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Regenerative Fuel Cell System Technologies Development

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Abstract
Before 2030 the moon Moon should see a return of humans on its soil. This time the aim will be to stay on our closest satellite and prepare humans for longer missions towards Mars. Thus, the moonMoon will become an exciting playground for testing technologies and assessing permanent human life in space. However, a lot of technological gaps are present and need to be addressed before thinking of a sustainable activity on the moonMoon is a reality. This is especially the case for space transportation (reliable lunar landers and rovers), habitat and human health (to provide efficient shelters for preserving human health) or ISRU (capability to use resources present on the Moon). A common point of all these different fields is the energy storage challenge. Indeed, the Moon's environment is known to be harsh with long periods of darkness and cold (many days to permanently).
During these lunar nights, the sun cannot provide power anymore but most of the equipment must be maintained at ambient temperature (or even "On") requiring electrical (or thermal) power. Thus, energy must be stored during lunar days to be provided during the nights. Most common energy storage systems today rely on mature battery technology. However, when energy for a long Lunar night is to be stored, the presently low energy density of batteries (around 200 Wh/Kg) becomes unattractive: to store enough energy for one rover (3 kW over 14+ days) gives at least 5 tons of batteries). Thus, a higher energy density system must be developed which is the case of RFCS (Regenerative Fuel Cell Systems). The principle is very simple. It consists of splitting the water molecule into H2 and O2 gases when energy from the sun is available and storing them. Then using the H2 and O2 in a Fuel Cell to produce electrical power during the night. An RFCS can reach energy density in a wide range, from 200‑300 up to 1000 Wh/kg (low power, very high energy stored). Therefore, the total mass of the energy storage systems can be drastically reduced. In long term vision, H2O value chain can be developed on the Moon and therefore RFCS can constitute a cornerstone for all the future infrastructures. Based on these highly interesting advantages, ALAT is working with CNES on technologies maturation for RCFS. Three axes are pushed in this study: Realisation of a TRL3 breadboard to be used for representative on ground test scenarios of lunar activities, development of a test bench and test of a novel passive management system, modelling activities on RFCS. This paper will present the results of this study and the upcoming activities on Air Liquide on RFCS.

1. Introduction

In the upcoming years of space exploration, energy storage solutions will be required to provide power on the moon surface during lunar nights. Great challenges need to be overcome in order to equip spacecraft with reliable power systems capable of surviving lunar nights. During these periods, temperature can drop below 100 K, and as no sun is available, both thermal and electrical energy must be provided to equipment and or people in order to ensure mission success.
Li-ion batteries might not be the best option for such applications, as they would require heating in order to survive. This would lead to additional energy to be consumed which, in turn, would lead to additional batteries mass. Additionally, state of the art lithium ion batteries present low energy densities (200 Wh/kg). Lunar bases, landers would require from several hundreds to thousands of kWh respectively. The batteries would therefore weigh up to several tons from a basic preliminary analysis.

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An alternative to this solution is presented in this paper. Named the Regenerative Fuel Cell System (RFCS), this technology allows to achieve higher energy densities ranging from 250 up to 1000 kWh/kg in the literature [1].
RFCS Relies on Fuel cells to supply power to the user while they use electrolyzers to store energy in chemical state. This paper will focus on Proton Exchange Membrane (PEM) technology, which is the subject of the work performed at ALaT. Figure 1 presents a macro level architecture of a RFCS.

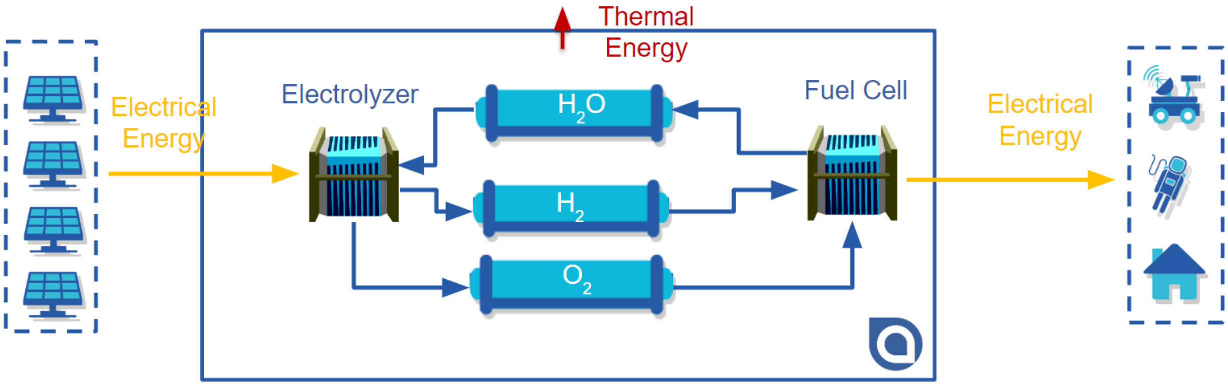

Figure 1: RFCS Architecture

More information is available in references [1] and [2].

2. Development of a TRL3 Breadboard

A TRL3 Breadboard was developed at ALaT and will shortly go under a small test campaign. This will allow the team to acquire experience and knowledge on how to operate in a closed loop environment without having as many restrictions and constraints as for a TRL6 or 7 object. The components found for this demonstrator are solely off the shelf and are hence not adapted for space applications. After completion of this project, the development of future RFCS will be realised more efficiently thanks to the experience acquired during this project. Additionally, after having served its initial purpose, this object could be used for educational purposes in order to present to a wide audience what a RFCS is.
In the respect of simplicity and ease of procurement, a low power breadboard is considered for this breadboard. Table 1 presents the specification used for the demonstrator.

Table 1: General specification of the breadboard

Parameter	Range	Unit
Power output	> 50	W
Peak Power	100	W
Power input (W)	> 150	W
Maximum night duration	75	Hours
Maximum day duration	75	Hours
Energy capacity	3,75	kWh
Voltage output	< 6	V
Energy density target	400	Wh/kg
MTBF	3000	Hours

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Number of start up/shutdown	20	-
Hydrogen quantity to store	236	g
Hydrogen storage pressure	16	bar
Oxygen quantity to store	1,9	kg
Quantity of water produced	2,1	kg

The demonstrator shall be able to provide 50 W of power during 75 hours, with an input of 150 W over 75 hours. A step down to a few minutes cycle will first be considered in order to simplify the test campaign. Additionally, only the H2 loop is operating in a closed manner to simplify the management of the object for the first time. A second project might have an objective to obtain a fully closed loop RFCS.

Therefore, the following test plan will be proposed for this breadboard.

Table 2: TRL3 Breadboard test plan

Test	Description	Control parameters	Output parameters
Commissioning of components	Performance and characterization of critical components	Power Flow Rate Pressure	Power Flow rate Pressure Temperature
Leak test	Characterization of the tightness of all assembled lines	Pressure (16 / 0,35 barg respectively for hydrogen and air lines)	Helium leak rate <1.10-5 mbar.l/s for hydrogen line Helium leak rate <1.10-3 for air line
Closed hydrogen line operation	Operation demonstration of a closed hydrogen line RFCS	Power input	Power output Pressures Temperatures Gas generation Gas consumption

Breadboard is assembled, as shown by Figure 2. Tests will begin once software implementation is performed in summer 2023.

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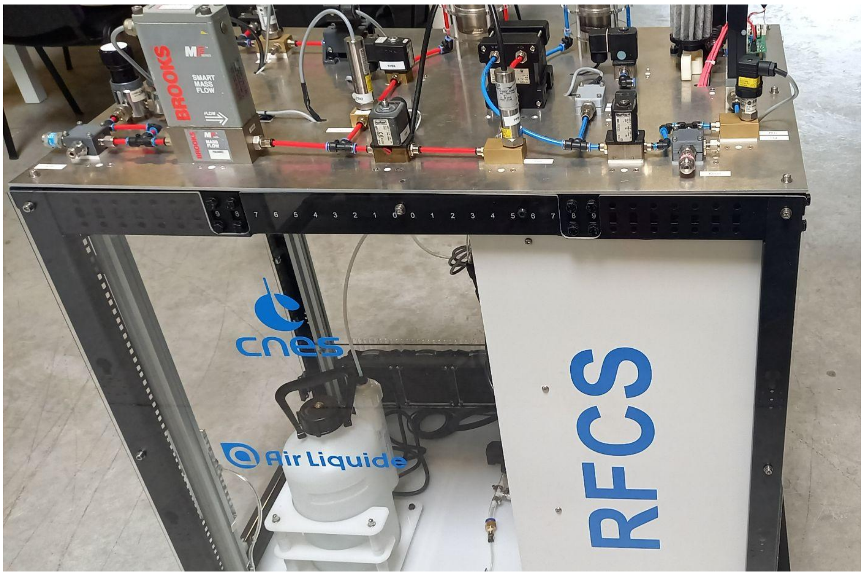

Figure 2. RFCS demonstration breadboard

All the fluidic components are mounted on the top plate including the FC in the centre. The ELY Gas generator, load, power supply and water storage is placed below the metal plate.

3. Passive water management solution

3.1 Passive water management presentation

In [2], a Passive Water Management solution (PWM) was introduced. Work has been carried out on this subject and is summarised in this section. As a reminder, Figure 2 presents the concept of the PWM for FC applications.

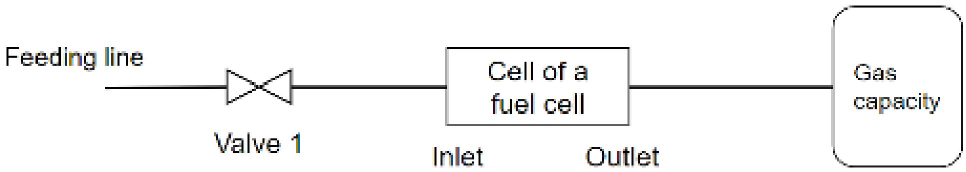

Figure 2: PWM Concept

The goal of this solution is to simplify the water management for fuel cells (i.e. replace the circulation pumps and gas humidifiers by a set of valves). In the case of Figure2, the valve is opened at defined intervals to replenish the cells with reactants. When these reactants are consumed, the gas capacity that contains some water saturated gas (from the previous cycle) will provide the needed reactants in between the valve openings, hence humidifying the active area of the cell. Once the pressure dropped at a low enough level, the cycle starts again by a valve opening. The pressure surge then allows for the cell to be purged from the produced water.
In order to demonstrate that solution in-situ, a dedicated pure oxygen fuel cell test bench has been assembled at ALaT facilities, as shown by Figure 3.

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Figure 3: H2/O2 Fuel cell test bench

Solution was only implemented at the cathode side, since it is the side where the majority of water is produced. If the solution proves to be efficient on that side, it shall also be applicable to the anode side where less water is found.

3.2 Parametric study presentation

Three different O2 Flow field plates were compared in a parametric study presented below. Flow field differences are not presented for confidential matters. Parameters of the parametric study were the followings:

- Flow field characteristics
- Pressure difference at valve opening
- Time with valve open
- Time between valve opening

These parameters were modified up to the limit of what was acceptable for nominal FC Stack operation.

3.3 Parametric study results

The results of the parametric studies are presented in table 3.

Table 3: Partial results of PWM parametric study, top to bottom: baseline flow field plates, modification 1, modification 2.

Parameter		**Valve opening time**		
		0.5	1	1.5
DP Opening (bar)	0.1	OK	OK	OK
	0.3	OK	OK	OK
	0.6	NA	NA	NA

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Parameter		**Valve opening time**			
		1	2	3	4
DP Opening (bar)	0.1	NOK	OK	OK	NOK
	0.2	NOK	OK	OK	OK
	0.5	NA	NA	NA	NA

Parameter		**Valve opening time**			
		1	2	3	4
DP Opening (bar)	0.1	NOK	OK	OK	NOK
	0.2	NOK	OK	OK	OK
	0.5	NA	NA	NA	NA

Modifications of flow fields intended to increase pressure drop across the channels which was thought to help the water to be evacuated. However it was seen that an increased pressure dropped did not help to perform purges.
Prolonged tests were performed using the baseline of the flow field plates. Over 20 hours of operation was performed without failure. It was observed that water accumulation in the gas capacity had to be removed every 15 hours at a minimum. For optimal operation, water removal shall be performed every three hours in the configuration used for tests.

4. Comparison to conventional solutions

4.1 Definition of baseline components for conventional solution

In conventional solutions, circulation pumps are usually the go to choice. In order to propose a relevant comparison for space applications, the following model from KNF of recirculation pump is used:

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Figure 4: KNF NMP 830 DC-BI pump

The following specification is provided by the supplier:

Table 4: specification of KNF NMP 830 DC-BI pump

Parameter	**Range**	**Unit**
Mass	161	g
Power (max)	6	W
Max flow rate	2,5	l/min
Max pressure	1,5	barg
Dimensions	56 x 58 x 33	mm

Alongside this pump, a humidifier and a pump control system shall be used. The humidifier can be assimilated to the phase separator / gas capacity used in the PWM system. Therefore it is possible to only compare the pump & valve as they will be the components responsible for the differences between the two solutions. The same argument can be made for the control system, even if a pump and a valve are controlled in different ways, the control system will most likely not contain the greatest part of the mass and will also be disadvantageous for the baseline solution as the pump is more complex to operate than a single solenoid valve.

4.2 Definition of PWM system components

Figure 5: NovaSwiss solenoid valve

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Table 5: specification of NovaSwiss solenoid valve

Parameter	Range	Unit
Mass	52	g
Power (max)	< 3	W
Max flow rate (at 200 bars)	350	l/min
Max pressure	500	barg
Dimensions	24 x 50	mm

4.3 Comparison

Characteristics of two solutions are compared in Table 6.

	Conventional	PWM
Mass	161 g	52 g
Dimensions	107 cm3	23 cm3
Power	6 W	< 3W
Energy consumption [a]	>2000 Wh	<60 Wh
Control system	Pulse wave modulation	On/Off

[a]For a RFCS cycle of 336 hours and valve openings every 6 s

Already looking at only these characteristics it is possible to see that the PWM system will provide a significant improvement over circulation pumps. The valve is lighter, more compact and requires less power to operate. Reliability shall be less of an issue using valves as less mobile parts are involved and especially these mobile parts are not operated for as long as pump rotors.

It is possible to go further in the energy comparison. The pump is operated continuously while the valve in the PWM system only actuates 1,5 seconds once every 6 seconds. The energy required to operate the valve in a RFCS using a 336 hour cycle is therefore:

$$Power \times time\ of\ operation \times number\ of\ operations = 3\,W \times 1,5\,s \times \frac{336\,hours}{6\,s} = 252\,Wh$$

While the pump would require 2016 Wh of electrical energy to operate.

The calculation made for the valve is also quite pessimistic as the 3 W of power is only required for actuating the valve open which takes 30 ms. Maintaining the valve open only costs 20 mW (value measured at ALaT on the Novaswiss valve). Using this lead to obtain a figure of 52 Wh for a whole RFCS cycle (336 hours for FC operation).

This solution therefore can save well over 3500 Wh of electrical energy given the fact that two circulation pumps would be required to operate both the anode and cathode of a FC.

Total mass would only be decreased by a few hundreds grams using the components presented in Table 3 which corresponds to a very small amount in percentage when compared to the mass of a whole RFCS but is still interesting to obtain.

More importantly, reliability issues shall be reduced greatly thanks to this solution. The pump proposed here is not compatible with gaseous hydrogen or pure oxygen, finding such a component with the required specifications can prove to be extremely difficult. The valve presented can be qualified for H2 and O2 usage.

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4.4 Conclusion on PWM

In this study, a passive solution for water management inside a fuel cell was tested in a pure O2 environment with an operating FC stack designed for air operation. Test campaign showed that it is possible to find a set of operating parameters suitable for real applications.Energy consumption reduction of over 3500 Wh can be expected for a RFCS compared to conventional BoP. Additionally, reliability, mass and volume of the BoP can be improved thanks to this solution.
In this study only the cathode of the stack was equipped with the PWM system. Anode side can also benefit from the implementation of this solution, no potential difficulties are foreseen in order to do so as less water is present in that side of the stack.
Microgravity applications of this system would be a challenging task as it relies on two phase flow separation through gravity. An alternative solution to the gas capacity shall be found if such an application is to be imagined.
Future activities could try to implement this solution in a dedicated O2/H2 PEMFC. Endurance testing of the PWM system implemented on both anode and cathode sides would be an activity that would benefit the RFCS development.

References

[1] Z. Pu et al, 2020, Regenerative fuel cells: Recent progress, challenges, perspectives and their applications for space energy systems, Applied Energy, vol. 283.
[2] L.Littré, C.Dupont, E.Claude, 2022, Regenerative Fuel Cell System for Space Exploration Applications.