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Regenerative Fuel Cell System for Space Exploration Applications

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Abstract

This paper presents a solution for energy storage on the moon to sustain the future space exploration missions. Most common energy storage systems rely on batteries. Even though this technology is highly matured (present in all satellites), it has some limits when the lunar night is too long. This is due to the presently low energy density of batteries (around 200 Wh/Kg). Thus, a higher energy density system must be developed. RFCS (Regenerative Fuel Cell Systems) could be a viable alternative for this application. The operating principle relies on basic electrochemistry concepts. It consists of splitting the water molecule into hydrogen and oxygen through electrolysis when energy from the sun is available and storing them in their gaseous form using tanks. This system can be built having an energy density in a wide range, from 200-300 Wh/kg up to 1000 Wh/kg (low power, very high energy stored), which can reduce the total mass of the energy storage system compared to batteries.

1. Introduction

1.1 Context

In the context of new space programs such as Artemis or the joint program between Russia and China which aims to bring humanity back on the moon, new technologies are required to solve the upcoming challenges that will be faced in these difficult tasks. In these programs, the firsts bricks of the different moon outposts should be laid on the lunar surface before 2030. To operate on the surface of the moon, equipment shall be able to survive the harsh conditions of the lunar environment including lunar day and night cycle. A lunar day lasts 672 hours and the duration of night and day varies depending on the location. To give an order of magnitude, at the equator, day and night time last up to 336 hours (or 14 earth days). The temperature of the environment fluctuates in a wide range starting from -175 °C (during the night) and up to 135 °C (during the day). It is hence required to provide thermal power to various equipment to allow them to operate properly. In this framework, Air Liquide advanced Technologies (ALaT) chose to work on the development of a promising technology for this energy application on the moon: The Regenerative Fuel Cell System (RFCS). This technology relies on development of fuel cell technologies since 2001 and the strong expertise acquired on test benches, fluidic aspects and space sector. This application can be adapted to different applications and power required. Figure 1 presents the order of magnitude of power and masses for different applications.

Missions	Power needed for lunar night survival	Battery mass estimation	RFCS mass estimation
Small rovers	10 – 100W	20 – 150kg	30 – 100kg
Small landers	100 - 500W	150 – 850kg	100 – 450kg
Lunar base	> 20kW	> 35 T	> 14 T

Figure 1. RFCS Target applications

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ALaT has a long history in space technologies development. For more than 50 years, the Group has worked to build strong credibility in this field and has deployed all the resources needed to ensure the reliability of its equipment and the performance of its products and services. Thanks to its expertise in cryogenics, Air Liquide is a partner for many of the world's largest international space projects: the European space program, observation satellites (Herschel, Planck, etc.), the International Space Station (MELFI) and the Rover Curiosity (SAM). As both a player in and a partner of the scientific community, Air Liquide conducts ongoing work to develop its cryogenic equipment and solutions of high technology. In support of the space industry, Air Liquide produces industrial gases, provides related services and manufactures cryotechnical tanks and equipment. On the Kourou launch pad in Guyana, but also at Cape Canaveral in Florida for NASA and at the Tanegashima Space Centre in Japan: at every rocket launch, Air Liquide teams produce and supply launcher propulsion and inerting fluids. Air Liquide is currently in the process of developing the innovations that will be mission critical for future generations of cryogenic propulsion launchers that will respond to the new challenges of the space industry.

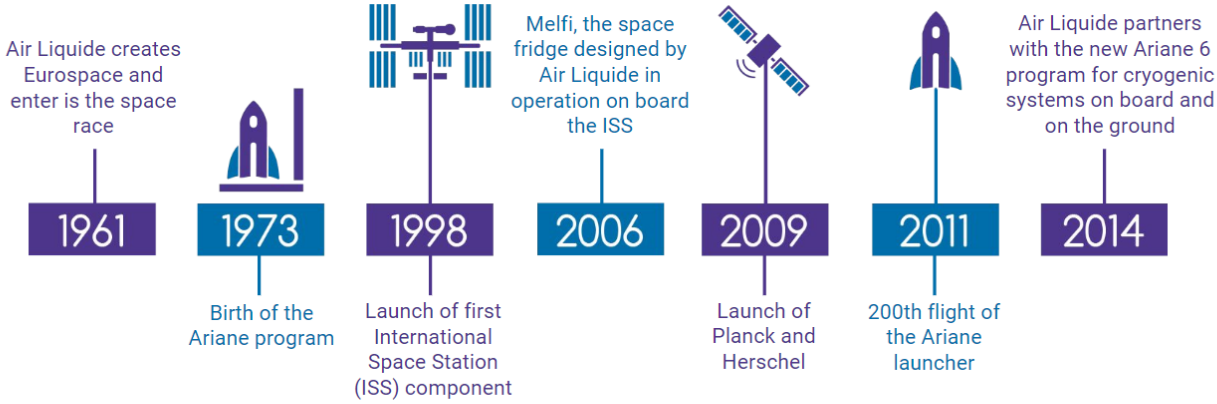

Figure 2. Air Liquide History in the space sector

Today, one of the new pillars is the development of technologies for sustainable space exploration. ALaT is involved in space exploration through different programs and collaboration and is present on a large portion of the value chain as illustrated in Figure 3. The key molecules that are part of the value chain for sustainable space exploration are water, hydrogen and oxygen.

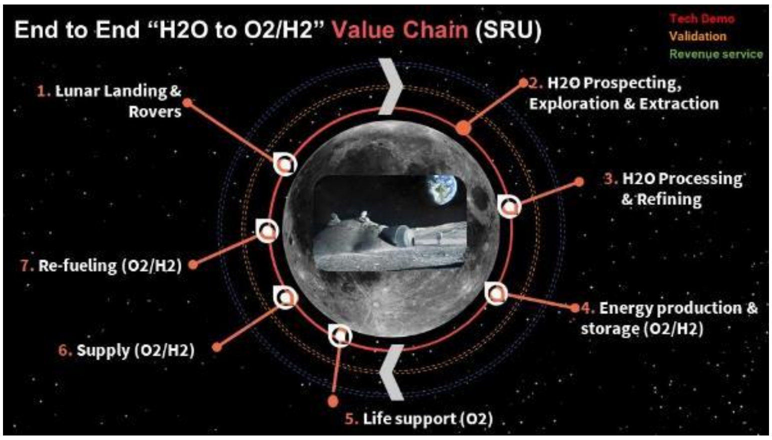

Figure 3. In-Situ Resource Utilisation - generic moon cycle

1.2 RFCS System Description

The principle of a RFCS is to store energy during daylight using an electrolyser and to provide energy when the primary energy source is not available (night). The schematic of a RFCS is presented in Figure 4. In this example, solar panels are the energy source of the RFCS.

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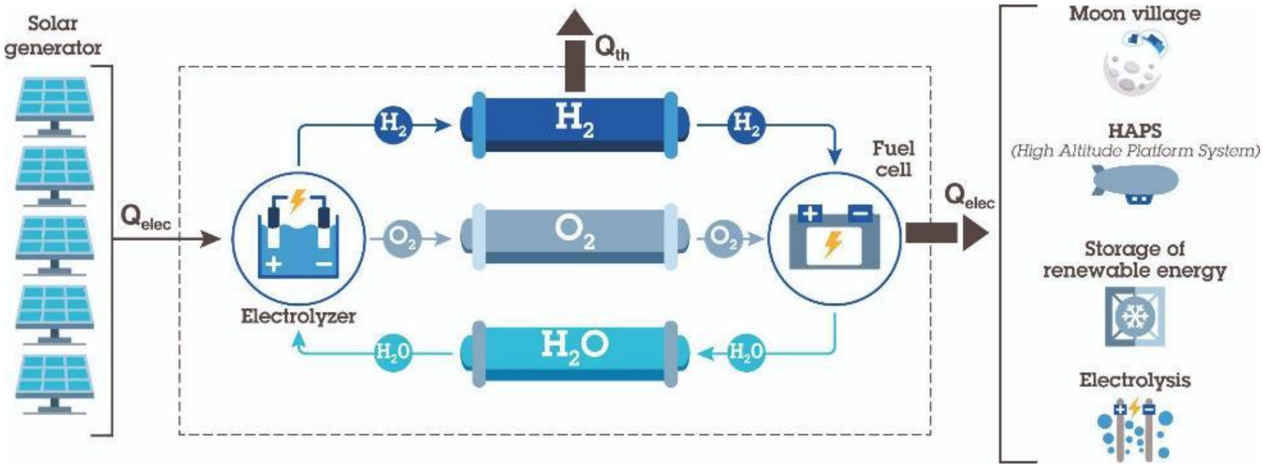

Figure 4: Overall principle of a RFCS.

The cycle starts with the charging phase using electrical energy coming from the solar panels during the lunar day which is delivered to the electrolyzer stack. Thanks to this energy and the water stored in a tank, the stack will generate hydrogen and oxygen gases following the reaction described by equation (1). Once the night time starts, the electrolyzer stops and the discharge cycle starts. Oxygen and Hydrogen gases are fed to the fuel cell stack, which will be able to generate electricity and heat following the reaction described by equation (2). The recombination of the hydrogen and oxygen gases will generate water molecules which will be collected to close the loop. This reaction also provides electrons which will be used to power the electrical loads of the application and waste heat that can be valorized for the application.

$$H_2O + Energy \rightarrow H_2 + \frac{1}{2}O_2 \qquad (1)$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Energy \qquad (2)$$

The reactions taking place in the stacks are not covered in detail here, if the reader wants to find more information about the electrochemical reactions covered here, A. Dicks and D. Rand [1] covers that subject in depth.

As it can be understood from the previous paragraph, the power rating and energy capacity of the system are not related unlike for conventional batteries. These parameters are given respectively by the power rating of the stack and the size of the tanks. Therefore, to modify the power rating of the system, only the fuel cell stack can be modified when only the tank size (and cycle length and / or electrolyser stack power) shall be changed to modify the energy capacity of the system. In the studies carried out at ALaT, the following performances are generally taken as targets for RFCS technology:

- Energy density: >400 Wh/kg (>600 Wh/kg if waste heat is recycled)
- Efficiency: >50% (>70% if waste heat is recycled)
- Lifetime: > 20 000 hours (or 30 lunar cycles)

The main components that constitutes a RFCS are presented below:

- Fuel cell stack
- Electrolyzer stack
- Hydrogen storage tank
- Oxygen storage tank
- Water storage tanks
- Thermal management system
- Equipped Hydrogen loop
- Equipped Oxygen loop
- Equipped water loops
- Electrical management system
- RFCS Computer and software

All these components are intercorrelated that makes this system complex and difficult to develop.

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1.2 Interest in RFCS

The RFCS technology has considerable advantages over batteries as it can provide a substantial amount of thermal power to various equipment to allow them to either operate in proper conditions or store them above freezing point which could lead to irreversible damages for specific systems. Following a state of the art study, it was shown that this technology could outperform current state of the art conventional batteries in terms of energy density (Wh/kg). It is possible to find theoretical values up to 1000 Wh/kg (see [2] and [3]) when compared to the 200-250 Wh/kg of state of the art batteries a potential mass reduction by a factor of 4 could be made for the same amount of energy stored. This first estimation is however quite optimistic and a more reasonable 400 to 500 Wh/kg shall be the first target of the RFCS, which would still provide a mass reduction by a factor 2 when compared to state of the art lithium ion batteries [4]. Preliminary models built at ALaT showed such an increase, as presented in Figure 5. In this figure, the grey area represents the state-of-the-art of battery technologies. This figure shows that RFCS are particularly interesting when the cycle time is long, that is particularly the cas on the moon. A second great interest of this technology is the possibility of providing thermal energy to other systems, as it was investigated in [5]. When batteries have a high electrical efficiency, it is difficult (if not impossible in specific applications) to use the waste heat of batteries as they provide a low thermal power output. With the RFCS, it is possible to both decorelate the power rating and the energy capacity (which is not feasible with batteries) and design the efficiency operating point to choose the repartition of thermal & electrical power output. The potential applications of this technology could hence be future lunar or martian missions where both thermal and electrical power are required. Microgravity applications (in orbit) are still as of today a challenging environment for the RFCS.

The technologies used for the fuel cell and electrolyser stacks relies on Proton Exchange Membrane (PEM) which in turns, rely on precise two phase (liquid and gas) water management inside the stacks. Microgravity is therefore a difficult application, ALaT is however working on new solutions that could allow for easier microgravity RFCS management, as it will be detailed later on in this paper. High Altitude Platform Systems (HAPS) are also part of the potential applications as onboard mass is an important parameter to reduce and no great amount of oxygen is available at HAPS operating altitude (above 30km).

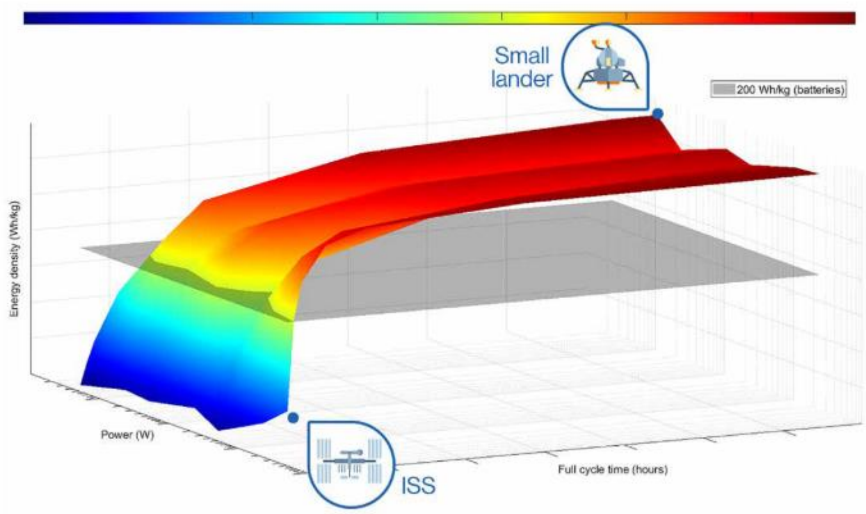

Figure 5. RFCS Energy density compared to battery.

2 Achievements and first results

2.2 RFCS Model development

A first model was developed in order to realise preliminary RFCS Designs. This model was designed based on mass and energy balance equations. An overview of the calculation sheet of the model is presented in Figure 6,

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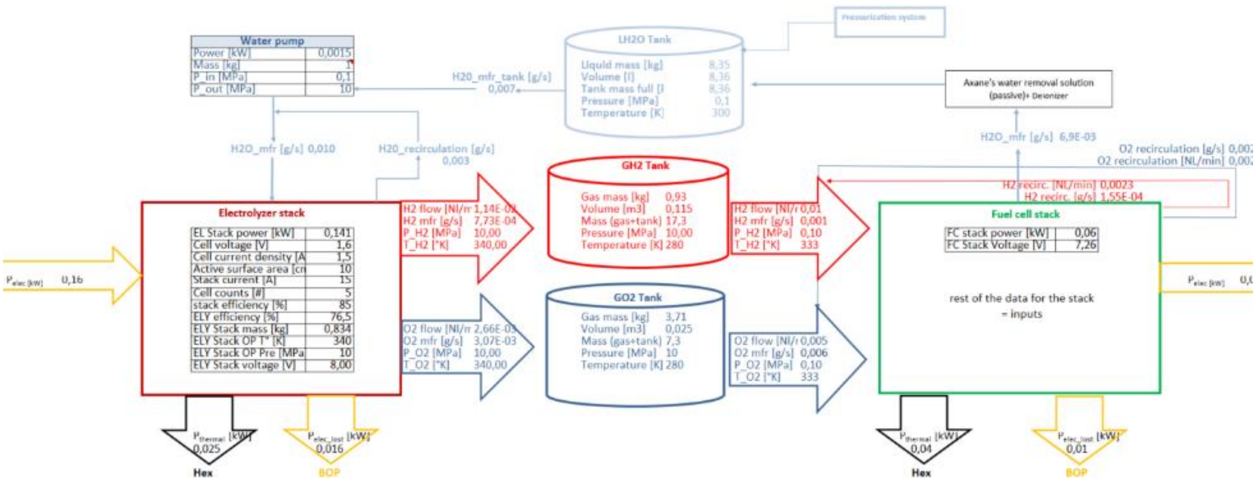

Figure 6. Overview of the balance calculation sheet of the RFCS preliminary model.

Thanks to this model, an estimation of the mass budget and performances of the RFCS can be computed. Few inputs are however required to get these results such as the cycle length and the power output. In this document, a generic application of 200 W electrical power at the lunar equator (336 hours day / 336 hours night cycle) is presented to show the capabilities of the model.

The performances presented in Figure 7 are the results of the mass and energy balance computation. Few assumptions such as tank materials and cell technologies are made to obtain rough order of magnitude for mass and volume figures.

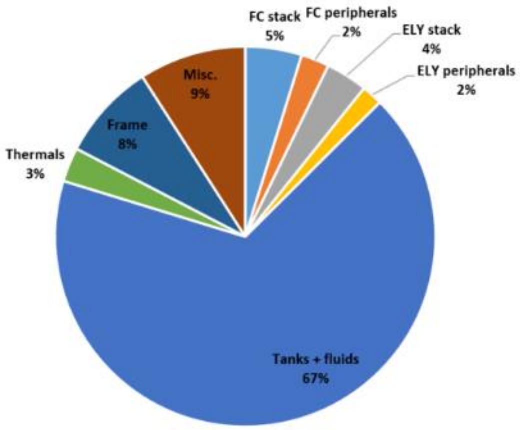

Figure 7. Mass repartition of a 200 We RFCS

This calculation shows the importance of the storage for this application compared to the rest of the system.

In this generic case study, a thermal energy need of 50% of the total generated thermal energy is considered as useful for the user. The total mass of the system estimated by the model is 188,9 kg. Using the thermal energy recovery assumption it is possible to compute the total stored energy as shown in equation (3).

$$E_{stored} = (P_{elec} + P_{thermal}) * night\ time = (0{,}2 + 0{,}077) * 336 = 93{,}1\ kWh \qquad (3)$$

Where:

- E_{stored} is the useful energy stored in the RFCS in kWh
- P_{elec} is the useful electrical power in kW
- $P_{thermal}$ is the useful thermal power in kW
- $night\ time$ is the night time in hours

Using the last two figures given in that paragraph, a total energy density of 492,5 Wh/kg is obtained, an improvement of a factor close to two over state of the art lithium ion batteries which have a density energy of 250 Wh/kg.

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This model is used to perform trade-offs between the various possible technological choices for the RFCS. These trade-offs are presented in the following paragraphs.

2.3 Conventional RFCS vs URFCS

It is interesting to note that reversible stacks exist and could simplify the RFCS technology. These stacks are often referred to as Unitized Regenerative Fuel Cell (URFC) not to be confused with RFCS (Regenerative fuel cell system, see Figure 4). URFC implemented into RFCS are referred to as Unitized Regenerative Fuel Cell System (URFCS); the architecture of such a system is presented in Figure 8.

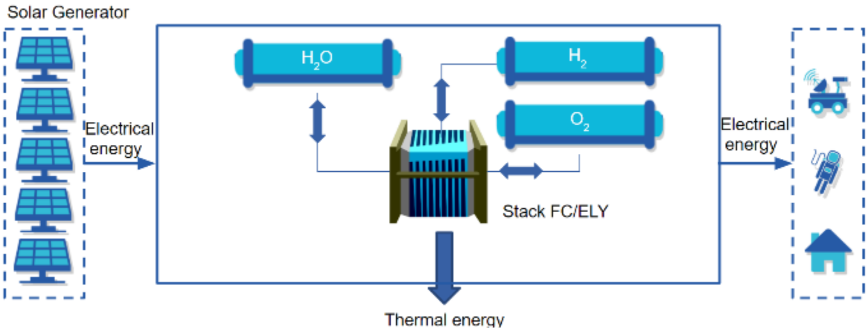

Figure 8. URFCS Technology architecture.

This concept has the advantage of greatly simplifying the Balance of Plant of the system (i.e. the components needed around the stack to allow proper operation of said elements such as valves, humidifiers, pumps, filters…) which could in turn lead to both mass savings and increased reliability. However, this comes at the cost of reduced efficiency and life time. These two drawbacks are, as of now, not worth the potential gain. As it was investigated in a study performed for CNES, state of the art URFC can reach efficiencies of 50 % in laboratory conditions at cell level with a lifespan of a few hundreds hours. This would lead to efficiency figures of around 20 % at system level and lifespan for the URFCS far from the desired target. In a conventional RFCS or Discrete regenerative fuel cell (DRFC), the system encompasses one stack optimised for operating in Fuel Cell mode, and one in electrolysis mode. The other components are used for the balance-of-plant (BoP) and control. A unitized regenerative fuel cell (URFC) system encompasses only one stack which can operate in both electrolysis and fuel cell modes. The two main advantages of the URFC are (i) the use of one single stack which greatly reduces weight (expected gain -20/30% vs. a conventional RFCS) and footprint for an improved energy density vs. battery and (ii) a lower material cost. However, too many technical challenges are currently remaining such as the design of bi-functionnal electrodes and the water management, which make URFC at a lower TRL, less power efficient and with a lower cyclability than conventional RFCS. Table 1 summarises the differences of the two architectures.

Table 1: URFCS and DRFCS comparison, data for URFCS.

	URFCS	**DRFCS**
Mass	80%	100%
Efficiency	<20%	>40%
Reliability	Tens of cycles	>1500 cycles
Number of stacks	1	2
TRL[a]	2	4
BoP	Less complex	Nominal

[a]Technology Readiness Level

In a discrete RFCS, the fuel cell and electrolyzer stacks are both dimensioned for operating at the highest possible efficiencies i.e. close to 70% (defined as electrical power output/ electrical power input). If the heat generated from the

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fuel cell is reused, this efficiency can be further improved. The targeted round trip efficiency of the RFCS, at the system level (including stacks and all BoP components' consumptions) is 50%.

2.4 Stack technologies trade-off

Several fuel cell and electrolyser technologies exist today and are briefly described in Figure 9. More detailed information can be found in Table 2 and 3 about different cell technologies.

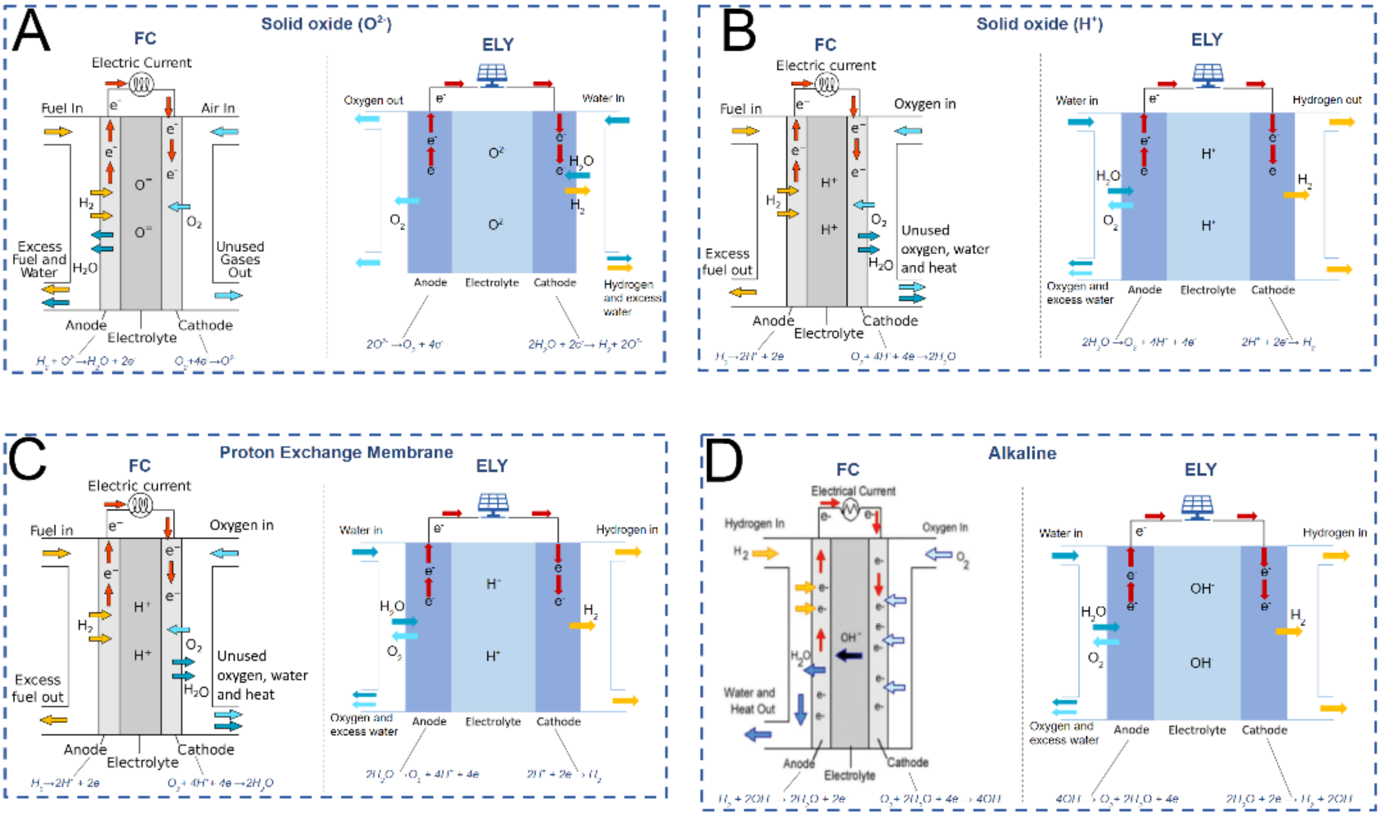

Figure 9. Schematic diagram of various technologies operated in FC and ELY modes: Solid Oxide with O2-(A) and H+ (B), Proton Exchange membrane (C) and Alkaline (D)

Other fuel cell and electrolyser technologies exist but might involve carbonated species which render the closed loop operation extremely difficult. Each technologies presented in Figure 9 have their own specific set of operating parameters and performances which are summarised in Table 2 and 3, including additional technologies to provide an overview of cell technology to the reader.

Table 2: Types of fuel cell: their operating parameters and expected performances, extracted from [2].

Fuel cell type	**Solid Oxide**	**Molten carbonate**	**Phosphoric acid**	**Direct Methanol**	**Alkaline**	**PEM**[a]	**HTPEM**
Anode chemical reaction	$2H_2+2O^{2-} \rightarrow 2H_2O + 4e^-$	$CO_3^{2-}+H_2 \rightarrow 2H_2O + CO_2 + 2e^-$	$2H_2 \rightarrow 4H^+ + 4e^-$	$CH_3OH+H_2O \rightarrow 6H^+ + 6e^- + CO_2$	$H_2 + 2OH^- \rightarrow 1H_2O + 2e^-$	$H_2 \rightarrow 2H^+ + 2e^-$	
Cathode chemical reaction	$O_2 + 4e^- \rightarrow 2O^{2-}$	$CO_2 + 1/2O_2 + 2e^- \rightarrow CO_3^{2-}$	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	$3/2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	$H_2 + 1/2O_2 \rightarrow H_2O$	
Power range (kW)	1-2000	100-5000	5-500	0,1-100	0,1-10000	0,01-1000	1-50
Power density (kW/kg)	140	100	10	40	100	700	TBD

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Operating temperature (°C)	>600	>600	200	60	60-90	60-80	100-200
Operating pressure (bar)	1-10	1-10	<1	<1	1	1	1
Cell voltage range (V)	0.7-1.15	0.8-0.9	0.6-0.8	0.4-0.7	0.7-1	0.6-0.95	0.3-0.8
Current density range (mA/cm²)	<1000	<200	<800	<200	100-200	<2000	<1000
Lifespan (hours)	50000	5000	40000	20000	5000	20000	TBD
Efficiency (%)	60	55	45	30	60	50	35
TRL (-)	5	5	5	5	6	5	3

[a]PEM: Proton Exchange Membrane

Table 3: Types of electrolyser: their operating parameters and expected performances, extracted from [2].

Electrolyzer type	**Solid Oxide**	**Alkaline**	**PEM**	**HTPEM**
Power range (kW)	10-1000	1-100	0,01-1000	TBD
Power density (kW/kg)	TBC	50	60	TBD
Operating temperature (°C)	>600	60-90	60-80	100-200
Operating pressure (bar)	1-15	1-50	1-100	1-10
Cell voltage range (V)	1-1,5	1,8-2,4	1,8-2,2	1,8-2,3
Current density range (mA/cm²)	<1000	<400	<2000	<2000
Lifespan (hours)	10 000	10 000	20 000	TBD
Efficiency (%)	95	75	80	60
Power consumption (Wh/gH_2)	40	60	75	75

PEM technology has benefited from interest in the automotive industry. In the last decades, great improvements on this technology have been realised. Thanks to this development, PEM technology is today the most performant solution for mobility applications and is hence chosen as the baseline solution in most RFCS projects seen in the literature such as [6] or [7].

2.4 Storage pressure

Pressure storage has a great impact on both RFCS system size and mass. As shown in Figure 7, the storage needs to be optimised as it is the major contributor of the mass of the system. Figure 10 shows the influence of pressure on storage mass and size for a 2kW power rating and a 10/14h day/night cycle as a reference which implies 1,84 kg of gaseous H2 and 7,31 kg of gaseous O2 to store.

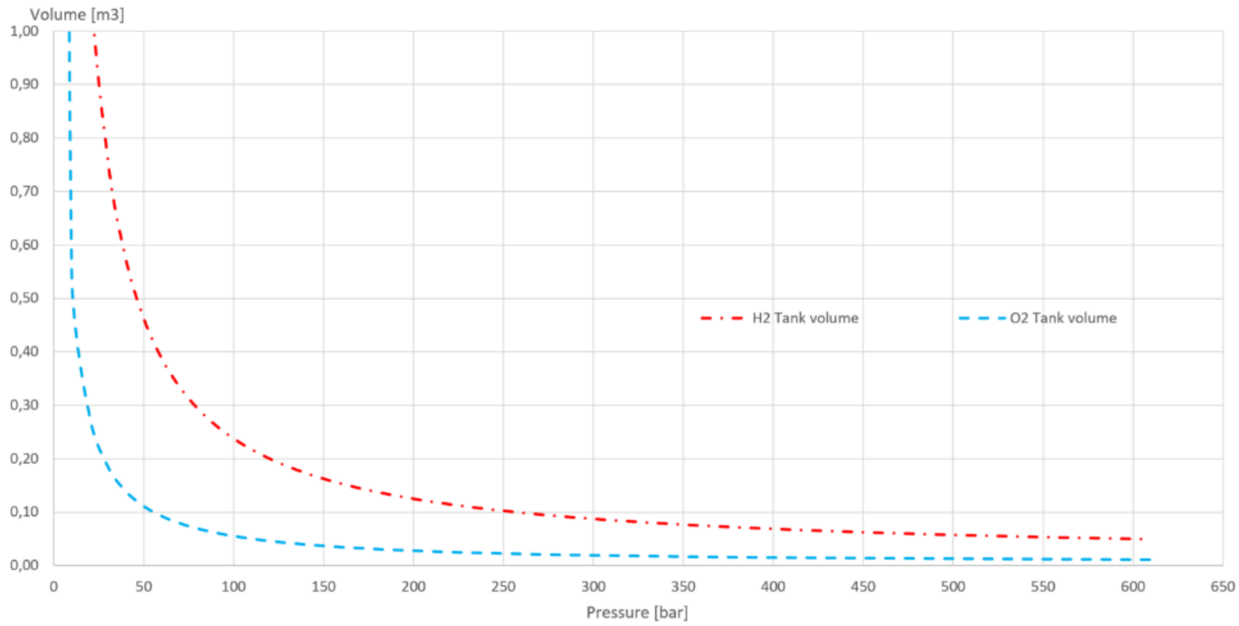

Figure 10. Evolution of storage mass and volume against storage pressure

In this case, looking for a pressure level above 100 bar for hydrogen storage is not interesting as more power and complexity would be added to the system than what is gained on volume storage. Indeed, increasing the pressure at 300 bar would mean higher power consumption for compressors, added complexity based on precedent parts and a higher system mass (i.e lower system performance), to gain around 50 litres for hydrogen and 5 litres for oxygen. It is hence easy to see that it is preferable to stay below 100 bar if the application allows it. For oxygen, this optimum point is closer to 40 bar.

2.1 Passive water management system

The management of water is one the most difficult parts to manage for a fuel cell and especially for space applications with low gravity or microgravity. A concept studied and tested is a passive water recirculation proof of concept. This system is presented in Figure 11. 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). The valves are 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.
To check the feasibility of this system, a transparent cell was assembled and tested to simulate a typical fuel cell operation.

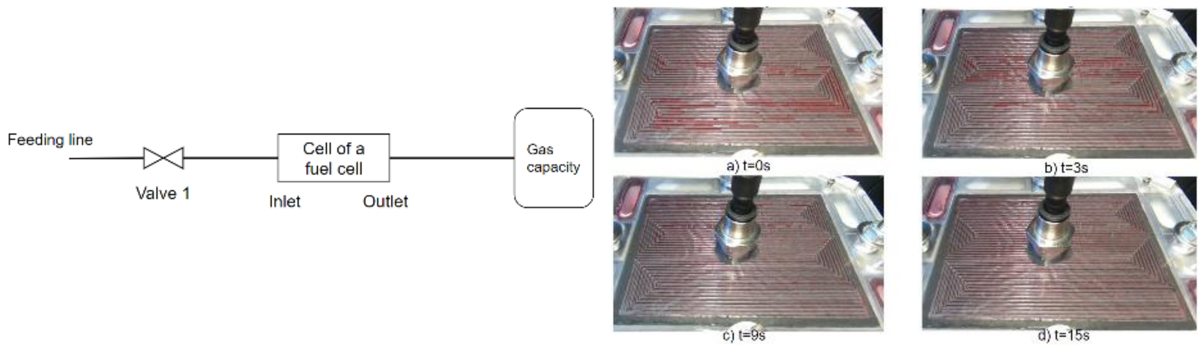

Figure 11. Concept of a passive water management solution for fuel cells (left) and proof of concept demonstration with a simulated operating fuel cell (right).

It is possible to see flow field channels from an air plate filled with colored (red) water in Figure 11 right. The top left picture a) shows a flow field plate filled with water in moderate quantities, which aims to simulate nominal fuel cell

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operation. In figure 11 d), the passive water management system has been operated for 15 s and shows that no water is left in the flow field of the cell. This first demonstration is promising for the undergoing in-situ study of this system. If positive results were obtained, this passive water management system could be implemented in the RFCS architecture and reduce the number of balance of plant components (hence increase the RFCS reliability) and help reduce the electrical consumption of the internal components.
The first iteration of this study demonstrated promising results and new tests are planned.

3. Conclusion & Future activities

Recent developments on RFCS technology at ALaT was addressed in this paper. It was found that RFCS potential energy density could outperform batteries by a factor of over 2 while also providing an interesting level of thermal power. A potential passive water management system was presented and is currently investigated at ALaT facilities. This system could greatly simplify the overall fuel cell balance of plant and potentially helps RFCS technology operate in microgravity environments. A brief introduction to RFCS potential technologies was presented and PEM stacks were shown as the most promising solution for the target applications. In the future of RFCS development at ALaT, a first breadboard will be developed at ALaT facilities. This prototype will allow demonstration of the technology. The power rating at the output of this RFCS is designed to be above 50 We and up to 100 We. In order to test the passive water management system in operation on a fuel cell stack, a hydrogen/oxygen test bench is being developed. This test bench will allow for operation of fuel cell stacks adapted for space applications in the range of 100 to 1000 Watts.

Acknowledgment

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