Scroll Pump Dust Tolerance Test for Martian Atmospheric Acquisition

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ABSTRACT

The ability to generate oxygen on the Martian surface will be essential to establishing a human presence on Mars. Flow generating devices such as pumps, compressors, and blowers will be essential components in Martian atmospheric acquisition and processing systems that need to work reliably during the mission duration. A concern with the reliability of the system is its ability to continue to perform nominally when Martian dust, if it bypasses the inlet filter, enters into the system. A series of tests were conducted to simulate the ingesting of Martian dust on a small scroll pump, similar to the one used on the MOXIE payload, during its pumping operation. The inlet of the pump was connected to a large volume closed-loop pipe system, known as the Mars Atmospheric Flow Loop, containing pure CO_2 gas at a Martian pressure of 7 Torr. A length of stainless steel tubing was extended from the inlet port of scroll pump, which was mounted outside the flow loop, to the inside volume of the flow loop using a feed-through compression fitting. A steady low-speed flow was generated inside the flow loop to continuously disperse and transport the dust toward the inlet tubing. JSC-Mars 1 Martian simulant was used to challenge the pump. The pump performance parameters such as flow rate, pump speed, pressures and temperature were monitored during these tests. Samples of the dust entering the pump inlet were taken prior to exposure tests, using an inline filter element to determine the rate of dust ingestion into the internal components of the pump. After two tests with exposure times of the order of 60 minutes, the data indicated that small changes in pump performance took place under high rates of dust exposure.

INTRODUCTION

The ability to generate oxygen on the Martian surface will be essential to establishing a human presence on Mars. Flow generating devices such as pumps, compressors, and blowers will be essential components in Martian atmospheric acquisition and processing systems that need to work reliably during the mission duration. The MOXIE (Mars OXygen In situ resource utilization Experiment) payload, for instance, is a 1/100th scale demo of a CO_2 atmospheric acquisition system that will be operated on the Mars 2020 rover (Meyen, 2016). This system uses a small scroll pump to pull in the CO_2 Martian atmosphere, and separate and collect the oxygen using solid oxide electrolysis. A concern with the reliability of the system is its ability to continue to performance nominally if, or when, Martian dust enters into the system.

Scroll pumps operate by trapping and pumping the gas between surfaces of the involute elements, with one typically rotating (or orbiting) and the other stationary. It is standard practice to use a high efficiency filter, e.g. HEPA, to clean the gas before entering the inlet of the pump. Without the filter, dust particles may enter the internal volume of the pump and damage sensitive components. For instance, the gap between the surfaces of the involute elements and at the tip seals are areas that may be compromised. In the Mars environment, use of a filter at the inlet may not be the most operationally favorable configuration, as the low Martian atmospheric pressure does not leave much margin for an appreciable level of filter pressure drop. As an alternative, a medium to low grade efficiency filter can be used, with the acceptance that, depending on media grade, there will increased number of particles that make it through the filter and reach the scroll pump. Another option is to place the HEPA filter after the pump to protect downstream components, and accept unfiltered gas at the pump inlet. This last option poses the most risk, and therefore it is necessary to test the pump to determine its tolerance to representative dusty flows.

A series of tests were conducted to simulate the ingestion of Martian dust into a small scroll pump, similar to the one used on the MOXIE payload. The paper presents the results and analysis of these dust exposure tests. Characterization data is provided on the dusty inlet conditions, and the pump performance exposed to Martian simulant dust.

BACKGROUND

In recent years, part of the trend has been the development of oil-free scroll compressors for food processing, medical systems, textile manufacturing, fuel cell systems, cryogenics, and other applications requiring clean operation. An overview of the mathematical modeling of oil-free scroll compressors, as well as a thorough literature survey, can be found in Halms (1977) and Chen (2000). Although scroll pump technology is mature, numerous innovations and patents continue to be filed annually (Bin, 2016). However, it seems that there is little, if any, currently available published data on the performance and degradation of oil-free scroll compressors in dusty environments.

EXPERIMENTAL SETUP

A commercial scroll pump similar to the one used in the Mars 2020 MOXIE payload was connected to the internal volume of the Mars Atmospheric Flow Loop (MAFL) housed at NASA GRC. The MAFL has been used previously to test filter media and filter systems under reduced atmospheric pressures for environmental control and life support systems (ECLSS), and at Martian atmospheric conditions for In-Situ Resource Utilization (ISRU) applications (see Agui et al. , 2010 and Agui, 2016). The test scroll pump can nominally pump a volume of air at 1 atmosphere at a rate of 20 slpm, and was expected to pump 15 lpm at 7 Torr. A schematic of the setup is shown in Fig. 1.

There were two main reasons for using the flow loop. First, by connecting the pump inlet to the internal volume of the flow loop, the flow loop helped maintain Martian atmospheric conditions at the pump inlet – specifically, nearly 100% carbon dioxide gas at 7 Torr. It served as a constant Martian pressure and CO_2 source with controlled injection of CO_2 into the MAFL to make up for the gas removed by the test scroll pump. The other reason for its use was to facilitate the introduction of simulant dust into the pump inlet. This was done by dispersing the dust inside the flow loop volume, with the flow helping to transport the Martian dust towards the pump inlet. A length of stainless steel tubing was installed on the flow loop using a compression fitting, to allow the capture of the particle flow from inside the flow loop to the test scroll pump. Figure 1 shows the tubing extending into the flow loop terminating with a 90° bend, and facing into the flow. A ball valve was installed to close off the connection between the flow loop and the pump when the pump was not being used. An in-line filter was used in one of two positions. It was used at the inlet of the test scroll pump (as shown in the figure) to facilitate particle flow sampling at the pump inlet. Secondly, it was also used to filter the flow going into the flow meter. A flow meter was installed in-line to monitor the pump flow rate. Finally, the outlet flow was directed towards a laboratory exhaust snorkel. Data of the pump speed, pump flow rate, pump outlet temperature and pressure were logged during the tests. Figure 2 shows the actual scroll pump mounted on the MAFL supports and plumbed to the flow loop. The pump microcontroller and the inline flow meter are also shown.

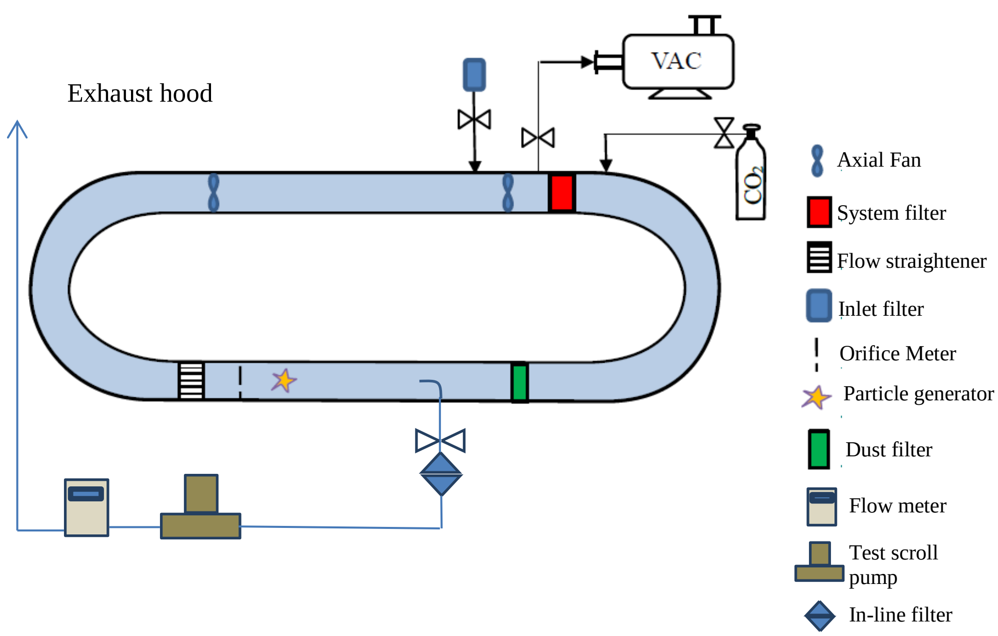

Figure 1: Diagram of experimental setup

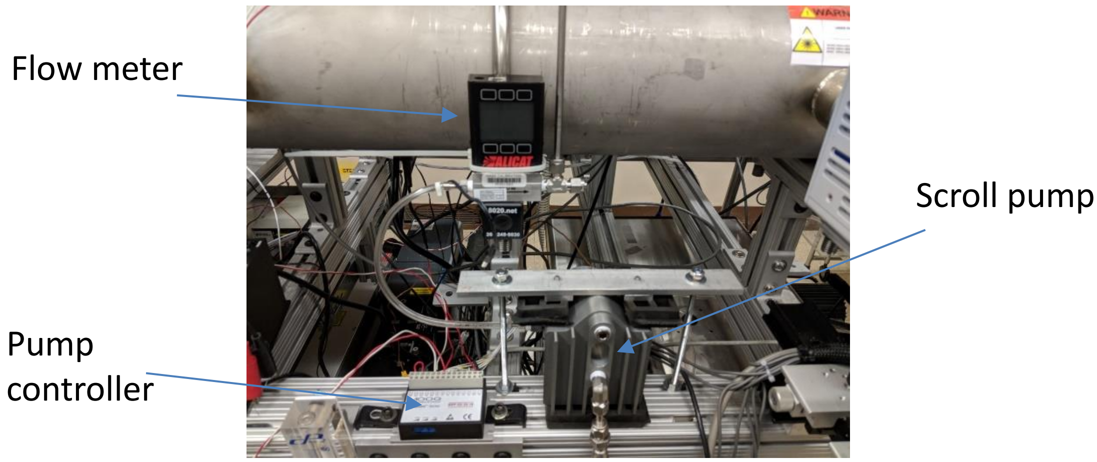

Figure 2: Scroll pump setup

The test were conducted by pumping down the air in the flow loop to < 40 mTorr and then backfilling with pure (99%) carbon dioxide gas from the supply bottle. Once the proper pressure was reached, the system axial fans (see Fig. 1) were activated in order to produce a recirculating flow. With the main flow activated, a solenoidal fractional valve to the regulated CO_2 supply bottle was opened. The particle generator, filled with the JSC-Mars 1 simulant, was activated to disperse particles into the flow. The particles became entrained in the flow and reached the tubing downstream in the flow loop that was connected to the inlet of the test scroll pump. The pump exposure test started the moment when the test scroll pump was activated and the valve to the pump inlet was opened. A muffin fan was used to cool the pump motor during the test. The pump flow rate, pump outlet flow temperature and pressure, and pump speed were monitored during the exposure test. During the exposure tests, the in-line filter in Fig. 1 was repositioned between the pump outlet and the flow meter inlet to prevent any dust from entering the flow meter. A small microcontroller with input from the system pressure transducer was used to control the valve opening on the fractional valve to the CO_2 supply and thereby control the operating pressure in the flow loop. Optionally, the fractional valve was manually controlled to maintain flow loop pressure.

Simulant preparation

Six batches of simulant were prepared for testing the pump. Each batch was sieved using an industrial sieve shaker. Several stages of sieving was performed by stacking different mesh size sieves and loading the simulant on the top (coarsest) sieve. The mechanical sieve ran for thirty minutes per sample. Yields of small particles ranged from a few percent to over twenty percent, depending on the preparation method. Table 1 provides a summary of the yield from each batch process. The reader will notice that the total yield does not sum to unity since some simulant was lost in the sieving process.

In the first three batches, three size fractions were produced with two different sieve stages. The first stage of sieving was performed with a either a 200 µm or 250 µm sieve, and the second stage with a 75 µm sieve. In these three cases, the majority of the particles (> 58%) were found to be greater than 200 µm while only very low yields of the smallest size particles were produced. In batch 4, an additional finer 53 µm sieving stage was added, and in batch 5 the 75 µm sieve stage was removed. The size fraction below 53 µm is more suitable for dust, however the yields are very low. To achieve sufficient yields of fine dust many batches of sieved simulant would be needed, while having to discard the bulk, up to 95%, of the simulant. Instead, for batch number 6 a tumbler apparatus was used to crush and grind the simulant prior to sieving. The apparatus was fashioned with a motorized roller used to continuously rotate a porcelain jar in a horizontal orientation, filled with the simulant and 2.54 cm cylindrical ceramic pellets to process the simulant. It also ran for thirty minutes per sample. Yields of small particles increased by a factor of ten to roughly 25%. Some slight discoloration was observed, as the crushed particles were noticeably darker than similarly sized particles that were only sieved. Because of the higher yield of small particles, the size fraction 4 from Batch number 6 was used for the sampling and exposure tests.

Table 1: JSC-Mars 1 simulant sieving results

		Fraction 1			Fraction 2			Fraction 3			Fraction 4		
Batch number	Batch mass (g)	size range (µ)	mass (g)	%	size range (µ)	mass (g)	%	size range (µ)	mass (g)	%	size range (µ)	mass (g)	%
1	47.732	> 200	27.921	58.5	75 to 200	15.594	32.67	< 75	3.25	6.81			
2	28.048	> 200	19.201	74.48	75 to 200	4.259	16.52	< 75	1.234	4.79			
3	37.427	> 250	24.849	66.41	75 to 250	9.2	24.59	<75	2.212	5.91			
4	73.923	>250	45.857	62.03	75 to 250	22.703	30.71	53 to 75	2.166	2.93	< 53	2.0789	2.81
5	98.272	>250	58.98	60.02	53 to 250	32.777	33.35	< 53	4.351	4.43			
6	43.748	> 250	12.115	27.69	75 to 250	15.376	35.15	53 to 75	5.799	13.26	< 53	10.358	23.68

Dust sampling

In order to determine the rate of dust ingestion in the pump during an exposure test, a separate test, prior to the exposure test, was performed to sample the dust at the pump inlet. The pump speed was adjusted so that the pump flow rate was close in value to the flow rate during the dust exposure tests, as determined by preliminary performance tests of the scroll pump. An in-line filter holder with a 2.54 cm diameter flat sheet filter media was installed for this test. Two perforated screens were used to sandwich the sheet filter to provide structural support. Any particles entering the tubing line were expected to be collected on the filter media and screens. The filter media and screens were weighed before and after the exposure test on a precision scale. The weighed amounts were used to calculate the amount of dust that collected on the filter media and screens during a sampling test of an extended duration, typically 30 to 40 minutes.

Imaging

After the dust sampling test, the filter media sample was imaged under an optical microscope to visualize the extent of particle capture. The images were taken with an attached DSLR camera with 1.4 megapixel resolution. The microscope was used with a 4X and 20X microscope objective.

RESULTS

A few preliminary tests, which included pump performance and dust sampling tests and imaging, were conducted prior to the dust exposure test. The pump performance test provided baseline performance on the scroll pump. The pump speed was incrementally ramped up to measure the corresponding flow rate. The same test was also performed after the exposure tests. A comparison of the performance tests prior to and after the exposure tests are presented later in this section.

The particle sampling test was performed using the in-line filter with a HEPA grade filter media to capture the ingested dust and to determine the rate of particle ingestion. Initially the flow loop's particle generator was kept in its nominal position, about 2 meters from the sampling station, where it provides suitable spreading of the dust throughout the cross-section of the pipe at the test section. This setup provides a fairly uniform particle cloud for filter testing. However, after a few particle sampling attempts, it was determined that the particle concentration sampled through the stainless steel tubing was not sufficient for a reliable dust exposure test. As a remedy, the particle generator was positioned closer to the test section and within a few centimeters of the inlet tubing connected to the test pump. After the sampling test, the sheet media was removed from the holder and weighed on a precision microbalance. The particle ingestion rate was found to be 0.02 mg/min based on the accumulated mass of dust on the filter media and screens, and the sampling time.

Additionally, the filter media sample was imaged under an optical microscope. Figure 3a shows the actual circular filter media sample after the sampling test, and the labels indicate the locations of the microscopic imaging. It is apparent that the particle collection was not uniform. The dust was found to be concentrated in the dashed labeled region. Figure 3b shows the simulant dust particle collected at the center of the filter media (position 1) with 4X magnification. It shows very good coverage and dispersion over an area 11.85 mm^2. Figure 3c shows a 20X magnification of the same spot on the filter media. The collection of particles through different layers of the filter media are evident. Figures 3d and 3e show the particle collection closer to the edge of the filter media where the highest collection density was observed. The imprint pattern of the circular perforations of the supporting filter screens are quite apparent. The close up of Fig. 3d shows much higher collection density in this area of the filter media than observed in the center of the media. Imaging at positions 3-5 showed a few to no particle collected. Therefore, it appears from the image analysis that most of the particle collection took place in the area bounded by dashed lines as marked in Fig. 3a.

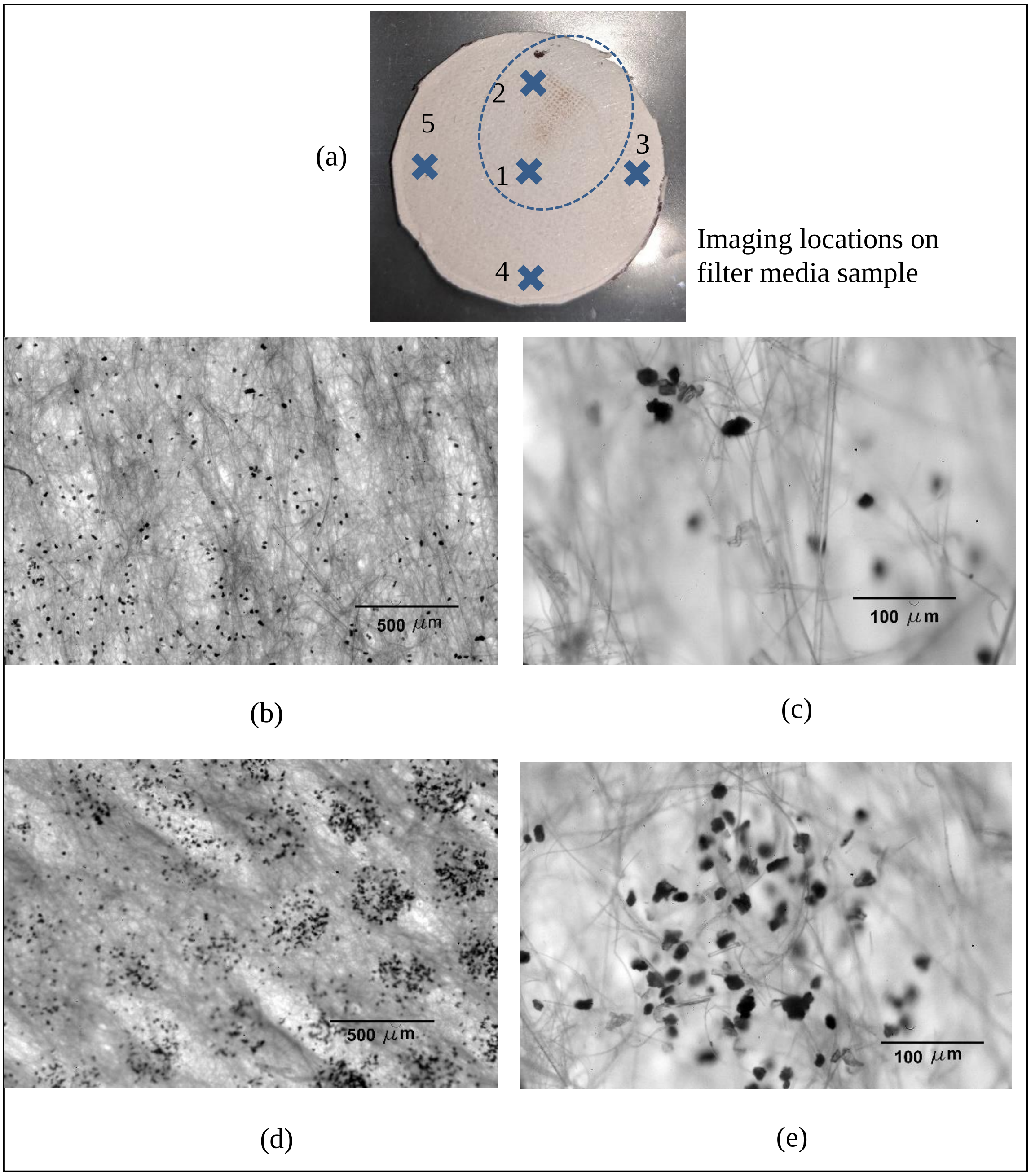

Figure 3: Microscopic imaging of filter sheet (a) Locations of imaging spots on filter media sample, (b) 4X magnification at position 1, (c) 20X magnification at position 1, (d) 4X magnification at position 2, (e) 20X magnification at position 2

Two dust exposure tests of an hour duration were conducted. Figure 4 shows the time history plots of the different operational variables monitored during the first one hour exposure test. The pump outlet pressure and temperature were steady during the hour long test. However, the pump speed increased slightly. The pump flow rate was constant throughout the test but exhibited a significant amount of fluctuations. A close up (see inset) of the oscillations show that the flow rate signal consisted of high frequency periodic behavior, possibly due to the mechanical pumping action of the orbiting involutes. Since the sampling frequency was only 10 Hz, this plot cannot reveal the actual frequency of the periodic behavior. Rather the signal only shows the aliasing of the higher frequencies of the pump which should be 50 Hz and larger. These fluctuations were not observed in the outlet pressure signal. One reason for this could be due to the use of small diameter tygon tubing between the pump outlet and the flow meter which may have effectively dampened the pressure fluctuations.

Figure 5 shows the traces of operational variables during the second exposure test. This test was run a slightly higher pump speed around 3100 rpm instead of 2600 rpm. In this case, the pump's flow rate signal exhibited larger fluctuations than observed in the first test. The pump pressure was steady, but the outlet temperature and flow rate exhibited transient behavior near the start of this test. During this phase, the pump speed was a little lower and the temperature began dropping. At the same time, a much lower frequency oscillation of the flow rate took place, which later increased in frequency. This effect could have been caused by a temporary obstruction from the ingestion of the dust. After this initial event, the data seem to exhibit more steady operating conditions. As in the first exposure test, the flow rate signal also locally exhibited the same type of periodic behavior.

Figure 6 shows the comparison of the pump performance tests prior to and after the dust exposure tests. It clearly shows a small drop in pumping performance after the dust exposure test. The difference was about a 12 % downward shift in the performance curve. Therefore, the data indicates a small degradation in pump performance after the two exposure tests, with a calculated total exposure of 2.4 g of JSC-Mars 1 simulant dust. This would be the equivalent of 10^9 hours of dust ingestion on the Martian surface based on 6 particles/cm^3 at a flow rate of 10 to 20 cm^3/min. Note also that the simulant was sifted below 53 μm, and therefore the dust that reached the internal components of the pump(based on the images of shown in Figs. 3c and 3e) was approximately 20 μm on average. It can be concluded that even though the dust exposure level may be considered severe, the pump performance degradation was only moderate.

CONCLUSIONS

A series of tests were conducted to simulate the ingesting of Martian dust on a small scroll pump, similar to the one used on the MOXIE payload, during its pumping operation. The use of the Martian Atmospheric Flow Loop set up in the lab served as a constant Martian pressure and CO_2 source and as a means of introducing simulant dust into the pump inlet, which greatly facilitated the testing of the scroll pump. Two dust exposure tests of an hour duration each and at dust exposure rate of .02 mg/min were conducted. The test results show small, but not insignificant, degradation in pump performance under high dust exposure rates. However, the projected operational time to accumulate this level of exposure, 10^9 hours, is significantly greater than the mission required time of 10^4 hours (11,000 hours) for ISRU surface systems (Kleinhenz and Paz, 2017). As far as the appropriateness of accelerated testing, it should be noted that exposure to the same total dust load in 30 to 40 minutes that would take 10^9 hours under expected concentration levels, is not exactly the same as running a test for long duration. For example, some dust may be able to migrate into small crevices over time. However, it is a reasonable indication that performance degradation will likely be negligible to modest in the worst case.

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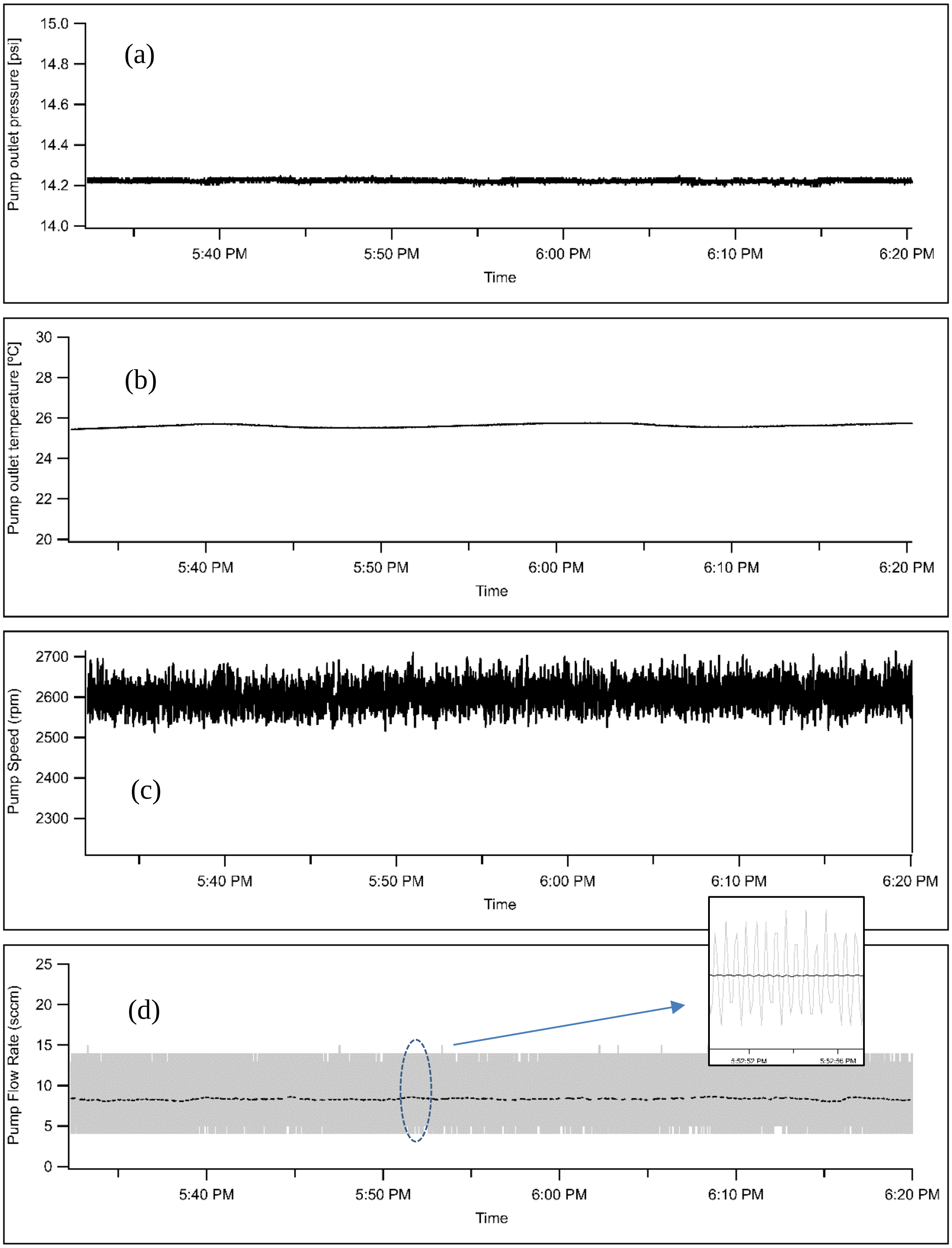

Figure 4: Dust exposure test #1 (a) pump outlet pressure, (b) pump outlet temperature, (c) pump speed, (d) pump flow rate (inset – expanded plot)

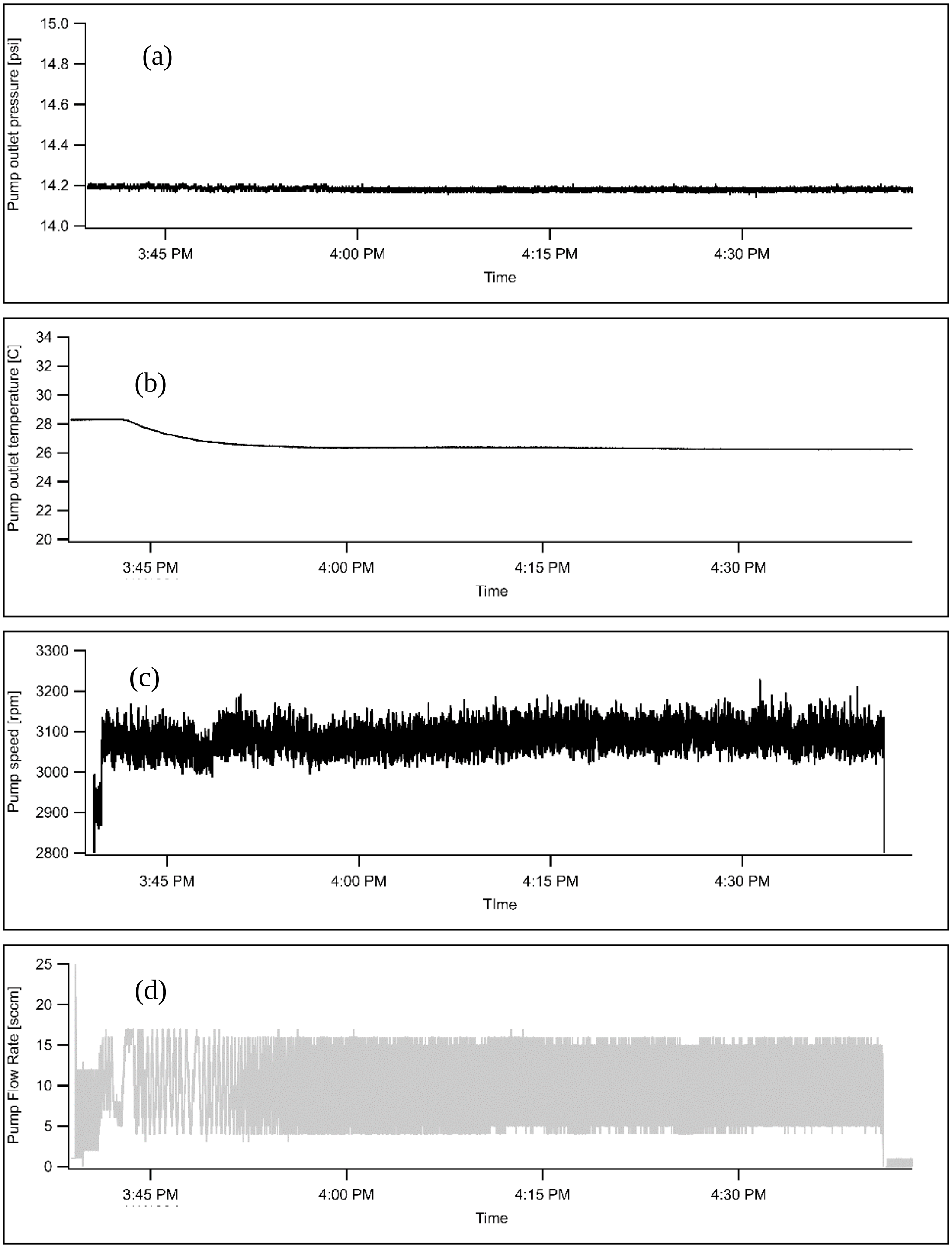

Figure 5: Dust exposure test #2 (a) pump outlet pressure, (b) pump outlet temperature, (c) pump speed, (d) pump flow rate

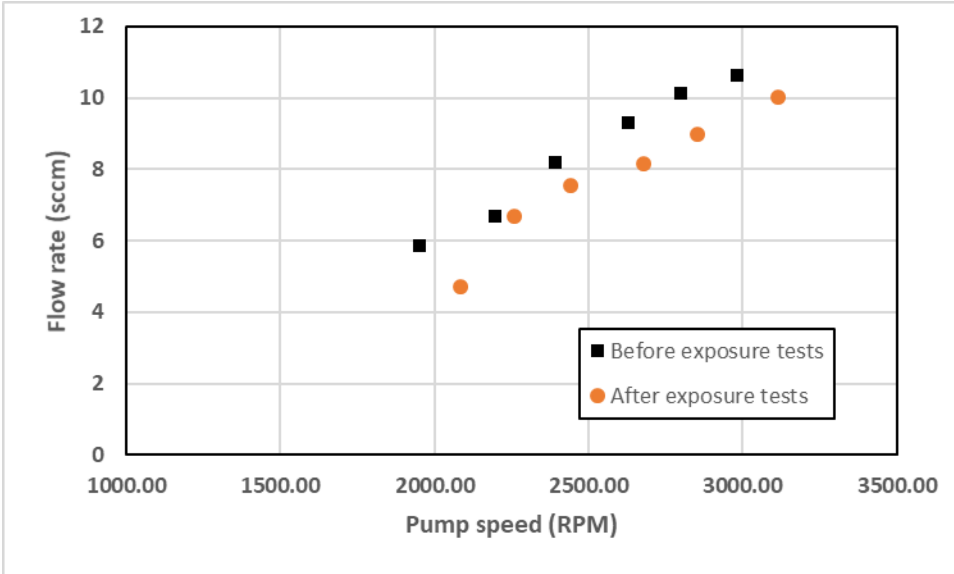

Figure 6: Pump performance tests