difference in temperature between the bodies in which heat transfer happens [6]. A change in temperature in different parts of a body can also cause thermal energy to shift in the body before it reaches thermal equilibrium. If there is no gas or liquid between two bodies that have different temperatures, heat can radiate from the hotter to the cooler one. This can happen in vacuum. Convection occurs in a medium containing free molecules, either liquid or gas that carry heat and produces a natural movement of the fluid, whereas conduction occurs in solid materials [7].

2.1 Heat transfer through conduction

In conduction heat is transferred as a result of vibrating molecules that pass their energy to their closest molecules. Conduction is the primary mode of heat transfer between solid objects in thermal contact. Heat conduction occurs in solids and is described by Fourier's law of heat conduction in equation 1 [8].

$$Q = -kA\nabla T \qquad (1)$$

where,
∇T is the temperature difference,
A is the cross-sectional area normal to the gradient direction, and
k is the thermal conductivity.

2.2 Heat transfer through convection

Heat convection is a mode of heat transfer by the mass motion of a fluid such as air. Heat convection occurs to the surface of an object where the surrounding fluid of an item is heated and takes energy away from the source of heat. Convective heat transfer occurs when the surface temperature differs from that of the surrounding fluid. The governing equation of heat convection is the Newton's law in equation 2 [9],

$$Q = hA\,(T_s - T_f) \qquad (2)$$

Where,
Q is convective heat on the surface,
A is a cross-section of boundary surface,
T_s is the surface temperature and
T_f is the temperature of the surrounding fluid.

2.3 Heat transfer through radiation

Radiative energy passes through a vacuum as well as gases. The heat transfer by radiation depends on the differences of the individual body surface temperatures to the fourth power. Heat transfer through radiation can be modelled with the Stephan-Boltzmann equation in equation (3) [8].

$$Q = \varepsilon\, \sigma\, (T^4_{high} - T^4_{low}) \qquad (3)$$

where,
Q is the heat flux,
ε is the emissivity,
σ is the Stefan–Boltzmann constant and
T is the temperature of the hot (high) and cold (low) bodies.

3. Use of COMSOL Multiphysics

COMSOL is a simulation package software, which is designed to solve real-world applications. The purpose of this simulation is to recreate the effects that take place during the experiments.

This application simulates the experimental investigation of an environmental chamber used to recreate at small scales the temperature and pressures environment of Mars. The purpose of this model is to investigate the resulting thermal gradients inside the chamber produced by the combination of conduction, convection and radiation and to quantify their influence on the net heat exchange.

Here we have considered all three modes of heat transfer. When the working plate is refrigerated, there is a temperature difference with its surroundings, and there is conduction. Because of the same difference, as the heat is transferred through CO_2 gas at low pressures, we must consider convection. Then, to address the radiation, we use a surface to surface radiation which can account for shading and reflection between radiating surfaces.

3.1 Model

We use the Heat transfer module's Conjugate Heat Transfer Laminar Flow model. The geometry of the model is shown in Figure 2. It is a 300x300 mm^2 2D model of the chamber. The chamber has a certain level of symmetry and to reduce the computational time we use a 2D model. In this model, the fluid domain is transparent, and the solid domains are opaque.

The material properties are taken from the library to account for the properties which change with temperatures. The chamber has different materials; the external wall is of stainless steel; the working plate is of aluminum, and the fluid within the chamber is carbon dioxide for Mars environment simulation. To monitor the temperature evolution over time, two domain point probes are located in the model, one on the working table and the other at the point (100 mm,100 mm). This is to compare the simulated temperature profile with the actual experimental values.

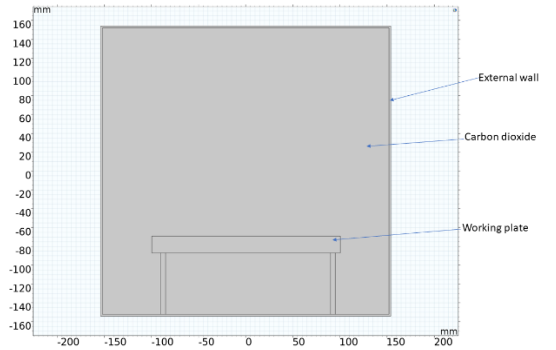

Figure 2. SpaceQ 2D model geometry. Dimensions are in mm.

The mesh (Figure 3) is a physics-controlled mesh with extremely fine element size. The study is time-dependent and is solved in the steps of 1 min up to 400 mins.

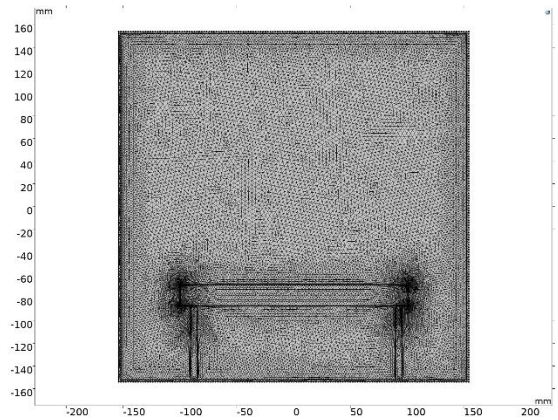

Figure 3. View of Physics-controlled, extremely fine mesh with a maximum element size of 2.06mm.

3.2 Boundary conditions

The convective heat flux through the external walls of the chamber in the model is described by external natural convection through the vertical and horizontal sidewalls, assuming ambient indoor laboratory conditions. Radiation is represented at the chamber's inner surfaces, by surface to surface radiation. The reference pressure level is set at 7 mbar for Mars conditions and 10^{-3} mbar for vacuum conditions.

4. Experimental Results / Simulation Results / Discussion

4.1 Mars Conditions

The simulation is a time-dependent model that solves the equations up to a time of 400 mins. Each simulation takes 10 mins of computing time. The temperature profile that is reached after 400 minutes of simulation is shown in Figure 4. We see that the working plate, which is refrigerated at the start of the experiment to 250 K, is interchanging energy with its surroundings, mainly through radiation, and the system has almost reached equilibrium.

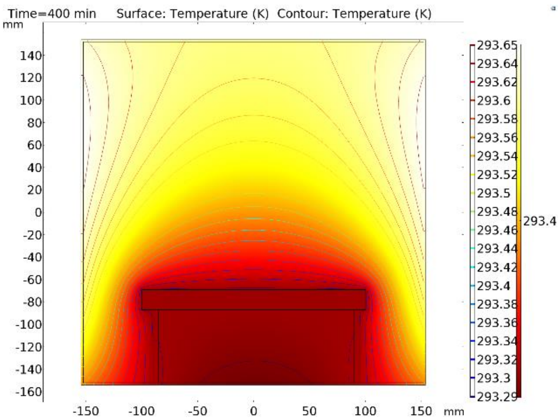

Figure 4. COMSOL simulation: thermal profile cross-section after 400 minutes of simulated evolution.

The temporal evolution of the temperature at the two control points, together with a point representative for the domain and one for the boundary is shown in Figure 5. This plot shows the slow temperature convergence of all the control points towards ambient laboratory conditions. The control points at (0,-87) and (100,100) represent the working plate and the position of the air temperature sensor inside the chamber, respectively. These two values can be used to compare with the actual reading from the experiment.

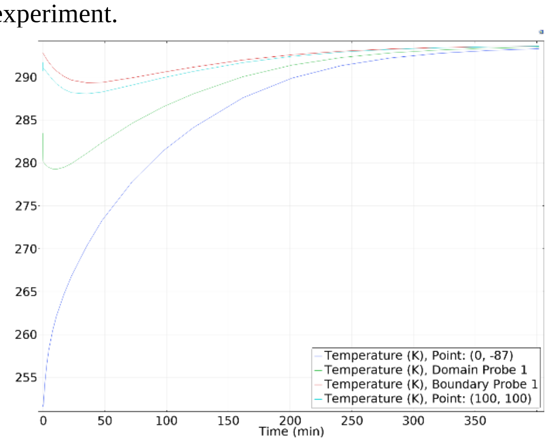

Figure 5. COMSOL simulation: the temporal evolution of the temperature at the two control points, together with a point representative for the domain and one for the boundary.

It is important to know what are the dominant sources of the heat flux inside the chamber. We observe the conductive heat flux in Figure 6, which shows a maximum of 0.15-0.25 W/m^2 at the edges of the working plate. Conductive heat flux is negligible inside the chamber.

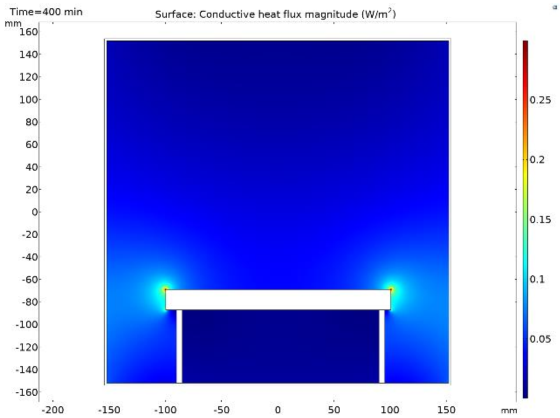

Figure 6. COMSOL simulation: conductive heat flux inside the chamber in W/m^2.

The convective heat flux inside the chamber is shown in Figure 7. We see that there is convection in the fluid domain, which is filled with CO_2 gas at 7 mbar. The large thermal gradients, together with the effect of gravity, produce convective cells. The maximum convective flux of 0.679 W/m^2 is observed at about 70 mm-120 mm above the center of the plate, and at the same height closed to the side walls.

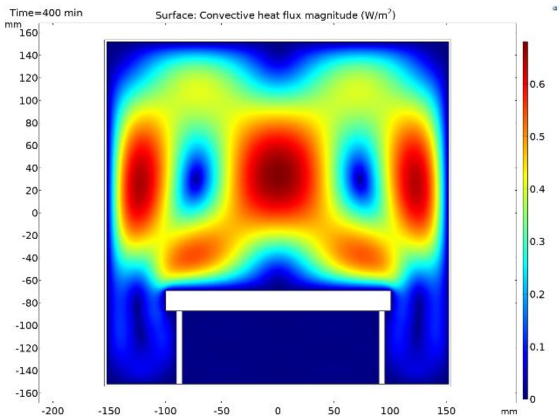

Figure 7. Convective heat flux inside the chamber

The most significant mode of transfer is through radiation, in this case, shown in Figure 8. The radiative heat flux of -0.4 W/m^2 and black body radiation intensity of 133.5 W/m^2*sr can be observed on the working plate and is transferred to the surroundings inside the chamber atmosphere.

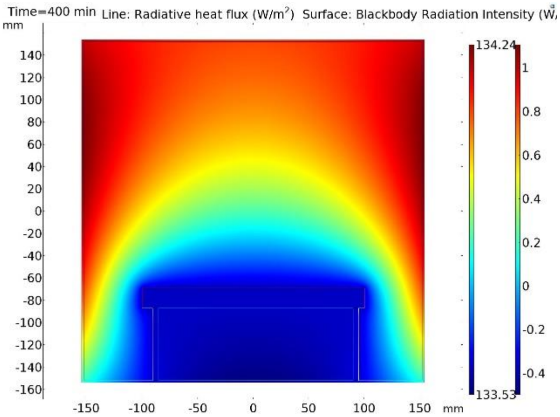

Figure 8. COMSOL simulation: radiative heat flux on the walls of the chamber in W/m^2 and blackbody radiation intensity inside the chamber in W/m^2*sr.

Next, we compare the time evolution of the temperature of the control points with the actual table and air temperature experimental values. The plot is shown in Figure 9; we can see that both the simulation and experimental values follow the same trend to reach the ambient temperature equilibrium. But the evolution of the table temperature shows a difference in temperature when compared to the experiment. This is because in the experiment, we pass liquid nitrogen through a pipe which has its thermal inertia. This pipe is probably slowing down the warming trend of the table. This is not simulated in this simplified COMSOL model. The other drawback is the fact we have simulated in a 2D model which considers two domains as fluid, whereas in the actual experiment, it is one whole domain. This issue will be addressed in the future work by modelling the chamber in a 3D and solving it under more precise conditions.

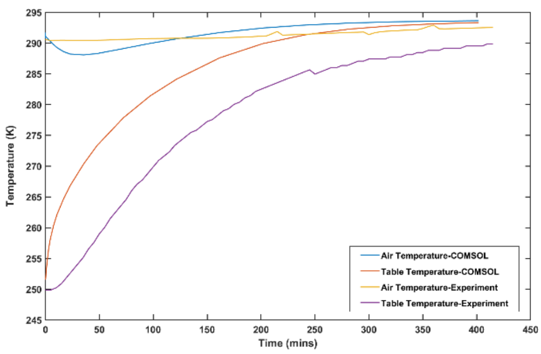

Figure 9. Temporal evolution of the temperatures: comparison of COMSOL simulation and the experimental measurements.

4.2 Vacuum Conditions

Here we simulate a time-dependent model to heat the chamber with an external heating jacket made of glass wool. This jacket has a thickness of 15mm and is custom made with Velcro fitting on the chamber. In the model, we use glass wool material with an input power of 700W as it is set to mimic the specification of the heating jacket used on SpaceQ. The properties for glass wool material are taken from the library. The initial condition of the chamber walls and the working plate is set at 293.15K as we start from ambient temperature conditions. The fluid domain in the chamber is set as air, and the pressure inside is 10^{-3} mbar. The solution is run for 120 mins by applying heat externally. We see the temperature profile inside the chamber in Figure 10. This shows that heat is transferred through the walls into the chamber.

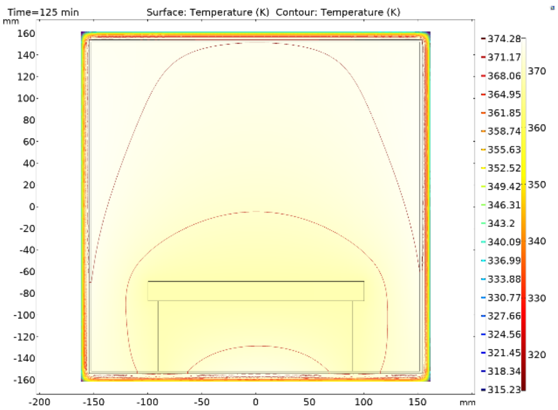

Figure 10. Thermal profile after 120 minutes of simulated evolution.

The temperature evolution inside the chamber over time can be seen in Figure 11. This shows the temperatures at two points, domain and a boundary from ambient lab temperatures to 420K. We observe that it takes more than two hours to heat the table where instruments would be mounted. If we take into account the mass of the instrument, this upper temperature limit will probably be reduced once instrumentation is set inside the chamber. This is an essential information to plan the duration of experiments.

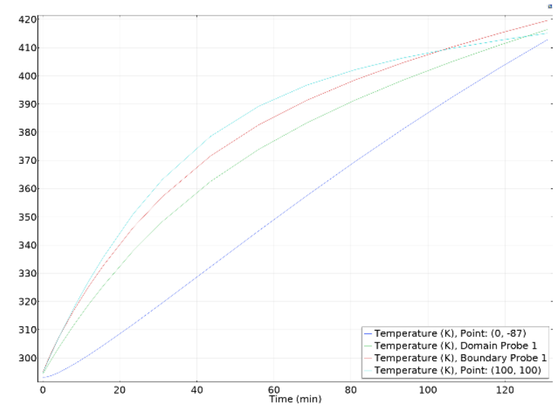

Figure 11. Evolution of the temperature profile when exposed to wall chamber heating in vacuum. The control points are at two locations along with a domain and boundary probe.

We observe in Figure 12 that the heat transfer through conduction is significant in this simulation as we see very high conduction around 1800 W/m^2 at the walls of the chamber. This is the heat that the heating jacket will provide which has maximal heat flux of 6500W/m^2.

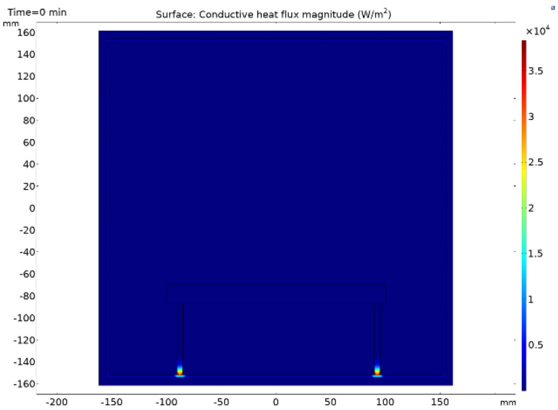

Figure 12. Conductive heat flux inside the chamber in W/m^2.

The convective heat transfer shown in Figure 13 plays a minimal role as the fluid domain is an almost low vacuum and does not affect the model in a significant way.

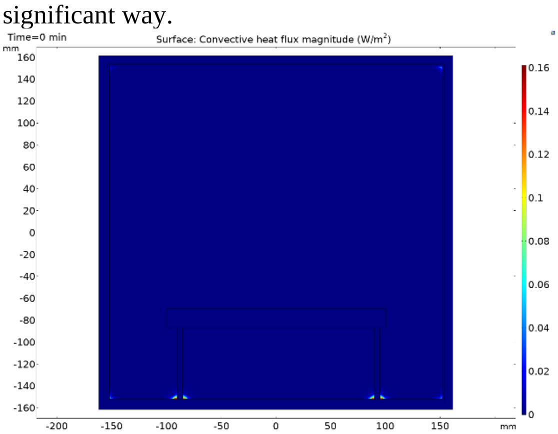

Figure 13. Convective heat flux inside the chamber in W/ m2.

If we look at the radiative mode heat transfer in Figure 14, it is seen that the surface to surface radiation accounts for the maximum on the walls of the chamber as it slowly radiates inwards into the chamber.

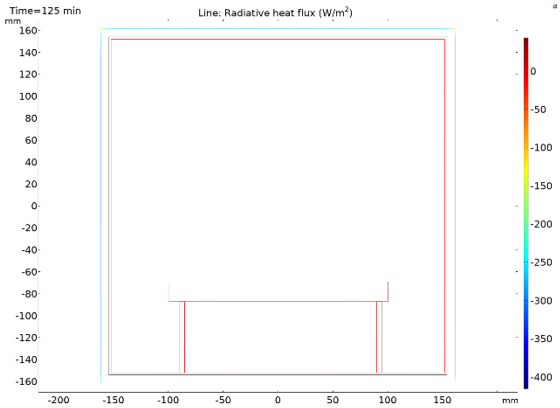

Figure 14. Radiative heat flux on the boundaries of the chamber in W/m^2

5. Conclusions

This paper is devoted to modelling the temperature distribution and its time evolution within the small-sized SpaceQ chamber facility. Other studies have been published before to simulate, for instance, the thermal environment in large rooms with specific thermal insulation and heat transfer for different external conditions [10]. To our knowledge, there are no published references about the thermal simulations of space simulating and qualification facilities. These studies can be used by other researchers and engineers to simulate other chambers and plan their experimental procedures.

As it has been mentioned before, to qualify and validate space instrumentation thermally, it is essential to perform this kind of studies in a dedicated facility. Accurate knowledge of the actual temperature, its evolution and gradients, and the heat-flux sources and sinks is critical to design and upgrade the chambers, to plan experiments and to interpret observations. When temperature gradients are required or where the thermal loads of components need to be monitored in real-time, one alternative is to install thermal infrared cameras within a space simulating facility [11]. This is not always feasible, mainly due to room limitations. Alternatively, the thermal simulations of COMSOL can be used to plan experiments and understand the observations and also to find the hot and cold spots that should be monitored with dedicated temperature sensors.

Our future studies will simulate the 3D behaviour and incorporate the simulation of other elements like the nitrogen pipe, which have strong thermal inertia.

The results of the 2D simulations shall be compared with the future measurements taken within our Martian environment under vacuum conditions and with a thermal heating jacket acting on the external walls. This simulation helps us to evaluate the order of magnitude required to reach a quasi-equilibrium situation and thus to plan for our experiments. The simulations also illustrate qualitatively the existing thermal gradients and the existence of small scale convective cells of about 10 cm size. In the case of water injection within the chamber, this may redistribute water through the different thermal environments.

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Acknowledgements

The Kempe Foundation funded the design and fabrication of the SpaceQ chamber. MPZ has been partially funded by the Spanish State Research Agency (AEI) Project No. MDM-2017-0737 Unidad de Excelencia "María de Maeztu"—Centro de Astrobiología (CSIC-INTA). AVR and JMT acknowledge support from the Wallenberg Foundation.