Techniques to verify the sampling system and flow characteristics of the sensor MicroMED for the ExoMars 2022 Mission"

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# Abstract

Suspended dust has a prominent role in Martian climatology. Several significant dust related phenomena can be observed at various scales, starting from global dust storms to local dust devils, which have important effects such as the increase of troposphere temperature, the modification of the wind regime and the localized motion of sand at the surface. These phenomena depend on dust grain characteristics such as the size distribution or the chemical and bulk composition. Currently, we do not have direct measurement of the dust properties; the only available information in this regard are derived from spectrometric measurements, optical depth, and albedo coming from instruments aboard satellites and in-situ. Herein, we describe the tests performed on the optical particle counter named MicroMED, designed and built to perform the first ever direct in-situ measurement of suspended dust grains in the Martian atmosphere close to the surface. MicroMED is a dust particle size analyzer which was selected to join the Dust Complex payload aboard the ESA/Roscosmos ExoMars 2022 mission. It has the capability to suck in dust that is suspended in atmosphere and to measure the sizes of single grain. The sensor sucks in the dust grains using a sampling system, guides the grains through ducts and concentrates them in an area illuminated by laser.Detecting the intensity of the light scattered by the grains during the crossing through the illuminated area, it is possible to determinate the size of grain. Here we present the innovative techniques in order to verify the performances in terms of dust suction efficiency of the MicroMED Flight Model, using a prototype called MM1.

# Keywords Mars, Dust, MicroMED, ExoMars, Eddies, Prototype

# Introduction

# One of the main goals of the ESA/Roscosmos ExoMars program is the study of the Martian surface environment characteristics through the analysis of the atmosphere and climate (Rodinov et al. 2017). A suite of sensors named Dust Complex Suite (DC) has been selected as part of the Kazachok Surface Platform (SP) payload (Vago, J. 2015 et al.). The DC is exclusively dedicated to analyze the dynamics and characteristics of the near ground sand and suspended Martian dust. Martian dust plays a leading role in the evolution of the planet’s climate, directly related to the dust seasonal and long term variable concentration (Vincente-Retortillo, A. 2018). These events can occur at various scales from global dust storms to local dust devils (Murphy et al. 2016 , Harrison et al. 2016 , Neakrase et al. 2016, Franzese, G. 2018 et al.). Dust grains scatter the solar thermal radiation, also acting as condensation nuclei for H2O and CO2, thus influencing the thermal structure, the balance and the circulation of the atmosphere (Banfield et al. 2020, Fedorova, A. 2009 et al , Smith, D. 2001) . The dust influence on the atmosphere’s heating balance is directly related to its size distribution,which in turn affects the atmosphere albedo . Dust also had long-term effects on the geology in cementing bedforms such as transverse aeolian ridges (TARs) (Geisler 2014 et al.) and even in covering entire dune fields (dust-sized volcanic ash) (Chojnacki et al. 2020, Runyon et al. 2021), thus augmenting the probability of dust layer preservation in the Martian sedimentary records.  In addition, the periodic albedo variations of the surface, related to the redistribution of dust by the wind, modify the climate and wind intensity, a process that is directly related to the grain properties (e.g. size, roughness, hardness) (Fenton et al. 2007).

No direct measurements of single grains of dust in the Martian Atmosphere have been performed yet, the only information about dust grain properties, such as size and composition, has been extrapolated from direct measurements of albedo and optical depth from which it was possible to obtain an effective radius (reff) of the observed dust distributions interposed between the sensor and the light source (Drossart 1991, Pollack, J. 1995, Tomasko, M. 1999, Kjartan M. Kinch et al. (2015) , H.Chen-Chen S. et al. 2020). The actual informations about the dust distributions derived from Martian atmosphere measuraments indicate that reff for these distribution hovers around a value of 1.3-1.8 μm (Wolff, M. J. et al.2006.). For this reasons we have developed an optical particle counter MicroMED able to measure the dust size distribution in the range of 0.4 to 20 μm.

The sensor MicroMED with the capability of sucking a single grain and directly to measure the size, has been chosen as part of Dust Complex Suite for Exmoras 2020 mission. In this article we present an overview of the MicroMED instrument focusing in particular on the subsystem that is responsible for the aspiration of dust in the atmosphere. It consists of 5 elements sampling head, inlet, outlet, optical head and pump. In the following paragraphs we will see in detail the individual elements. The design, development and testing phase of the suction system required the development of a new but at the same time simple technique to confirm the results of the simulations. . In order to verify the performances of MicroMED, two breadboard versions have been constructed and tested: i) the sampling system (MM1) and ii) the optical and acquisition system (MM2). To understand if the sampling system complies with all scientific and technical requirements and to validate the theoretical simulation results, we performed several experimental tests. We used techniques able to simulate the operation in Martian conditions, as well as guarantee low cost and reliable results. We describe here the performance of the MM1 prototype.

2. MicroMED an Optical Particle Counter

MicroMED Flight Model (Figure 1) will participate to ExomMars 2022 mission and it will be placed on Kazachok Lander produced by the Russian company Lavockin as shown in Figure 2. It is an instrument that uses the principle of light scattering by dust in order to determine dust grain size, (see schematic in Figure 3). The device consists by three subsystems i) sampling system, ìì) optical system and ììì) detection system all integrated in an aluminum box called optical head (Figure 4) The size (W; L; H) of optical head are : 50 mm x 50 mm x 33 mm.

* The sampling system that represents the object of our study consists of an inlet duct, which in turn, is divided into an external part connected to the optical head in contact with the atmosphere and an internal part inside the optical head that focuses the air flow sucked into a light source, also the outlet is divided into an internal and an external part connected to the pump (Fig. 4).
* The optical system generates the sampling volume and consists of a laser diode with a wavelength of 830 nm and power of 150 mW, a group of lenses (300 group Fig. 4) that focuses the laser light in an optical fiber ( core 50 μm, cladding 125 μm and NA 0.21) which is connected to the lens group 210 integrated in the optical head. Group 210 determines the shape, position and size of the sampling volume. The shape of the sampling volume is elliptical, the dimension is 1.078 mm x 1 mm x 0.3 mm and it is positioned in the middle between internal inlets and outlets. Along the direction of propagation of the laser beam there is a light trap that breaks down the straylight.
* The detection system includes a mirror with a 135 ° field of view and a photodiode. The mirror collects and focuses the scattered light by dust crossing the sampling volume on the photodiode, which returns a signal proportional to the size of the dust grain.

In the figure 5 and 6 are shown some examples of signal relative to single particles sucked during tests with Flight Model (Fig. 1). It’s possible to note that the amplitude of signals depend of grain size.

The instrument has two channel of acquisition with two different amplifier stages Low and High channel. The low channel is used for particles with a size of 10 μm until 20 μm while with the high channel is possible to measure the particles with diameter lower than 10 μm. In figure 5 are rappresented signals relative to particles of 1 μm and below of 8 μm. The amplitude of signal generated by grain of 1 μm is 1.06 volt and about 2 volt for grain of 8 μm. The same happens in figure 6 where displayed signals for 11 μm and 20 μm particles.

In Table 1 some physical characteristics of MicroMED and some details of the mission are highlighted.

|  |  |
| --- | --- |
| **Physical characteristics of MicroMED and operational details of the mission** | |
| Mass (gr.) | 509.4 |
| Power Consumption (W) | 2.9 |
| Size (Width x Length x Height) (mm) without consider the height of inlet | 63 x 126 x 110 |
| Height of Inlet ( external part) (mm) | 84,5 |
| Flow rate | 1 l/min |
| Measuring size range of dust (μm) | 0.4 to 20 |
| Measure size distribution of dust during : | Feather Weather, Dust storm, Dust devils |
| Number of runs in 1 sol | 6 |
| Duration of the mission | 2 years |

**Table 1:** Physical characteristics of MicroMED Flight Model and operational details of the mission ExoMars 2022

Table 1 shows that the sensor is light, has small dimensions and low energy consumption. MicroMED's objectives consist in providing dimensional distribution of dust in the following cases: during dust storm, at the passage of dust devils and in feather weather.

The configuration of the MicroMED flight model was obtained on the basis of the test results performed on the three subsystems described above. The performance of the sensor and the characteristics of the subsystems: optical and detection system strongly depend on the sampling system. It has been designed and developed considering that aspirated particles were all concentrated in an area of 1 mm x 1 mm. The flow size in terms of 1mm diameter ensures that all aspirated particles pass through the sample volume which has dimensions of 1,078 mm x 1mm. Indeed, if the air flow exiting the internal inlet had dimensions greater than 1,078 x 1 mm, it would mean that many dust particles would pass outside the sampling volume and therefore would not be revealed, invalidating the concentration measurement.

# 2.1 Sampling System

In order to aspire the suspended dust in the Martian atmosphere, a sampling system has been designed, tested and integrated. It consists of an inlet duct, an outlet duct and a pump, connected downstream of the ducts.

*2.2 Requirements of sampling system*

The sampling system has been conceived in according to the following scientific requirements:

1) The instrument shall be able to aspire dust grains in the range of diameters 0.4 - 20 µm.

2) The formation of eddies inside the instrument main box shall be avoided, as that would cause dispersion of grains in the instrument box, leading to grains missing the laser illuminated spot, as well as depositing on the sensitive elements of the instrument, such as the mirror and the photodiode.

3) The flow shall be laminar throughout the instrument duct.

4) The flow diameter shall be comparable to the sampling volume size.

Keeping in mind the size of instrument (see the table 2) and on the basis of the listed scientific requirements, numerous simulations were performed in order to verify the behavior of the flow ( laminar, absence of eddies and etc..) inside the ducts and in a region included between inlet and outlet inside optical head. Figure 7  shows an example of the results obtained by means of a Computational Fluid Dynamic (CFD) analysis performed with the software Ansys Fluent ®, aimed at defining the flow field along MicroMED ducts. The input parameters were: CO2 atmosphere (Mars atmosphere is mostly made of carbon dioxide), a temperature of 300 K (not related to Martian atmospheric conditions but rather to the temperature conditions experienced during the tests at the INAF – OAC facility), ambient pressure of 700 Pa, particles with a diameter of 0.4 µm and a flow rate ≅1 l / min.

The CFD simulation of Figure 7 shows the grain trajectories  starting from the inlet duct. It is clear how this configuration is able to avoid the generation of swirls and to maintain the flow in a laminar regime. The flow laminarity is guaranteed by the extremely small characteristic dimensions of the ducts, that make the Reynolds number less than the transition threshold value of 2300 Furthermore, in the region between the inlet and the outlet inside the optical head there is a widening of the flow. The estimate of this flare is 1 mm. This result is important because the flux flare must be less than the sample volume size ie 1.078 mm. On the base of this result, it was possible to set the physical and geometric characteristics of the ducts as summarized in table 2 and to realize the prototype MM1.

|  |  |
| --- | --- |
| Physical and Geometrical characteristics of Inlet and Outlet | |
| Bulk | Aluminum alloy Al 6082-T6 |
| Internal diameter of the Inlet duct (external part of optical head) (mm) | 6 |
| Outside diameter of the outlet duct (external part of optical head) (mm) | 6 |
| Internal diameter of inlet (internal part of optical head) (mm) | 1· |
| Internal diameter of outlet (internal part of optical head) (mm) | 3 |
| Length inlet external part (mm) | 42 |
| Length inlet (internal Part) and length outlet (internal part) (mm) | 18 |
| Distance between inlet and outlet inside  Optical Head | 4 |
| Sampling head diameter (mm)  Diameter of Hole (mm) | 10  2 |
| Diameter of the holes on the sampling head (mm) | 4 |
| Optical Head size (mm) | 36 x 40 x 43 |

**Table 2**: Physical and Geometrical characteristics of MM1 prototype. .

Table 2 shows the size ducts used for CFD simulation. The inlet and outlet ducts, as mentioned above, are divided into an external part and an internal part with respect to the optical head. The external part of the ducts has a different diameter from the internal part. The inlet duct (external part) has a cylindrical shape with a inner diameter of 4 mm, while the inlet (internal part ) inside the optical head has the same shape but with a inner diameter of 1 mm.,  The outlet duct has a similar structure. It is composed by two cylindrical sections of 1 and 3 mm of internal diameter, respectively. The distance between the ducts inside the Optical Head is 4 mm as shown in Figure 8.

The inlet (Figure 8) has got a sampling head, equipped with 4 holes equally spaced of 90°on its lateral surface. It allows an efficient detection of grains while protecting the ducts from the deposition of dust when the instrument is inactive. The diameter of a hole is 2 mm. For new requirement of mission the version of the inlet had then to be updated, as will be shown later (Section 3.4).

*2.3 Prototype of MicroMED.*

The MicroMED MM1 prototype (Fig.9) was equipped with a commercial pump (Thomas G04-EB) connected to the outlet duct and able to generate a flow rate ≅1 l/min. The pump is able to work at Martian environmental pressure, namely between 6 and 8 mbar and has the same performance as the pump used for the flight model but obviously being a commercial pump it was built with not space qualify materials. The prototype has two special grooves that allow the insertion of a particular frame, equipped with a blade, as shown in Figure 10 and 11. The blade is positioned so that it is intersected by the longitudinal axis of the inlet and outlet ducts inside optical head. The frame is conceived to intercept and to capture the aspired grains that come out from inlet. Hence, a strip of adhesive carbon was glued on the central blade of the frame in order to block the grains aspired. The blade is able to stop the grains carried by flow that are concentrated close to the duct longitudinal axis, where the laser illuminated region is located. Dust grains will tend to follow the fluid streamlines and avoid the blade, however a significant amount of them would still get captured by the strip, allowing their detection by means of a visual inspection, confirming that grains actually follow the desired trajectory along MicroMED.

All tests have been performed in a Martian atmospheric chamber, situated at the INAF-OAC facility, where Martian conditions in terms of pressure, atmosphere chemical composition and dust presence can be reproduced (Cozzolino, F. 2020). The dust grains used for tests are spherical calibrated particles produced by Microparticles Gmbh. The properties of calibrated particles are summarized in table 3. We have choosen this kind of particles for testing because the silicium is the chemical most abundant element present in the composition of dust grains on Mars (Berger et al. 2016). In order to understand the correlation between flow and particle trajectory as a function of size it is advisable to use monodisperse particles rather than a Martian simulant such as the JSC-1, polydisperse sample, which would make both verification and analysis of test results difficult.

| **Properties** | **Silica-Particles** |
| --- | --- |
| Density | 1,85 g/cm3 |
| Refractive index | 1.42 |
| Particle diameter | 0.4 µm – 25 µm |
| Monodispersity | CV < 5% |
| Particle shape | spherical |
| Surface charge | anionic |
| Functional groups | silanol |
| Hydrophilicity/Hydrophobicity | hydrophilic |
| Crosslinking | crosslinked |
| Porosity | non-porous |
| Temperature stability | to 1000 °C |
| Mechanical strength | robust |
| Solubility in acids and bases | soluble in HF and bases |
| Stability in solvents without swelling | water, alcohols, all solvents and oils |
| Biocompatibility | biocompatible |

**Table 3:** Properties of calibrated particle used during thew tests on MM1 prototype.

*2.4 Verification of aspiration ability.*

The verifications about the capability of the sampling system to collect the particles were performed by inserting the frame shown in Fig.10 inside the MM1optical head (Fig.11) in order to intercept the particles injected into the Martian atmospheric chamber and captured by MicroMED.Tests were performed for each dust grains size in the entire nominal MicroMED measuring range, i.e. 0.4-20 µm in diameter. After the tests, the frame was analyzed with the SEM (Scanning Electric Microscope) to count the grains eventually captured.

*2.5 Verification of particles turbulent path.*

In order to identify potential swirls or turbulence inside the instrument box, we installed 4 aluminum stubs, covered with carbon disks, positioned on the bottom of the instrument box as shown in Figure 12. The aim of these stubs was to collect the grains dispersed inside the box in case of turbulent motion. In the case of laminar motion, the flow exits from the inlet duct and enters into outlet with little dispersion of grains. Conversely, we expect a large dispersion of grains in the case of turbulent or whirling flow, inducing grain enrichment on the stub collectors. The stubs are successively analyzed by means of the SEM to count the number of deposited grains. Each stub has a diameter of 13 mm. The grains used for this test have a diameter of 0.5 µm, because the smaller grains (0.5 µm is close to the minimum detectable by MicroMED) are the ones that have the biggest tendency to disperse. This tendency is indeed related to the grains Stokes number, which characterizes the behavior of particles suspended in a fluid flow. As also stated by Mongelluzzo, G. 2019, for dust grains flowing along MicroMED the Stokes number can significantly change, going from 0.67 for the smallest grains to 33.45 for the largest ones. For the execution of the test we used 50 mg of calibrated particles with a diameter of 0.5 microns. The injection of all the particles into the chamber lasted 5 minutes, while the acquisition time of the MM1 prototype is 15 minutes. The injection times and acquisition times have been chosen on the basis of the concentration of particles that occurs in the different points of the Martian simulation chamber We have placed the prototype MM1 in an area where the deposit of grain correspond to a concentration of 1500 particles per mm2.

*2.6 Technique to measure maximum displacement of flow outgoing from the inlet.*

In order for dust grains to be detected by MicroMED, they must cross the sampling volume generated by the optical system. This volume is placed inside MicroMED box and equally distanced from the inlet and outlet ducts. Consequently, in order to maximize the volume intersection, it is crucial to measure the locations and characteristic dimensions of the grains with respect to the optical volume. To perform a measurement of the flow maximum displacement, three different frames have been used, inserted into the prototype as shown in Figure 6, each one with a different distance between the blade and the sampling volume center. The first frame has a blade-sampling volume center distance of 0.4 mm, the second frame 0.5 mm and the third 0.6 mm. The position of the spot has to be centered not only with respect to the duct axis, but also with respect to the edge of the two ducts. The inlet and outlet ducts are indeed separated by a gap, and the spot should be equally distant from the two ducts.  We focused on the measure of grains displacement from the center of the sampling volume, observing if they deposit on the frame blades. For example, if deposited grains are observed on the frame of 0.~~4~~ mm it means that the grains are dispersed up to a distance  larger than 0.4 mm from the duct longitudinal axis. On the blades, strips of adhesive carbon have been used. The test was repeated for different grain sizes:  0.50, 1.30, 2.80, 4.32, 6.36, 8.43, 11.00, 14.98 µm.

# For each particle size injected into the chamber, flow displacement measurements were made using all frames. Measurements were also repeated with the frames turned upside down in order to measure the displacement on both sides in relation to the center.

# 

# 3. Results and discussion

*3.1 Verification of aspiration ability and grains trajectories.*

An example of image, relating to the test described in paragraph 2.4, obtained from SEM analysis is shown in Figure 13. It shows a section of the surface of the frame blade that has intercepted aspirated grains of 0.5 µm. This kind of images allows us to confirm that the aspiration system has worked correctly.

The results of tests described in section 2.5 are summarized in tables 4 and 5. Table 4 shows the number of grains deposited on each stub. The first column represents the stub number , enumerated as shown in Figure 12, while the second column shows the number of the particles deposited on the stubs. The number of particles has been determined analyzing stubs with the SEM. The size of grains used in these tests is 0.5 µm.

|  |  |
| --- | --- |
| Results analysis Stubs | |
| # Disc | Counted Particles |
| 1 | 1 |
| 2 | 3 |
| 3 | 1 |
| 4 | 2 |

**Table 4**: Result of the count of the particles size 0.5 µm deposited on the test discs.

The maximum number of grains deposited on the stubs is 3. This allows us to be confident that there is no turbulence inside MicroMED box, therefore the assumption of laminar flow regime is confirmed. The same test was repeated inserting, in addition to the stubs, the frames described in Section 2.6. In this way it has been possible to verify if the frames induced significant perturbation on particles trajectories.

|  |  |  |  |
| --- | --- | --- | --- |
| Results Stubs Analysis (Frame inserted into prototype) | | | |
| # Disc | 0.4 mm | 0.5 mm | 0.6 mm |
| 1 | 8 | 2 | 4 |
| 2 | 2 | 1 | 4 |
| 3 | 2 | 8 | 5 |
| 4 | 3 | 4 | 2 |

**Table 5:** Result of the stub counts in the presence of the frame.

From the analysis of the stubs, shown in Table 5, it emerges that the number particles deposited on stubs is negligible. Thus, the frame insertion does not perturb the flow laminarity.

*3.2 Measurement of the maximum displacement of flow outgoing from inlet.*

Results of the tests provided important indications on the flow behavior. The images analysis shows that the displacement of the particles decreases as the grain’s radius increases. Therefore, from the images shown in Figure 14 and in Figure 15, the maximum deviation is greater for the smallest grains. For 0.5 µm diameter grains (Fig.14) it is possible to see the deposit on the blades at 0.4 and 0.5 mm (Figs 14a and 14b), while no deposition is visible at 0.6 mm (Fig 14c). Instead, for 11.00 and 14.98 µm grains (Figs 16b and 16c) the maximum deviation is smaller than 0.4 mm, since no deposition on blades is observed. For 4.32 µm diameter grains (Fig. 15), there is deposition only on the edge of the blade at 0.4 mm (Fig 15a). On the 0.5 mm frame (Fig. 15b), only one particle is visible, while no grains are detected on the 0.6 mm frame (Fig 15c). This means that most of 4.32 µm grains experience a displacement from the center smaller than 0.4 mm.

*3.3 Elongated version of the inlet.*

# Results shown above allowed the development of the first inlet duct design. However, due to mission requirements, the length of the inlet had to be increased. MicroMED will indeed be placed on the ExoMars Surface Platform under an 80 mm thick thermal blanket. Given the need to keep the sampling head outside of the blanket (to expose the sampling head to outer atmosphere), a new elongated version of the inlet duct was designed (Fig.17) (125 mm long, while the original inlet length was 40 mm) and the entire verification process was repeated. CFD simulations have been run for the updated geometry, and tests have been performed to verify the simulation results. The installation of the newly designed inlet implied little time consumption, given that, because of the peculiar structure of the instrument, it is possible to simply remove and substitute the inlet duct. Figure 18 shows that the grain behavior inside MicroMED while using the elongated version of the inlet is comparable to the behavior already shown in Figure 7 and relative to the short inlet. Grain trajectories do not show interferences due to eventual swirls or eddies inside the instrument box. They experience a slight deflection due to the expansion of the fluid streamlines inside MicroMED’s main box, however they are still concentrated in extremely high percentages in the sampling volume (over 90% for the entire instrument measuring range both considering Martian and laboratory environments) and they all enter the outlet duct as evidenced by results presented in table 5. They clearly show that the aspirated particles do not disperse inside the box. The differences between the two inlet versions are mainly related to the pressure force generated by the pump on. Such difference is related to the instrument ability to sample grains rather than to the ability to concentrate the grains in the laser illuminated region of the instrument. The elongation of the inlet has indeed the effect of reducing the pressure force that the pump is able to generate on grains, thus grains with high inertia (either large or fast moving grains, or both) could be more difficult to collect. These considerations let to the development of the MM2 prototype of MicroMED and then, , to and the realization of the instrument Flight Model (Fig.1).

# **Conclusion**

MicroMED is an Optical Particle Counter selected for ExoMars 2022 SP mission. The instrument aims for the first ever direct measurement of airborne Martian dust at the surface. It was conceived, developed and realized for optimal behavior in Martian environment. The first prototype of MicroMED has been built for testing the sampling system designed and built on the base of fluid dynamic simulation results.

Innovative techniques have been developed in order to confirm the capability of the instrument to aspire dust grains, to generate a laminar flow and to measure the displacement of grains in relation to designed position of sampling volume, that will be placed equally distant to the inlet and outlet ducts. The experimental results are in good agreement with theoretical results provided by the simulations. Tests carried out on the sampling system, allowed to deduce that it is able to aspire grains and to achieve laminar flow inside the instrument. The results highlight the absence of turbulence and swirls in the instrument. The maximum displacement suffered by the particles of 0.5 µm diameter is 0.5 mm, while the large ones pass inside 0.4 mm from the center. The knowledge of the displacement of grains is important in order to to realize an optical system able to produce a sampling volume whose size is comparable with the observed maximum grains displacement. This analysis has highlighted the need for a sampling volume with a size along the axis being perpendicular to the grains flow of ≥ 1 mm.

**ACKNOWLEDGMENT**

This work has been supported by ASI (contract’s grant number: 2016/41/H.0). The instrument development was funded and coordinated by ASI under the scientific leadership of INAF-Naples, Italy. The data used in this paper can be accessed upon personal request to the first author

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