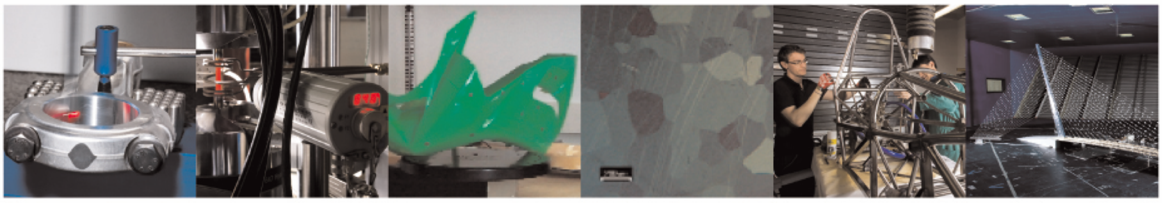
POLITECNICO MILANO 1863

DIPARTIMENTO DI MECCANICA

mecc



Development and characterization of a volume flow measurement system for low-pressure gases

Saggin B.; Scaccabarozzi D.; Valiesfahani A.; Valnegri P.; Magni M.; Esposito F.; Molfese C.; Mongelluzzo G.

This is a post-peer-review, pre-copyedit version of an article published in *Measurement: Journal of the International Measurement Confederation*. The final authenticated version is available online at: http://dx.doi.org/10.1016/j.measurement.2020.108230

DIPARTIMENTO DI MECCANICA ■ POLITECNICO DI MILANO
via G. La Masa, 1 ■ 20156 Milano ■ EMAIL (PEC): pecmecc@cert.polimi.it
http://www.mecc.polimi.it
Rev. 0

Development and characterization of a volume flow measurement system for low-pressure gases

Bortolino Saggin [a,*], Diego Scaccabarozzi [a], Arash Valiesfahani [a], Pietro Valnegri [a], Marianna Magni [a], Francesca Esposito [b], Cesare Molfese [b], Giuseppe Mongelluzzo [b]

[a] Politecnico di Milano, Dipartimento di Meccanica, Lecco's Campus, Italy
[b] INAF-OAC Napoli, Italy

A B S T R A C T

This paper presents the design and validation of a volume flow measurement system developed to measure volume flowrate of gas at pressures below 1 kPa. The system had to be developed because a suitable commercial transducer was not available for the unusual working environment, where outgassing and sublimation phenomena become relevant for many materials and the rarefied atmosphere changes dramatically its heat and mass exchange parameters. The development of a low-pressure compatible measurement system comes from the need of measuring the flow rate of a rotary vane pump working under an environmental absolute pressure in the range between 600 and 1000 Pa, mostly composed by CO_2 i.e. the average condition of the Martian atmosphere at the surface. The pump will be a key component of the MicroMED particle analyzer, an instrument of the ExoMars 2020 ESA-Roscosmos mission payload. The measurement system is based on a control volume, made by a stainless-steel bellow, which has been designed accounting for the environmental requirements and the expected flow rate. The measurement system has been calibrated at ambient condition and tests in low-pressure have been performed to validate the measurement system and to derive the flow rate characteristics of a pump mock-up at different environmental pressures.

1. Introduction

In this work the development of a flowrate measurement system operating at low pressures is presented. The need of measuring the volume flow rate at low pressure arose within the framework of the MicroMED (Micro MEDUSA) project [1–3]. MicroMED is a dust analyzer developed for the Exomars 2020 Dust Suite instrument. MicroMED will measure the abundance and size distribution of dust in the layer of Martian atmosphere close to the surface, where dust lifting occurs. The pumping system of the MicroMED has a key role in matching the expected instrument performances [4,5] because the sampling efficiency (in terms of number of detected particles with respect to the total entering the instrument) depends on the atmosphere pressure, temperature, and on the volumetric flow rate provided by the pump. Thus, in order to achieve MicroMED performances the pump must provide the required pressure difference at every expected environmental condition. In order to demonstrate the compliance of the pump performances with the requirements, the characterization must be carried-out in low pressure conditions, like the ones expected on Mars. The development of an accurate flowrate measuring system compatible with Martian like environmental conditions is therefore fundamental both for the development of the pumping system and the characterization of the instrument fluidic system. Available flow meters are generally not designed to operate in low pressure and adapting them to these conditions lead to many issues related to outgassing of materials, low sensitivity, possible failures due to the insufficient heat exchange provided by the gas. The two order of magnitude pressure reduction of the Martian atmosphere with respect to the Earth one changes dramatically the gas properties (i.e. density viscosity, thermal conductivity) making most measuring systems totally ineffective or, affecting their metrological characteristics; in this view ultrasonic [6] or thermal [7] devices are clear examples. Calibration under the expected operating conditions would require a reference measurement system nevertheless, most of them [8] can operate only in laboratory environment. The implemented system is actually based on the volume measurement principle used in most calibration standards but, with the trade-off changes deriving from the need of operating inside a vacuum chamber.

2. Measurement system design

A sketch of the conceived measurement system is shown in Fig. 1. The working concept is rather obvious, i.e. once the pump is switched on, the control volume is deformed along one direction as consequence of the injected flow. Thus, measurement of the control volume displacement (in Fig. 1 evidenced as x) together with time allows the indirect measurement of the volumetric flow rate. While in an ideal system the volume stretching might happen without resistances, any real container will have a stiffness that will lead to the need of a pressure difference to achieve a displacement.

The relationship between volumetric flowrate Q at pump inlet and mass flow rate $\dot{m}$ can be written as:

$$\dot{m} = \rho_0 Q \tag{1}$$

where ρ_0 is the gas density at the environmental pressure. Assuming that the gas within the volume goes through isothermal transformations, the mass conservation law allows writing:

$$\dot{m} = \frac{d(V\rho)}{dt} = \frac{d\left(\rho_0\left(1+\frac{kx}{Ap_0}\right)(V_0+xA)\right)}{dt} \tag{2}$$

k and A are the axial stiffness and the effective cross-section area of the bellow, p_0 the environmental absolute pressure. V_0 is the bellow volume at the beginning of the test that can be expressed as the product: $V_0 = L_0A$ where L_0 is the bellow length at rest. One can notice that in the above equation the pressure inside the control volume has been determined from its displacement and stiffness in fact, thanks to the low stiffness, this measurement has proved to be more accurate than that achievable with common manometers. The measurand is Q i.e. the volumetric flowrate with reference to the conditions of the gas at the pump inlet i.e. standard conditions for tests in lab and Martian-like atmospheric conditions for the nominal operation. The low pressure tests reported in the following, carried-out to validate the system, were performed at temperature close to 20 °C but with absolute pressures specific of each test in the range 200–600 Pa. Combination of Eqs. (1) and (2) allows writing the volumetric flowrate:

$$Q = \left(\frac{kL_0}{P_0} + \frac{2kx}{P_0} + A\right)\frac{dx}{dt} \tag{3}$$

In the above expression one can recognize that the last term within brackets would be the only one present in case of incompressible fluids while the others are proportional to the control volume stiffness and increase as the environmental pressure p_0 decreases. The bellow stiffness actually generates a loading effect of the measuring system that does not allow performing flowrate measurements without the "side effect" of generating a pressure opposing to the flow. The ideal bellow would have no stiffness while for technological reasons the stiffness has a lower limit. Given the achievable bellow stiffness it can be seen that in the pressure condition of interest (600–1000 Pa for the intended application), the correction for the bellow stiffness effect becomes mandatory in order to avoid underestimation of the volumetric flow rate while, in earth atmospheric pressure the stiffness is almost negligible.

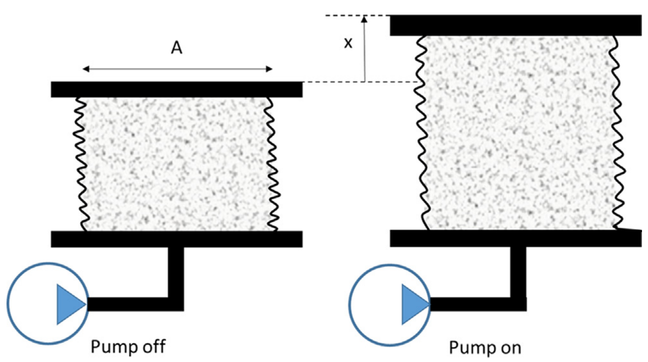


Fig. 1. Sketch of the measurement system: control volume geometrical configuration when pump is not working (left) and is working (right).

3. Measurement system characterization

3.1. Measurement system description

In order to create the control volume, a stainless-steel bellow was manufactured by MEWASA company. The design had been performed accounting for many requirements. The bellow must withstand 5 kPa which is the maximum differential pressure for test of the pump at ambient conditions. The bellow stiffness should be minimized to reduce differential pressure increase during the pump testing. Finally, the bellow size must be restrained to 300 mm diameter and 440 mm height to fit within the available vacuum chamber. It has to be noticed that the choice of the bellow material was restricted to high vacuum compatible components because the materials outgassing at the low pressures of interest has been identified as a critical issue in a previous setup [9].

The bellow is described in detail in [10]; it provides a theoretical stiffness k of 1.7 N/mm, geometrical effective cross section area of 221 cm^2. In order to complete the measurement setup a displacement transducer is required to measure the bellow extension. This task has been accomplished with the triangulation laser displacement transducer optoNCDT ILD-1400 from Microepsilon, having a measuring range of 100 mm. The laser was pointed in the centre of the upper bellow disk to minimize the effect of tilts. A test was actually performed driving the upper bellow disk with a linear bearing but, no noticeable change was evidenced in the measurement noise with respect to the free upper bellow condition therefore, the latter was eventually used as working configuration. The optical measurement allows placing the device outside the vacuum chamber, just exploiting an optical window to access the bellow end; with this configuration pressure and temperature inside the chamber do not affect the transducer that can be a common one. During tests in ambient condition a differential pressure sensor, Honeywell 26PC Series with a range ± 35 kPa, has been used as well. The measurement chain was completed by a NI9215DAQ board from National Instruments.

3.2. Ambient condition tests

In order to measure the actual characteristics of the bellow and allow for its usage as a flowrate measurement system, some tests in laboratory conditions were performed. The airflow was provided by a rotary vane pump (Thomas G 6/04 EB) that was used for the MicroMED laboratory mock-up. As reference, a commercial flowmeter (Honeywell AWM5102VN type, standard uncertainty 1.8% of the reading) was mounted in series to the developed measurement system. A picture of the measurement setup is provided in Fig. 2 along with a block diagram.

The pump generates an air flow that is measured by the reference flowmeter and by the bellow since the two are mounted in series. The pressure inside the bellow is monitored with the differential pressure sensor.

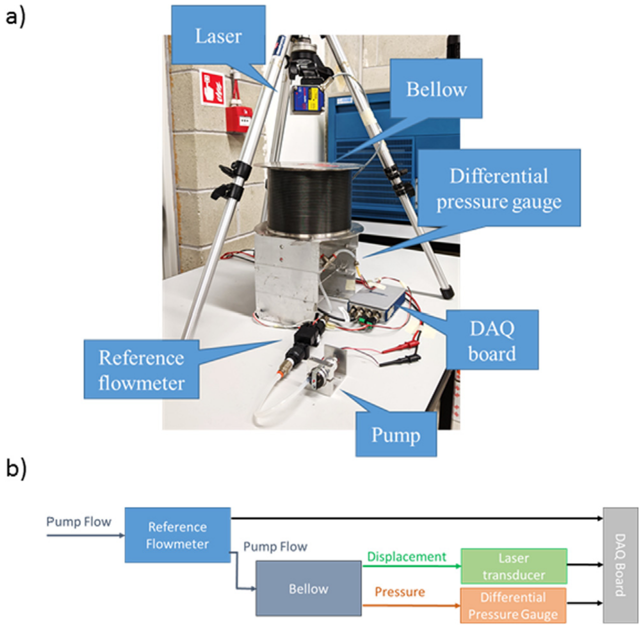


Fig. 2. (a) Picture of the measurement setup for tests in normal conditions. (b) Functional scheme of the setup.

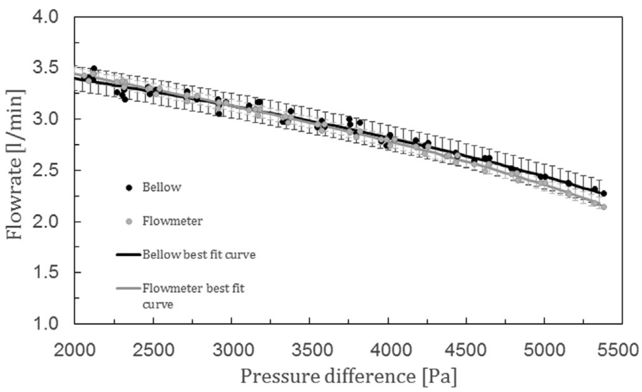


Fig. 3. Comparison between measured flowrates by means of the bellow (black points) and of the reference flowmeter (light grey points). Best fit trends are shown with 2σ uncertainty bands.

The purpose of this activity was the validation of the designed volume flow measurement system by comparison with the commercial one. Four tests were performed to inspect measurement repeatability. In Fig. 3 least square fit with 2nd order polynomials have been inserted along with measurement data for both the flowmeter and the bellow measurements.

The obtained curves are compatible, within the investigated pressure range, since the differences in the measurements are smaller than the sum of the two uncertainties i.e. 0.06 l/min (σ repeatability) and 0.052 l/min (from specified accuracy) of the bellow and the flowmeter, respectively. However, one can notice that when the range of pressure difference approaches the 5 kPa the matching starts to worsen. One reason of this deviation has been identified in the elasticity of the bellow that is non-linear for large values of the bellow's extension. This was somehow expected because the large bending deformation of the diaphragms leads to geometric non-linearity; a characterization was therefore performed. Nevertheless, for tests in ambient condition the heating of the air due to the pumping becomes significant and a drift of the temperatures of the system was observed. This was taken as a limitation of this kind of test without working it out because in conditions of low pressure i.e. the system nominal working conditions, the temperature was stable.

3.3. Bellow' stiffness characterization

The stiffness of the bellow was measured with the setup shown in Fig. 4.

Forces were generated by means of calibrated masses and the bellow extension was measured by a laser triangulation displacement transducer. Three tests with ten masses for each test were performed.

The derived relationship between the applied force and the displacement of the bellow is shown in Fig. 5, where best fitting of the measured data with a cubic polynomial is represented along with the linear equation corresponding to the nominal bellow stiffness.

It can be noticed that the nominal stiffness is the characteristic for near zero load or in general for small displacements i.e. 25 mm corresponding to pressure differences below 2000 Pa. In fact, the maximum deviation of the local stiffness and the nominal one in this range is less than 1.5% of the nominal value. Increasing the bellow displacement, the difference becomes larger, up to 25% of the nominal value. The characterization anyway allows evaluating the stiffness k to be used in Eq. (2). For large displacements k becomes a function of the displacement x, and, Eq. (3)) is no more valid. Nevertheless, for the low-pressure difference like those of interest in the environmental pressure of interest in our application, the limitation to 25 mm displacement is fulfilled, therefore, the evidenced non-linearity can be treated as an uncertainty of the constant of stiffness, k.

3.4. Measurements at low-pressure

The tests at low pressure are based almost on the same set-up described for tests in air but,

- the pressure sensor and the flowmeter used for system validation were no more present;
- the bellow and the pump were placed inside a vacuum chamber with an optical window on the top and a feed-through for the electrical signals of the pump;
- a vacuum pump was used to reduce the pressure of the air inside the chamber to the required values.

A scheme of the setup is reported in Fig. 6.

The purpose of these tests was verifying the measuring system performances in conditions similar to those of interest.

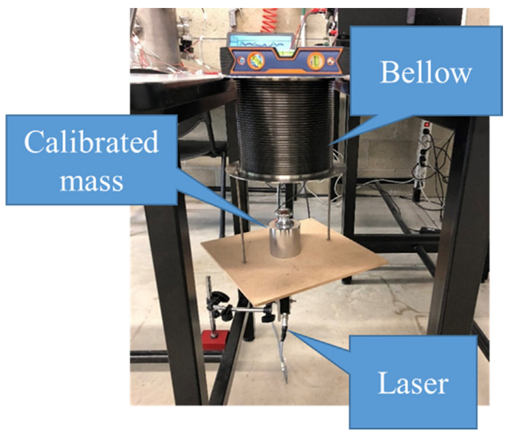


Fig. 4. View of the setup for the bellow stiffness measurement.

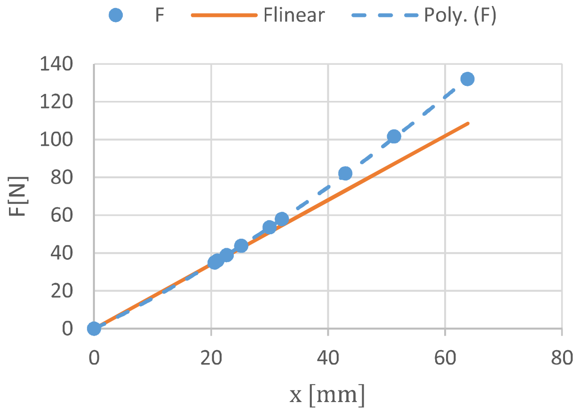


Fig. 5. Results of the stiffness measurement test: experimental data with a 3rd order polynomial fit and linear fit for the 25 mm displacement range.

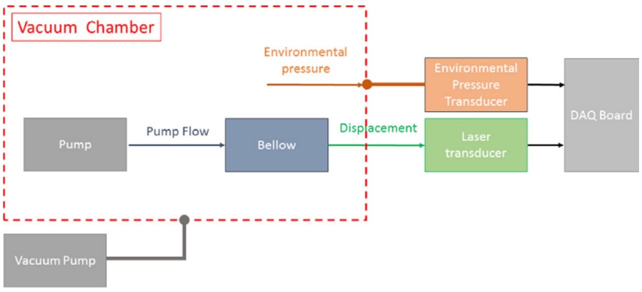


Fig. 6. Scheme of the low pressure tests setup.

3.5. Uncertainty assessment

As shown in Eq. (3), the flowrate measurement can be written as a function of six variables:

$$Q = f(P_0, x, \dot{x}, A, k, L_0) \tag{4}$$

where $\dot{x}$ is the bellow displacement time derivative

Equation (4) can be used to estimate the uncertainty, according to [11] the uncertainty propagation leads to the following Eq. (5)

$$u_Q = \sqrt{\left(\frac{\partial Q}{\partial P_0}.u_{P_0}\right)^2 + \left(\frac{\partial Q}{\partial x}.u_x\right)^2 + \left(\frac{\partial Q}{\partial \dot{x}}.u_{\dot{x}}\right)^2 + \left(\frac{\partial Q}{\partial A}.u_A\right)^2 + \left(\frac{\partial Q}{\partial L_0}.u_{L_0}\right)^2 + \left(\frac{\partial Q}{\partial k}.u_k\right)^2} \tag{5}$$

in which u_{P0}, u_x, $u_{\dot{x}}$ are uncertainties in measurement of environmental pressure, bellow's displacement and its derivative, whereas u_k, u_{Lo} and u_A are the uncertainties in the bellow stiffness, initial length and cross section area. Time uncertainty has not been included in the analysis because the specified accuracy of the board sampling step, 50 ppm leads to negligible contributions in the speed determination.

Partial derivatives can be evaluated from equation obtaining 3:

$$\begin{cases} \frac{\partial Q}{\partial P_0} = -(kL_0 + 2kx)\frac{\dot{x}}{P_0{}^2} \\ \frac{\partial Q}{\partial x} = \frac{2k}{P_0}\dot{x} \\ \frac{\partial Q}{\partial \dot{x}} = \frac{kL_0}{P_0} + \frac{2kx}{P_0} + A \\ \frac{\partial Q}{\partial A} = \dot{x} \\ \frac{\partial Q}{\partial k} = \left(\frac{L_0}{P_0} + \frac{2x}{P_0}\right)\dot{x} \\ \frac{\partial Q}{\partial L_0} = \dot{x}\frac{k}{P_0} \end{cases} \tag{6}$$

The uncertainty u_x has been derived from laser transducer datasheet where non-linearity lower than 0.2% of the full scale (i.e. 100 mm) is granted. Considering a uniform probability distribution for the linearity error, the standard uncertainty $u_{x\_las} = 200\ \mu m/\sqrt{3}$ has been determined. Nevertheless, since preliminary data measurements evidenced noise and disturbances induced by mechanical vibrations [10] leading to large uncertainty, mainly due to the direct evaluation of the displacement time derivative, a different data processing procedure was developed. The time history of the bellow displacement is low pass filtered (third order Butterworth low-pass filter, 10 Hz passband) then a best-fitting is performed with a double exponential curve. The curve derived from the fitting is then used as x(t) in equation (3). The uncertainty due to the fitting is considered and combined with the contribution of the transducer alone (named u_{x_las} in the following). Root mean square of error (RMSE) obtained from the fitting has been used as uncertainty of the fit, i.e. u_{x_fit}. The total uncertainty of $\times$ then becomes:

$$u_x = \sqrt{u_{x\_las}{}^2 + u_{x\_fit}{}^2} \tag{7}$$

The displacement has been fitted with a two-term exponential function in the form:

$$x = A + Ce^{\alpha t} + Be^{\beta t} \tag{8}$$

The selection of this curve was suggested by the fact that a single exponential would be the theoretical evolution for a model of the pump as an ideal flow generator with internal leakage and a rigid volume. Considering the bellow compliance leads to a non-linear differential equation but, local linearization lead to the exponential. Using a single exponential fitting the residual error was significant, with RMSE in the range of 0.2 mm. The usage of two exponentials reduces the RMSE of the fitting in the range of 50 µm lower than the laser transducer instrumental uncertainty. In the plot of Fig. 7 an example of the fitting of the experimental data with the double exponential function is reported.

Evaluation of the first derivative of the displacement, $\dot{x}$ is then based on Equation (8) whose time derivative gives $\dot{x}$ as:

$$\dot{x} = C\alpha e^{\alpha t} + B\beta e^{\beta t} \tag{9}$$

In order to evaluate the uncertainty of the speed, the speed has been determined from different fitting functions obtained changing the convergence criteria of the iterative fitting algorithm. The root mean square of the differences between the various speed profiles and the average one has been used as standard uncertainty.

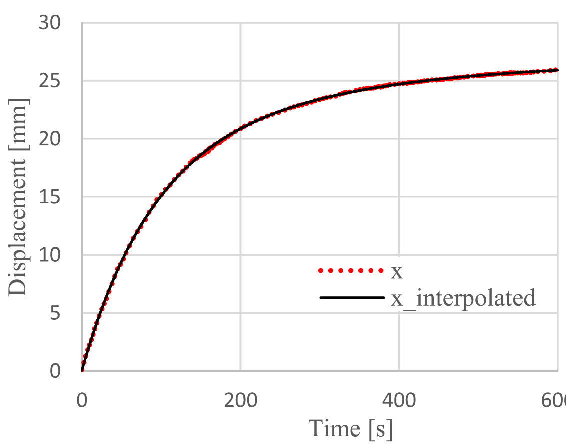


Fig. 7. Experimental data and double exponential fit-curve for the bellow's displacement, data from a test at 600 Pa environmental pressure.

The uncertainty in the environmental pressure measurement u_{Po} has been obtained from the pressure sensor (Inficon CDG020D vacuometer) specified accuracy, i.e. 1% of the reading.

The uncertainty of the bellow effective area A was evaluated from the procedure adopted for its evaluation. The bellow effective area was determined from tests in ambient conditions by comparing the flowrates measured by the bellow and those measured by the reference flowmeter. The area of the bellow was determined through a least square fitting by equalling the measured flow rates. The standard uncertainty of A derived from the LS fitting, combined with the reference flowmeter standard uncertainty was 5% of the nominal value. The air compressibility in this kind of tests has an influence in the range of 10% of flowrate so the uncertainty in its correction is negligible with respect to the above. Concerning the initial bellow length, L_0, the standard uncertainty of the displacement transducer, i.e. 0.12 mm, has been used.

The last contribution to the flowrate uncertainty is given by the bellow stiffness k. As discussed above, the bellow shows a nonlinear elastic behaviour for large displacements. However, for the working conditions of interest, i.e. a pressure difference in the range of 2000 Pa, non-linearity leads to a standard deviation of the stiffness, (from the least square fitting), below 1% of its value.

Given the uncertainties of the six variables contributing to the measurement of the flowrate, u_Q can be evaluated from Eq. (5). It can be noticed that u_Q is a function of the bellow displacement x and its derivative $\dot{x}$ therefore, the instrumental uncertainty will depend on the flowrate.

The following, as an example, the measurement of the flowrate generated by the breadboard pump, at 600 Pa environmental pressure, has been reported along with the evaluated standard uncertainty. The uncertainty, in a test at low pressure is more relevant than at ambient because, as one can see in Eq. (6)) most sensitivity coefficients are inversely proportional to the environmental pressure P_0.

Fig. 8 shows the evolution with time of the flowrate. The performance curve of the pump and the measuring uncertainty are shown in Figs. 9 and 10.

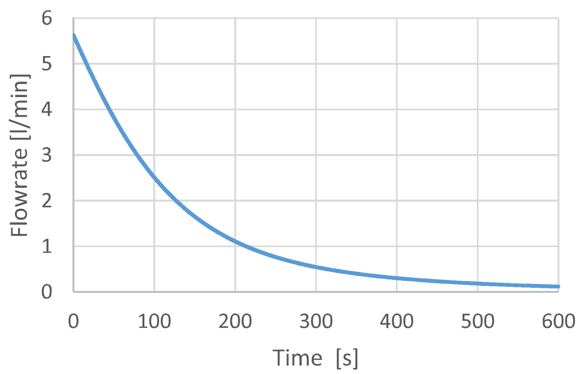


Fig. 8. Evolution of the flowrate during the test.

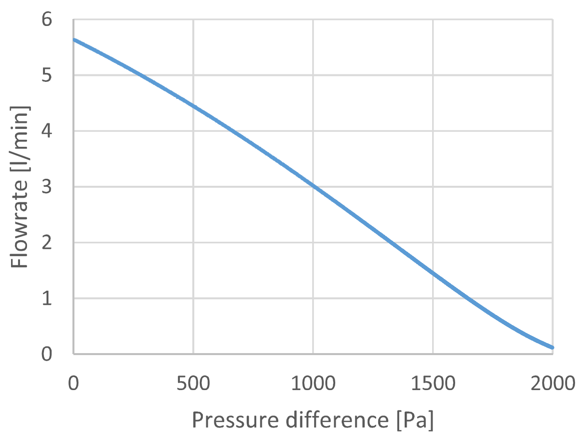


Fig. 9. Flowrate vs differential pressure for 600 Pa environmental pressure.

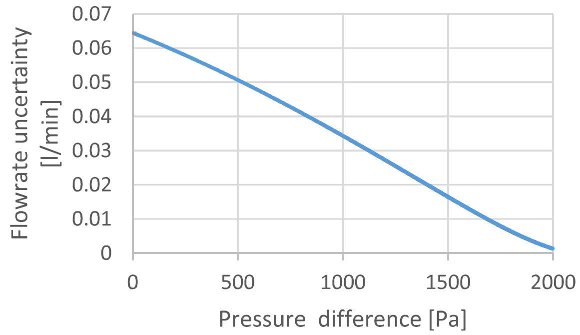


Fig. 10. Bellow's flowrate standard uncertainty trend vs differential pressure for the 600 Pa environmental pressure test.

Table 1
Uncertainty breakdown.

Factor	Standard Uncertainty of the factor	Factor contribution to the total variance [%]	Single factor effect as fraction of total uncertainty [%]
Lo	0.00012 m	1%	7%
k	17 N/m	68%	83%
A	0.0011 m^2	6%	25%
dx/dt	0.058 μm/s	Negligible	Negligible
x	0.00013 m	3%	16%
Po	3.5 Pa	23%	48%

4. Discussion

It can be noticed from Figs. 9 and 10 that both the measured flowrate and its uncertainty are larger at the beginning of the pump's run, and then decreases. Despite the relative uncertainty is not strictly constant, it oscillates between 1.1% and 1.2% in the overall range. Thus, the obtained result provides a 1.2% as instrumental standard relative uncertainty for the volume flow rate measurement system, which is a good approximation with a very small overestimation in some conditions. It can be pointed out that the analysis of the relative contribution of each parameter to the overall uncertainty evidenced that stiffness uncertainty, u_k, is the most significant component, which alone would generate about 80% of the total uncertainty.

In Table 1 the break-down of the uncertainty budget is reported. Column three reports the contribution to the overall variance i.e. the addends of Eq. (5) divided by the sum of all.

The terms of column four are the square root of the computed variances contributions (column three) providing fraction of the total uncertainty that each factor would generate if the other terms had negligible uncertainty, this allows more directly evaluating the effect of strong reduction of the dominating factors.

Despite the uncertainty of the bellow stiffness cold be reduced by using the non-linear model obtained in the characterization (see Fig. 5), the second term is the environmental pressure that alone would generate an uncertainty of almost 50% of the total. The con-

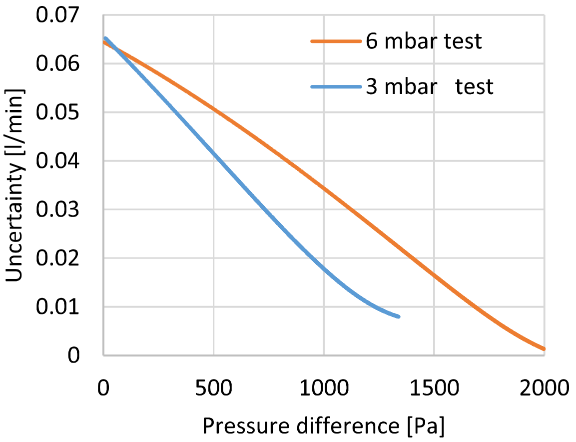


Fig. 11. Comparison of assessed flowrate uncertainties vs differential pressure for two different environmental pressure.

tribution due to the bellow area is not so far from the previous one so, the achieved uncertainty has been considered an acceptable limit of the setup and in order to significantly reduce it, a different measuring system should be devised.

The uncertainty assessment has been carried-out for tests at 300 Pa chamber pressure. Fig. 11 compares the evaluated uncertainties for the two cases, i.e. 600 Pa and 300 Pa environmental pressures.

One can notice that with the lower chamber pressure the uncertainty in flowrate measurement is almost the same for the largest flow rates (or lowest differential pressure) but becomes smaller as the pressure difference increases. Once again, the trend is quite similar to the flowrate, but the relative uncertainty is slightly increasing with pressure difference, actually it goes from 1.1% to 2%.

The performed uncertainty analysis, fully in line with the needs of our application, is limited by the adopted pump characteristics: for instance, the uncertainty for pressure differences larger than 1500 Pa cannot be assessed when the environmental pressure is at 300 Pa simply because the pump maximum generated pressure is lower than that. The relevant conclusion is that for our application, the system always warrants an uncertainty in the range from 1% to 2% of the measured flow rate, in line with the requirements.

Additional tests carried-out in the range of environmental pressure between 200 and 600 Pa led to the family of performance curves of the pump reported in Fig. 12. Similar curves were eventually obtained with the MicroMED flight model pump using a carbon dioxide atmosphere to simulate the expected operating conditions at Mars.

The relative standard uncertainty of the measured value at 300 Pa differential pressure in the test at 300 Pa environmental pressure is about 1.2%. This is particularly relevant for the application because this is the reference working point identified by fluid dynamic analyses of the MicroMED instrument [12] so the most relevant condition in our tests.

The achieved measurement uncertainty is compatible with the requirements for the intended application where the developed instrument will be used also as reference to calibrate the MicroMED flowrate measurement system, whose relative uncertainty should be lower than 5%. If needed, nevertheless, the accuracy of the measurement system could still be improved with “little effort” by using a non-linear model of the bellow stiffness and measuring more accurately the bellow effective area, for instance through the weighting method when filled by a liquid, but the limit would be the environmental pressure measurement uncertainty.

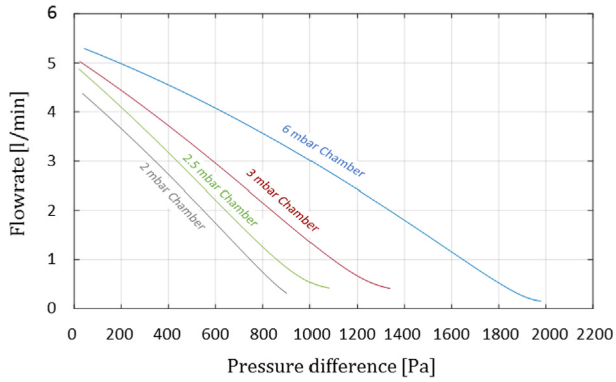


Fig. 12. Evaluated performances of the commercial pump at different pressures.

5. Conclusions

In this work, the design and validation of a volume flow measurement system to be used for gases at low pressures was presented. The devised measurement system was developed for the characterization of the performances of a pump, designed to be mounted on a dust analyzer for Mars atmosphere. The measurement system has been at first validated in laboratory condition and then exploited at different environmental pressures between 200 and 600 Pa, eventually also in carbon dioxide atmosphere, to simulate the Martian conditions. These initial tests were carried-out on a mock-up of the pump that allowed verifying the measurement system and also to derive preliminary information on the performances of this kind of pumps in the expected working conditions. The system, nevertheless, is devoted to the test of the flight components of MicroMED instrument. The assessment of the instrument's uncertainty in the reference working condition has proved that the required measurement accuracy has been achieved and there still some margin for improvements.

CRediT authorship contribution statement

Bortolino Saggin: Supervision, Conceptualization, Methodology, Funding acquisition. **Diego Scaccabarozzi:** Conceptualization, Methodology, Investigation. **Arash Valiesfahani:** Writing - original draft, Investigation, Methodology. **Pietro Valnegri:** Validation, Investigation. **Marianna Magni:** Validation, Writing - review & editing. **Francesca Esposito:** Funding acquisition, Writing - review & editing. **Cesare Molfese:** Formal analysis, Writing - review & editing. **Giuseppe Mongelluzzo:** Formal analysis, Writing - review & editing.

Declaration of Competing Interest

None.

Acknowledgements

This work was performed within the ASI agreement 2017-41-H.0t.

References

[1] D. Scaccabarozzi, B. Saggin, C. Pagliara, M. Magni, M. Tarabini, F. Esposito, C. Molfese, F. Cortecchia, F. Cozzolino, G. Dolnikov, I. Kuznetsov, A. Lyash, A. Zakharov, Thermo-mechanical design of a particle analyzer for Mars, in: 4th IEEE International Workshop on Metrology for AeroSpace, MetroAeroSpace 2017 - Proceedings, (2017), pp. 234–238.
[2] D. Scaccabarozzi, B. Saggin, C. Pagliara, M. Magni, M. Tarabini, F. Esposito, C. Molfese, F. Cozzolino, F. Cortecchia, G. Dolnikov, I. Kuznetsov, A. Lyash, A.

Zakharov, MicroMED, design of a particle analyzer for Mars, Meas. J. Int. Meas. Confed. 122 (2018) 466–472.
[3] G. Mongelluzzo, F. Esposito, F. Cozzolino, C. Molfese, S. Silvestro, G. Franzese, C. I. Popa, M. Lubieniecki, F. Cortecchia, B. Saggin, D. Scaccabarozzi, A. Zakharov, CFD analysis and optimization of the sensor "MicroMED" for the ExoMars 2020 mission, Meas. J. Int. Meas. Confed. 147 (2019).
[4] G. Mongelluzzo, F. Esposito, F. Cozzolino, G. Franzese, A.C. Ruggeri, C. Porto, C. Molfese, D. Scaccabarozzi, B. Saggin, Design and CFD analysis of the fluid dynamic sampling system of the "micromed" optical particle counter, Sensors 19 (2019).
[5] G.V. Messa, S. Malavasi, D. Scaccabarozzi, B. Saggin, M. Tarabini, F. Esposito, C. Molfese, Preliminary design of the inlet duct of a dust analyzer for Mars, in: 3rd IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2016 - Proceedings, 2016, pp. 604–608.
[6] W. Zhao, J. Yu, S. Zhang, C. Huang, J. Lin, "A gas ultrasonic flowmeter for low pressure applications," in: I2MTC 2017 - 2017 IEEE International Instrumentation and Measurement Technology Conference, Proceedings, 2017.
[7] K. Komiya, F. Higuchi, K. Ohtani, Characteristics of a thermal gas flowmeter, Rev. Sci. Instrum. 59 (1988) 477–479.
[8] F. Cascetta, G. Rotondo, A. Piccato, P.G. Spazzini, Calibration procedures and uncertainty analysis for a thermal mass gas flowmeter of a new generation, Meas. J. Int. Meas. Confed. 89 (2016) 280–287.
[9] D. Scaccabarozzi, M. Tarabini, L. Almasio, B. Saggin, F. Esposito, F. Cozzolino, "Characterization of a pumping system in Martian-like environment," in: 2014 IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2014 - Proceedings (2014), pp. 150-154.
[10] B. Saggin, D. Scaccabarozzi, C. Pagliara, A. Valiesfahani, F. Esposito, C. Molfese, F. Cozzolino, F. Cortecchia, "Design of a flowrate measurement system for low-pressure gases," in: 5th IEEE International Workshop on Metrology for AeroSpace, MetroAeroSpace 2018 - Proceedings (2018), pp. 279-283.
[11] International Organization for Standardization. and International Electrotechnical Commission., Uncertainty of measurement. ISO Guide 98 Part 3, Guide to the expression of uncertainty in measurement. (International Organisation for Standardization, 2008).
[12] G. Mongelluzzo, F. Esposito, F. Cozzolino, D. Saccabarozzi, B. Saggin, "Optimization of the sensor "microMED" for the ExoMars 2020 mission: The flight model design," in: 2019 IEEE International Workshop on Metrology for AeroSpace, MetroAeroSpace 2019 - Proceedings, 2019, pp. 749–753.