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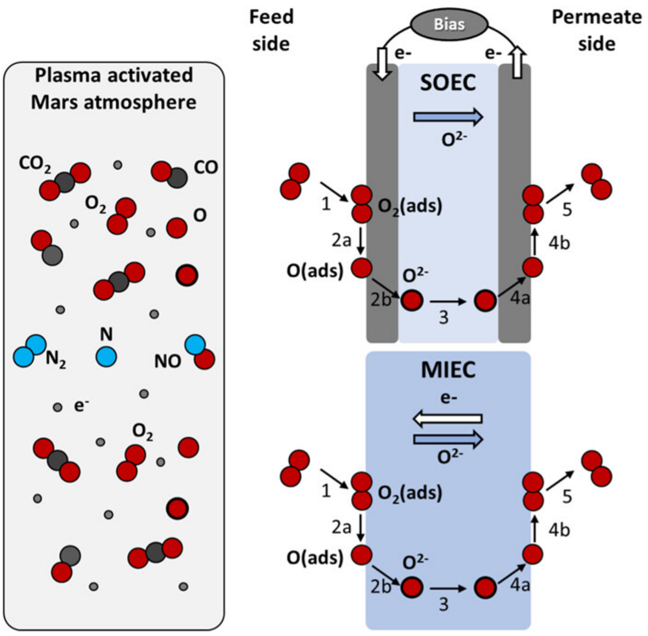

ISRU on Mars: Plasma conversion of CO_2 from the Martian atmosphere

Executive summary

Early technology development

OSIP Open Channel

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Activity summary:
A new approach to produce oxygen from the Martian atmosphere is proposed, linking two emerging technologies: non-thermal plasmas and ion-conducting membranes. Microwave plasma sources lead to high conversion rates and enable plasma ignition with light and compact solid-state generators. The unique pressure and temperature conditions on Mars are favourable for plasma CO_2 decomposition, and the experiments and simulations carried out anticipate a competitive oxygen production per mass and volume of hardware in a future prototype. Measurements of enhanced oxygen pumping through the membranes by plasma demonstrate synergy and establish the proof-of-concept of a new and promising technology for ISRU.

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Project PERFORMER (ISRU on Mars: Plasma conversion of CO_2 from the Martian atmosphere) was conceived with the ambitious goal of utilizing plasmas to decompose CO_2 from the Martian atmosphere into oxygen and carbon monoxide for ISRU applications on Mars. Both CO and O_2 can be used in a propellant mixture, while O_2 can be collected and made available for breathing.

Plasmas have demonstrated remarkable efficacy in facilitating CO_2 decomposition. Their potential is closely tied to the generation of reactive species that enhance dissociation. Additionally, the unique conditions on Mars create an optimal setting for plasma operation, as the low atmospheric pressure (~600 Pa) and typical dimensions involved in the breakdown in a plasma reactor (~0.01 m) match nearly perfectly the minimum breakdown voltage required to sustain the discharge. The most significant obstacle to the progress of plasma ISRU technology revolves around gas separation.

The driving force behind PERFORMER was to explore the anticipated synergy between plasmas and conducting membranes. The performance of such integrated devices should be increased in relation to conventional setups, for two reasons: the prior dissociation of CO_2 in the plasma, and the heat produced by the plasma (as the membrane conductivity becomes significant at temperatures of typically 600 K and higher). The aims of the project were to demonstrate the validity of these ideas, establish a proof-of-concept and study their potential for building products of interest to ISRU.

To address the challenge, the integration of separation membranes (both mixed ionic–electronic conducting (MIEC) membranes and solid-oxide electrolyte cell (SOEC) membranes) in various plasma sources was studied. The project had three work packages: characterisation of plasma sources, modelling, and proof of concept.

The assessment of plasma sources involved a thorough investigation of DC glow and RF discharges, nanosecond pulsed discharges, inductively coupled RF, microwave and brushed electrode discharges. The various sources tested achieved CO_2 dissociation degrees of 25-30%. Since MW do not suffer from electromagnetic noise and enable plasma ignition with compact and light solid-state generators, they are the choice of election for space applications in the context of ISRU.

A volume-averaged self-consistent kinetic model to describe the oxygen production in plasmas sustained under Martian conditions was developed and validated. The modelling results revealed that the unique pressure and temperature conditions on Mars are favourable for plasma CO_2 decomposition and can significantly amplify vibrational nonequilibrium, which impacts electron-impact dissociation occurring from various vibrational levels of CO_2.

The feasibility to trigger oxygen permeation through a MIEC ceramic membrane n direct contact with a glow discharge at pressures from 1 to 5 Torr was proven using mass spectrometry to analyse the gas inside the membrane. In addition, a thorough characterization of oxygen permeation fluxes across a SOEC membrane was carried out. Typical measurements reveal a significant oxygen pumping enhancement by plasma. This oxygen flux enhancement phenomenon is stable and reproducible. A maximum enhancement of the oxygen flux of ~173% was observed. The results also indicate that the oxygen permeation has the potential to drain the oxygen completely from the plasma side.

The coupling of plasmas with separation membranes was achieved and synergy demonstrated, establishing PERFORMER's proof-of-concept. The results with MIEC membranes are at an earlier stage than with SOEC, although recent results yield promising results. Therefore, despite further work that still must be done in the characterisation and study of SOEC and MIEC membranes, at this stage SOEC is recommended for manufacturing a first pilot.

A significant advantage of plasma systems is their versatility. For instance, PERFORMER also explored the production of NO, which is vital for the synthesis of fertilisers and plays a significant role for agriculture-based ISRU. NO can be created in a plasma ignited in a N_2-O_2 mixture with a similar reactor as used for oxygen production, where N_2 must be separated from the atmosphere and O_2 may be obtained from CO_2 decomposition. Moreover, the versatility of plasmas extends beyond ISRU applications on Mars, as the reactive species generated by these systems at relatively low gas temperatures open a wide range of applications relevant to the realm of space exploration.

It is possible to envision the development of a prototype based on microwave (MW) plasma technology, which may serve as a foundation for future research endeavours, and compare it with the performance of the low-power MOXIE experiment. Evidently, it must be acknowledged that: on the one hand, this is a comparison between an estimation (supported by the present results) with the production from a real device already operating in-situ; on the other hand, the two technologies scale differently when aiming at a full scale setup. Anyhow, a low-power (~250 W) MW system with similar requirements as the current version of MOXIE is estimated to be below 6 kg and, assuming that half of the produced oxygen can permeated (which seems realistic considering the results obtained), the production of an oxygen stream of 1.21 g/h per kg of hardware sent to Mars is anticipated. This estimation is very encouraging as it is about 3 times larger than the current MOXIE experiment, and stimulates further research and the development of the technology.