TRIBOELECTRIC WIND TURBINE FOR MARS EXPLORATION

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ABSTRACT

The aim of the work has been to develop an efficient and robust turbine demonstrator that can efficiently operate under Mars environmental conditions. A combination of low friction and high inherent triboelectric charge density materials have been integrated into the Triboelectric Generator (TEG) architecture operating under a freestanding mode and including 4 generators. Each generator is compounded by Al+PTFE stator and H-DLC+Al rotor and the complete efficient design has 2 rotors and 4 stators. Then the vessel where the generators are located is pressurized achieving an Earth atmospheric pressure value (1000 mbar) and Mars atmospheric composition (96 % CO2) because the power generation is increasing by 31.84 % in comparison with power generated under Earth atmospheric composition and 98 % under Mars atmospheric pressure. Moreover, the turbine mechanical elements such as blades, sealings, and vessel have been designed, simulated, manufactured, assembled, and tested to achieve the correct operation based on Mars's environmental requirements.

1 WIND POWER IN MARS AND ENVIROMENTAL CONDITIONS

The human and robotic exploration for Mars will require total independence from Earth, and as in the Earth, the energy stable availability will become crucial to allow permanent habitats [1]. In addition, Mars dust storms can last more than 6 months becoming solar energy unusable for that period, consequently causing a lack of available energy for future astronauts. This work wants to take advantage of Mars's environment to convert wind energy into electrical energy and use it as the auxiliary energy source of solar cells. However, the usual Electromagnetic Generators (EG) are unsuitable for planetary exploration due to their heavy weight, leading to high launch costs. The alternative to EG could be the Triboelectric Generator (TEG), a relatively new technology which converts external mechanical energy into electricity by a conjunction of the triboelectric effect and electrostatic induction [2].

The main atmosphere parameters that change on Mars regarding the Earth are density and velocity. The atmosphere density on the Earth is 1.217 kg/m3 and on Mars 0.020 kg/m3, both at surface level. The wind speeds measured on Mars give a range between 5 and 30 m/s. The benefit of the power production equation is that the extraction potential for wind power is a function of velocity cubed and only proportional to density. So, the effect of the Mars atmosphere density parameter has a smaller impact than the velocity, for the power that can be extracted from the winds. This work has been developed using real data measured by NASA's Insight mission at the Elysium Planitia to find out how the turbine works in real Martian conditions [3]. In addition, Table 1 shows the summary of Mars's environmental conditions.

Table 1. Summary of Mars airflow and environment conditions.

		Mars	Earth
Airflow factors	Air density (kg/m^3)	0.02	1.225
	Wind velocity (m/s)	25.8-41.0	6.2-11.5
	Wind power density (W/m^2)	172-689	147-932
Environmental factors	Atmospheric pressure (Torr)	1-10	760
	Majority composition	CO2	N2,O2
	Average temperature (K)	218	288
	UV-C & UV-B intensity (W/m^2)	46	6
	Gamma ray intensity (rad/year)	26.3	0.03

The main question is that even though on Mars there are wind seasons with high-speed winds, the atmosphere density is very low. It is not obvious that a wind turbine would move under those conditions. The good part of the power production equation is that the extraction potential for wind power is a function of velocity cubed and only proportional to density. So, the effect of the Mars atmosphere parameter is less worthwhile than the velocity regarding the power that can be extracted from the winds [4]. Figure 1 shows the Martian meteorology of three typical sols experienced by InSight, which shows a diversity of scales involved from the planetary scale to local turbulent scales:

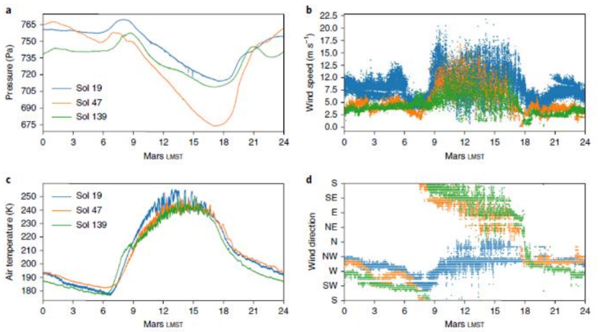

Figure 1. Measurements of pressure (a), wind speed (b), atmospheric temperature (c) and wind direction (d) are shown [3].

This turbine aims to convert the mechanical energy of the Mars winds to electric energy. For that, the turbine is designed to convert the wind mechanical energy into rotational movement, then the triboelectric generators which are moved with the rotation movement of the axis produce the electrostatic energy, and finally, the electrical energy must be achieved converting from the electrostatic energy with a power management.

Finally, this work is the continuation of the previous [5] presented in AMS2022. In this case, the complete turbine system, the triboelectric generator, the implementation, the test campaign related to power generation and the operation at the Mars wind tunnel, and finishing the achieved conclusions.

2 TRIBOELECTRIC GENERATOR

The functionality of TENGs is based on triboelectrification (or contact electrification) and electrostatic induction phenomena (see Figure 5). TEG architecture involves two materials with different charge affinity during contact [6]. The freestanding TEG has more advantages of a contact separation mode as it does not require attachment to the moving triboelectric layer with an electrode and a lead wire. In this work, a freestanding mode as the one represented in Figure 5 is considered. In this scenario, a grating structure is manufactured in the rotator and stator where the output power depends on the material selection, contact surface characteristics, grating number, and electrode gap.

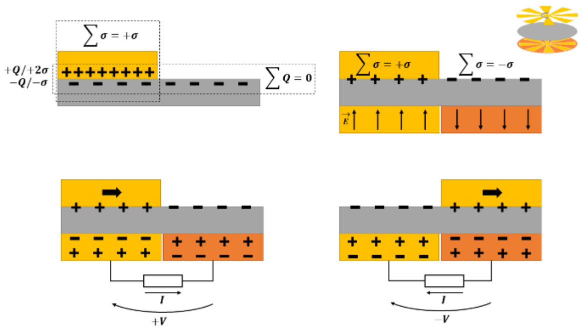

Figure 2. Electric charge and electric charge density generated on materials surface.

The Figure 3 shows the TEG generator design-based trade-off design and on mechanical simulations also the 4-layer TEG generator dividing the 4 stators and the 2 rotors are shown. The stator blades to generate the positive and negative charges are fixed to PEEK support elements which include 3 anti-rotation elements and the preload springs. Finally, each generator will be connected to wires via the output point of connection to measure the power generated by the turbine.

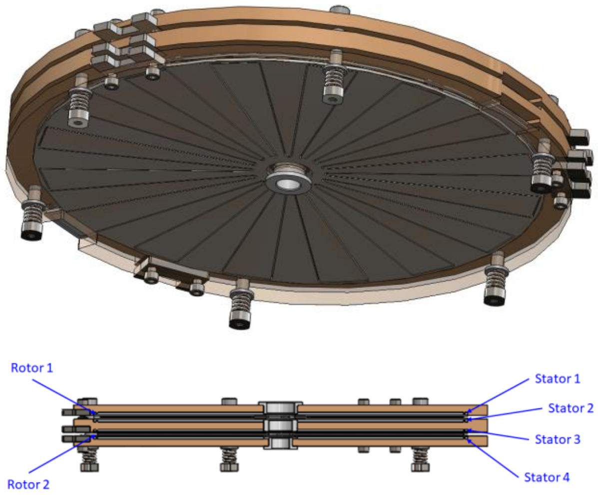

Figure 3. The TEG generators structure.

The pressure and the CO_2 are the two main parameters that affect the TEG's power generation which decreases at lower pressure levels (CO_2 effect is also decreased). In higher pressure levels the CO_2 effect (due to the Paschen law) on the materials increases the generated power in comparison with Earth's atmospheric conditions.

3 TURBINE SYSTEM

3.1 Turbine system design

The system has a basic operation principle, the total resistive torque must be lower than the wind-generated torque to achieve the correct rotation operation. Thus, the system design must be oriented to accomplish this requirement. For that different types of loads acting on the wind turbine have been identified, simulated, and analysed: Wind forces, centrifugal forces, internal pressure in the vessel, and thermal loads. During this work, the mechanical simulations including the aerodynamic design of the blades have been carried out oriented to the system operation under Mars winds and conditions. Figure 4 shows the achieved results during these processes:

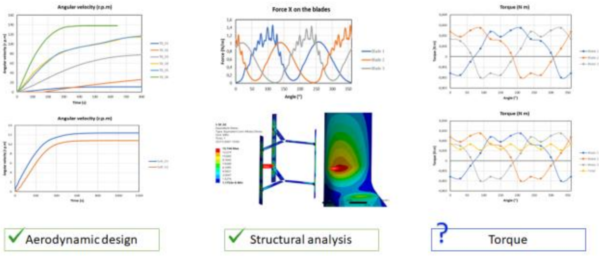

Figure 4.Results of aerodynamic, structural, and torque simulations and analysis.

As in usual Earth wind turbines, the TEG generator rotates thanks to the movement of the axis. To allow the rotatory movement with the minimum required torque while avoiding dust insertion and maintaining the pressure level the next elements have been included in the final design: The sealing element that allows the rotatory movement, the up bearing to support the radial and axial forces, the down bearing to support the radial forces, the labyrinth to void the insertion of the dust in the sealing rotatory system. In addition, the vessel is compounded by a skeleton architecture that ensures the pressurization of the vessel without any damage. Finally, the blades are made with space compatible carbon fiber and fixed in the up and downside of the axis. These elements are shown in Figure 5:

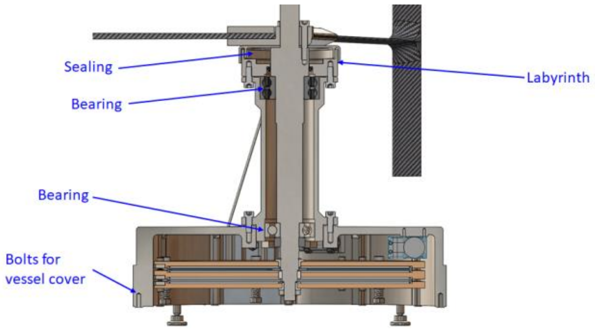

Figure 5. Mechanical view of the turbine from a cut view.

Figure 6 shows the pressurization and cleaning system of the vessel. The pressurization system is composed of a nm particle filter to avoid the insertion of the Martian dust and damage the compressor which increases de vessel pressure. In addition, a pressure sensor is included to measure and control the vessel pressure. Then, the cleaning system is composed of an electrovalve which decreases the pressure in case that is necessary and at the same time cleans the vessel thanks to the difference in pressure between the vessel and the Martian atmospheric pressure.

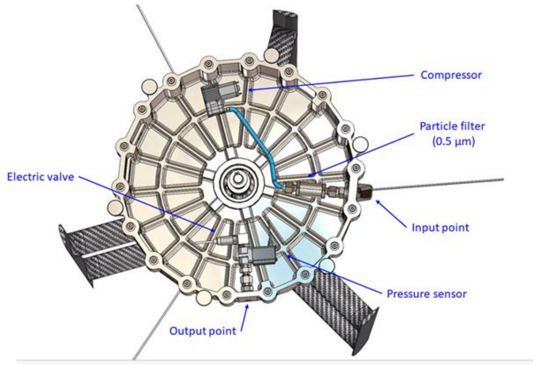

Figure 6. Pressurization and cleaning systems inside the vessel.

Finally, it has made a linear estimation of sealing lifetime versus axis different Ra value. Table 2 shows the calculated estimations for the sealing lifetime under Martian atmospheric (temperature and pressure) and turbine operation conditions:

Table 2. Continuous working at 160 rpm as average value.

Ra (µm)	Lifetime (h)	Lifetime (days)	Lifetime (sols)	Lifetime (months)
0.4	4000	166.67	162.21	5.56
0.2	8000	333.33	324.41	11.11
0.1	16000	666.67	648.83	22.22
0.05	32000	1333.33	1297.66	44.44
0.025	64000	2666.67	2595.32	88.89
0.01	160000	6666.67	6488.3	222.22

4 PROTOTYPE MANUFCATURE AND ASSEMBLY

In this work a prototype has been manufactured, being the prototype dimension 12 kg of weight and 0.9 m of height. This system is totally scalable; however, the selected height has been based on the limitation set by the dimensions of the Mars wind tunnel testbench. Figure 7 shows the turbine totally assembled.


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Figure 7. Prototype of the wind turbine for Mars.

I'm electromagnetic generators, the impedance matching changes the system torque. In the TEG this effect is also detected but does not depend on the velocity, it remains constant. As has been detailed, the system must be pressurized with 1000 mbar to increase the power generation, affecting the sealing system torque where must be considered the friction force between the sealing and the axis, and the force made by the pressurization. Finally, the TEG torque is generated by the flatness of the TEG "sandwich", the preload set by the selected springs, and the area quantity. Being the torque total of the system the next one:

$$T_{Total} = T_{TEG} + T_{Pres} + T_{IM} \quad (1)$$

So, in this system, the pressurization torque is 0.3 N/m, the friction torque from sealing is 0.2 N/m and the TEG friction is 1 N/m for the 4 generators. Being the total system torque 1.5 N/m. Figure 8 shows the preload springs.

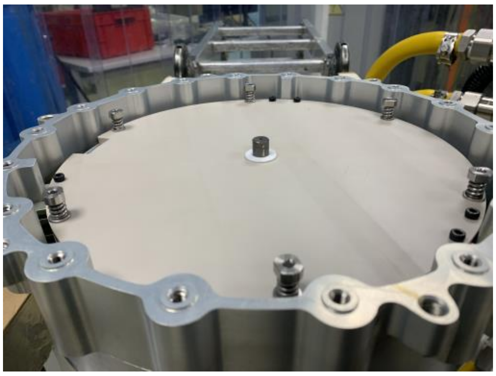

Figure 8. The vessel with holes for the enclosure, the preload springs, and the 4 TEG generators packaged.

5 TEST CAMPAIGNS

The turbine has been tested to validate the pressurization behaviour of the vessel, the power generation, the preload values, the lifetime of the generator materials, and the operation in Mars wind conditions. All the tests have been carried out under different rotatory conditions.

5.1 Voltage and power generation

First of all, it must be considered that the distance between the generator and the measuring system or load affects dramatically due to the losses that are produced in the wire (low current signals are generated by the TEG).

The voltage and power generation tests have been carried out under Earth, Mars, and Mars pressurized conditions and different rotational velocities which have been: 50,100,150, 200, 250, 300, 350, 400, and 432 RPMs (being the origin of the aerodynamic design simulations). To simulate the Mars environmental conditions the Titan machine (available at Tekniker facilities) has been used which allows external control and measurement of the systems and is capable to generate the required 6 mbar and 96 % CO_2 environmental conditions. The test setup for the voltage and power generation test campaign is shown in Figure 9.

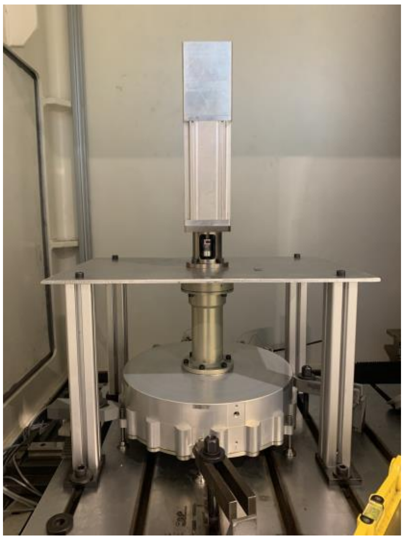

Figure 9. Test setup for generator with an engine to simulate the rotatory movement inside the test chamber.

5.1.1 Voltage generation

The first step has been to measure the voltage level generated at the different 3 conditions with the aim to understand the TEG's energetic capabilities. The voltage in the open circuit condition of the TEG must be measured in no-ground condition [7] to have a real value of the voltage and don't lose any charge. Figure 10 shows the voltage signal generation at different environmental conditions and angular velocities.

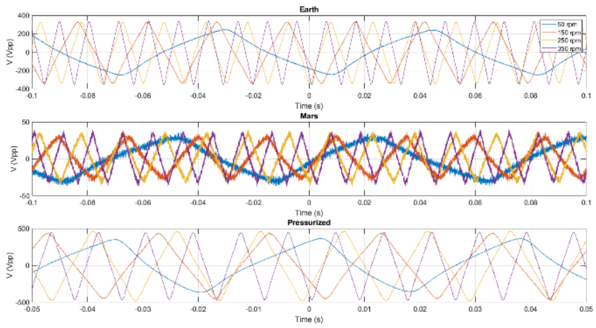

Figure 10. Generated voltage signals at different velocities under Earth, Mars, and Mars pressurized conditions.

Note that the generated triangular signal is an effect of the mechanical triangles of the stator and rotor. In addition, the TEG generator is dramatically affected by the load that is connected (oscilloscope shunts in this case), reducing the real voltage generated. The no-ground condition must be used to measure the real generated voltage level, i.e., the positive and negative sides of the generated signals.

As can be seen in Figure 11, the maximum Voc is 953.98 V in Mars pressurized condition and 200 rpm. The voltage increases until 200 rpm angular velocity and in higher velocities decreases. As in trade-off tests, the Mars condition is not able to operate the system. The voltage level increases on average 26.64 % when the turbine operates in Mars pressurized conditions. The increase of the voltage generated before 50 rpm is much more rapid than after 50 rpm.

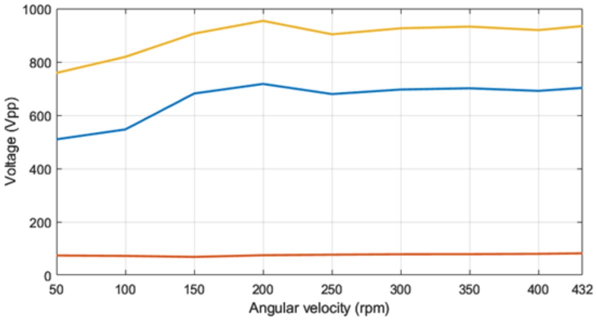

Figure 11. Voltage generated by the TEG generators at Mars, Earth, and Mars pressurized conditions.

The system is totally repeatable, the system remains stable in voltage generation and frequency value in each operation condition. The difference between the theoretical frequency of the generator at different velocities and the measured is less than 0.62 % on average, as is shown in Figure 12.

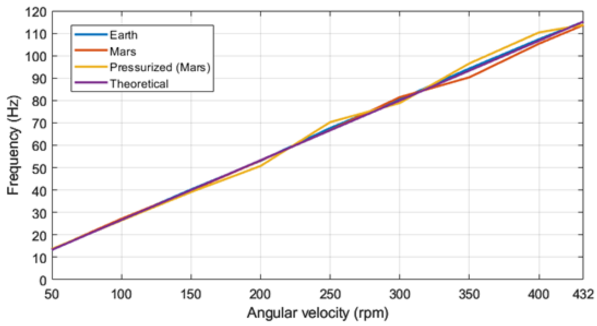

Figure 12. Signal frequency of the TEG generators at Mars, Earth, Mars pressurized conditions, and theoretical value.

5.1.2 Power generation

The impedance matching condition will provide the maximum output power condition of the generator for each rotatory velocity. For TEG the impedance matching conditions are achieved with a RC load [8]. The TEG is a capacitor in which the internal power must be extracted with a capacitor, and then with a resistive load act as usual in power generation systems. The maximum achieved power is 15.144 kW in Mars pressurized condition, 432 rpm, and RC of 10 Ω and 0.094 µF. The maximum achieved power in Earth's atmospheric condition is 4.09 kW at 400 rpm, and RC of 10 Ω and 0.094 µF. The power level increases on average by 31.37 % when the turbine operates in Mars pressurized condition. Figure 13 shows the achieved results:

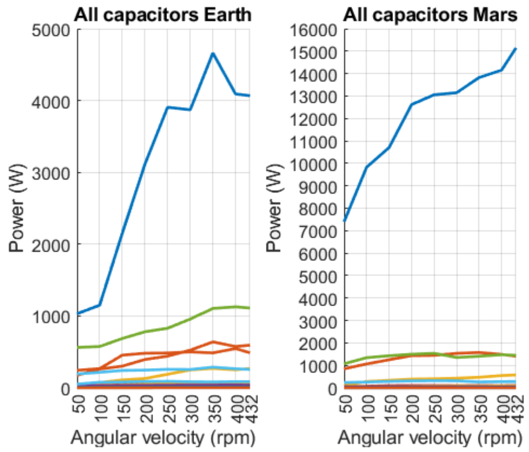

Figure 13. Produced electrostatic energy by the turbine at Earth and Mars pressurized conditions.

Then, the generated power increases with the angular velocity and lower RC load. The charge time of the capacitor decreases with higher angular velocity and lower capacitor value. The discharge time is always the same (with the same RC load), i.e., doesn't vary with the environmental condition (Earth and Mars). In addition, the charge time decreases in Mars pressurized condition with regard to Earth's atmospheric condition. This allows the quicker charge of the capacitor, so, quicker power extraction of the TEG. Figure 14 shows results with different capacitors and the same resistive load for Earth and Mars pressurized conditions.

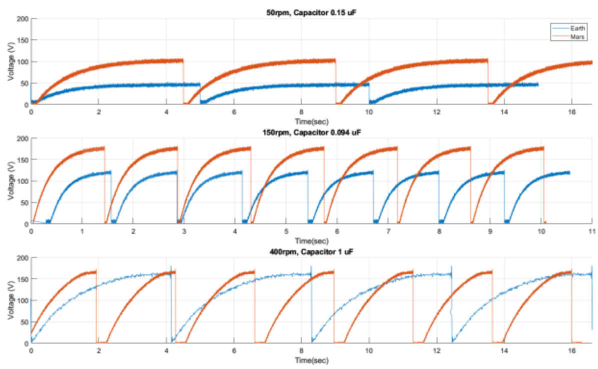

Figure 14. Charge and discharge of different C loads and effect of Earth and Mars pressurized conditions.

5.2 Mars wind tunnel

Mars Simulation Laboratory of Aarhus University has a

Mars wind tunnel which simulated the Mars atmosphere and winds. The facility shown in Figure 15 has a cross section of 1 m x 1 m within which they can generate winds up to 25 m/. In addition, the wind tunnel performs dust exposure testing and has been used to test the wind turbine.

Figure 15. Mars wind tunnel facility at Aarhus University.

5.2.1 Turbine operation under Mars winds

The objective of this test campaign has been to verify and validate the complete turbine behaviour in a wind tunnel analysing the system structural behaviour and rotative movement in a similar Mars environment, as can be seen in Figure 16. In addition, during this test campaign, the self-starting capability of the turbine has been verified, the achieved results have allowed to make a comparison between the mechanical simulation results with real tests measured results (for scalability and performance in Mars) and have been analysed the dust effects on the turbine behaviour and turbine sealing system verification. The tested pressures have been such as 8, 11, 14, 16, and 50 mbar (the last one is not possible on Mars but is useful for the simulations).

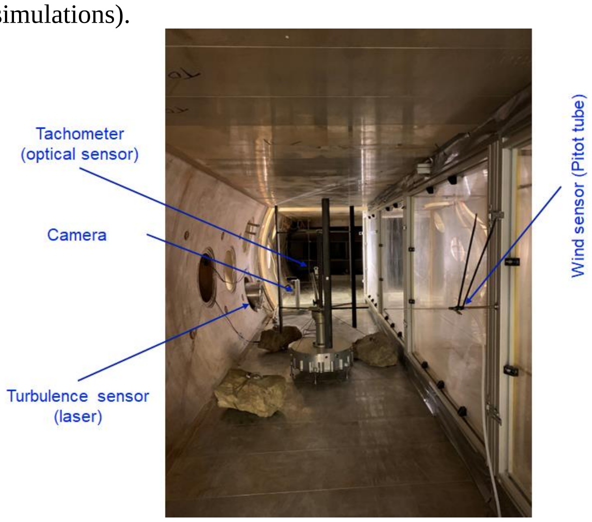

Figure 16. The wind turbine installed in the Mars wind tunnel to carry out the test campaign and attachments to rocks to maintain stability.

The turbine has rotated at different pressures and wind velocities, so, it is possible to use Mars winds to move wind turbines. As has been expected, as higher is the pressure or/and the wind velocity the turbine's angular velocity increases. The attachments of the rocks (simulation of Mars environment) work correctly and maintains the turbine stable. However, with the current dimensions of the blades, the turbine doesn't rotate when the wind velocity is between 5 and 9 m/s. One of the reasons is the behaviour of airflow in the wind tunnel. At low angular velocities, the "opposite" blade to the wind flow acts as a brake due to the compensation of forces. The achieved rotational velocities of the turbine vs pressure and vs wind velocity are shown in Figure 17:

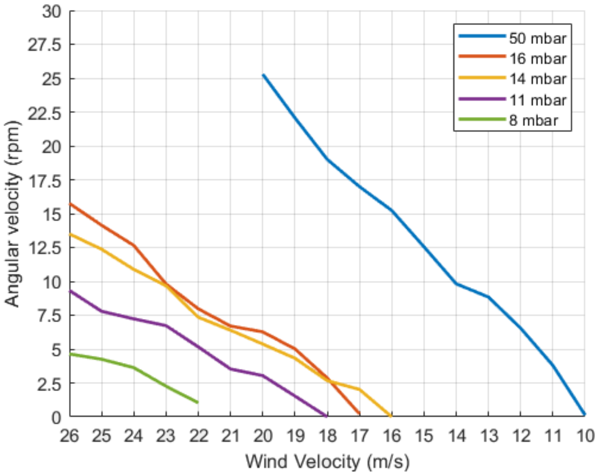

Figure 17. Turbine rotational velocities at different pressures and wind velocities.

A maximum deviation of 28.58 % and a minimum of 3.10 % have been measured as stability at different velocities. Being the average deviation or stability of 16.65 %. As turbulences are 20 %, the turbine movement can be considered stable for all the wind velocities. Also, as has been expected, the starting time changes with the pressure and wind velocity, where Figure 18 shows the achieved results:

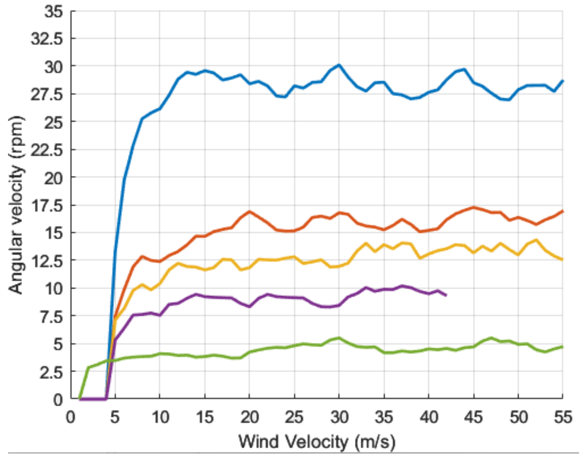

Figure 18. Self-starting curves at different pressures and maximum wind velocities.

5.2.2 Dust exposure

Controlled dust exposure within the facility entails injecting a known mass of Mars analogue dust together with a known (relatively small) volume of gas (typically at 1 bar pressure). This amount of gas is extremely small compared to the volume of the chamber however the resulting jet may temporarily disturb the wind flow. Depending upon the wind speed and the gas density the dust will become deposited after some time (typically a few minutes at low wind speeds) [9].

The Mars dust analogue used in these tests is produced by milling and sieving (<20µm) the commercial MGS-1 Mars regolith analogue. Size determination gives an average grain diameter of 3µm. This fulfils ESA requirements; RV-GDIR-2454 / RV-PLAT-647 / T, A and RV-SAA-2050, RV-GDIR-5411 [10]. Two target dust concentrations have been sued during dust exposure. These were 75mg/m^3 and 90µg/m^3. In addition, during the dust exposure tests a sensor system has been used to monitor the dust concentration. This system measures the laser light power transmitted through the environmental chamber, i.e., across the wind tunnel. Suspended dust within the wind tunnel will obscure (absorb) light depending upon the grain size and concentration (independent of wind speed). Figure 19 shows the light transmission measurements during the dust exposure cycles (11 injections of 1.9g).

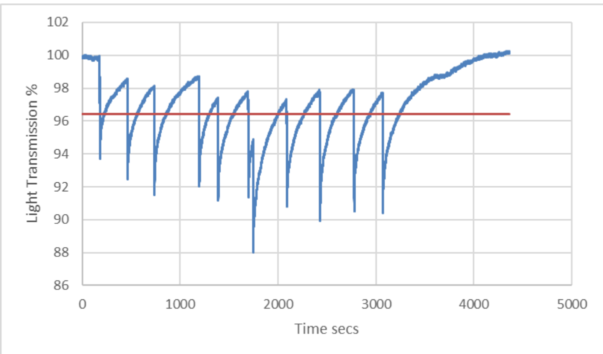

Figure 19. (blue); measured light transmission power in % of original-final value, the red line is the average over the 1 hour (3600 seconds) of dust exposure.

The average measured dust concentration (opacity) during the 1 hour of dust exposure was around 96.4% corresponding approximately to the concentration following the first injection of 1.9g of dust, i.e., a concentration of around 75mg/m^3. The test chamber status at the end of the dust exposure test can be seen in Figure 20.

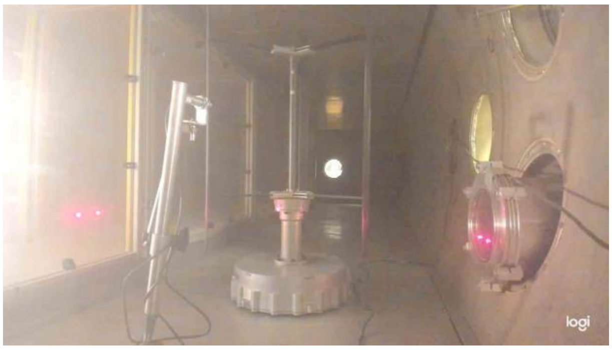

Figure 20. Turbine dust exposure test inside the Mars wind tunnel.

Using the opacity measurements (light transmission) and knowing the average size of a single MGS-1 dust grain, it has been possible to determine the (average) dust concentration during this dust exposure being equivalent to 70 sol.

Finally, after the dust exposure test the turbine has been analysed to detect any structural damage or dust insertion into the vessel. Satisfactory results have been achieved without any damage and without the detection of any dust particles inside the vessel. Figure 21 shows the dust deposition in different parts of the turbine.

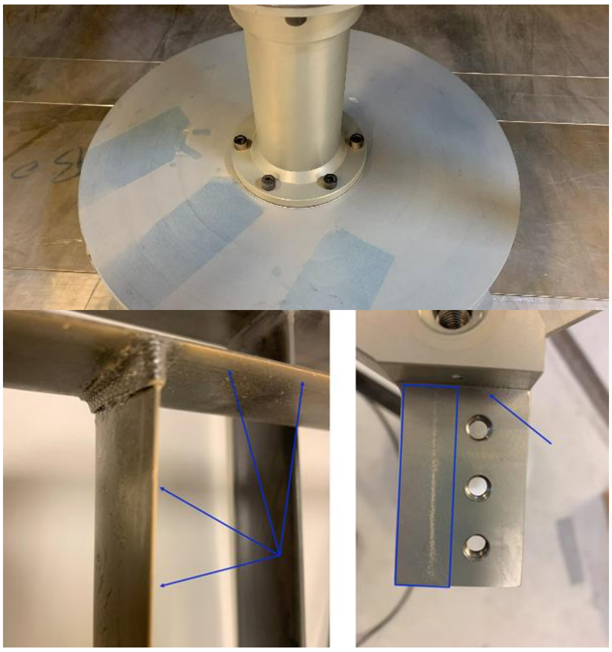

Figure 21. Dust deposition in different mechanical parts of the turbine.

6 CONCLUSIONS

In this work has been verified that wind turbines can rotate on Mars, thus, wind power can be used in future missions as a secondary power system. In addition, the TEG generators will reduce the turbine weight and size facilitating their transport to Mars, and their efficiency are increased under Mars environmental conditions.

However, several improvements will be required for the optimal wind turbine for Mars.

The major challenges have been the reduction of the torque to allow the rotatory movement with the available winds and atmospheric pressure based on the generators preload, pressurization, sealing; the dust effects in the turbine and inside the vessel; the pressurization of the vessel allowing a rotatory movement of the axis; and achieving the compromise between the lifetime and the power generation considering parameters such as wear, abrasion, lubrication, durability, and materials oriented for good triboelectric effect.

7 ACKNWOLEDGEMENTS

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