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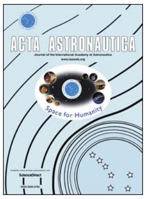

Combined energy production and waste management in manned spacecraft utilizing on-demand hydrogen production and fuel cells ☆

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ABSTRACT

Energy supply and waste management are among the most significant challenges in human spacecraft. Great efforts are invested in managing solid waste, recycling grey water and urine, cleaning the atmosphere, removing CO_2, generating and saving energy, and making further use of components and products. This paper describes and investigates a concept for managing waste water and urine to simultaneously produce electric and heat energies as well as fresh water. It utilizes an original technique for aluminum activation to react spontaneously with water at room temperature to produce hydrogen on-site and on-demand. This reaction has further been proven to be effective also when using waste water and urine. Applying the hydrogen produced in a fuel cell, one obtains electric energy as well as fresh (drinking) water. The method was compared to the traditional energy production technology of the Space Shuttle, which is based on storing the fuel cell reactants, hydrogen and oxygen, in cryogenic tanks. It is shown that the alternative concept presented here may provide improved safety, compactness (reduction of more than one half of the volume of the hydrogen storage system), and management of waste liquids for energy generation and drinking water production. Nevertheless, it adds mass compared to the cryogenic hydrogen technology. It is concluded that the proposed method may be used as an emergency and backup power system as well as an additional hydrogen source for extended missions in human spacecraft.

1. Introduction

Since the beginning of human space missions, hydrogen–oxygen fuel cells have been used for electric energy production onboard spacecraft because of their high specific energy storage capabilities compared to batteries. In the Gemini space program (1962–1965) the acidic ion exchange membrane IEM fuel cell was used, providing an average power of 620 W and a maximum power of 1 kW. The Apollo mission to the moon (1968–1972) used alkaline fuel cells to supply electric energy. Three modules supplied a maximum power of 1.5 kW. Alkaline fuel cells remained the main energy source in the Space Shuttle. One may note that the specific power of the fuel cells has shown major improvement (about 4 fold) of specific power from Apollo to the Space Shuttle, from about 14–23 W/kg to 63–100 W/kg, respectively [1]. Three fuel cell modules were installed in the Space Shuttle, each capable of supplying 7 kW continuous power (and 12 kW peak power for a short time) [2].

Spacecraft aiming for long term human stay such as the International Space Station ISS, Mars missions, and space exploration systems, use Regenerative Fuel Cells, RFC, as a means of energy storage. RFC's utilize solar energy for water electrolysis, splitting water to hydrogen and oxygen, and generating electric power via fuel cells when no (or low) electric power is provided by the solar panels (mainly during eclipse) [3–5]. The water produced by the fuel cells is used again as a source of hydrogen and oxygen. However, manned spacecraft for short term missions of a few days, such as the Space Shuttle, are not equipped with solar panels; hence, they have to store the power reactants (hydrogen and oxygen) internally, on-board. This paper deals with this type of human spacecraft.

In the short term missions conducted so far, the power reactants have been stored in liquid state in cryogenic tanks. This work focuses on the hydrogen storage and supply. Hydrogen can be stored as liquid at a low temperature of about 20 K. In this state its density is about 71 kg/m^3. It should be mentioned that hydrogen refrigeration process requires about one third of its chemical energy. The low temperatures involved in liquid hydrogen storage

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makes it challenging both technically and economically. In addition, heat losses from the cryogenic tanks leads to boil-off losses that can be as high as 3% per day [6], limiting the time of storage [7].

This paper presents and discusses a concept for hydrogen production on-board a manned spacecraft for short term missions, utilizing waste water and human urine available on-board. It further investigates the management of combined energy generation and storage and fresh water production in human spacecraft. It was found, that the presented method can be used for reserve, on-demand extra hydrogen production for the fuel cells when an extended spacecraft operating time is required as well as a backup for the cryogenic hydrogen tanks and supply system.

2. Traditional power management systems in short flights – the Space Shuttle as an example

The present work discusses and investigates electric energy production based on fuel cells in manned spacecraft, where the hydrogen and oxygen are stored on-board, and are not generated by electrolysers during flight. The most recent system designed for this kind of applications, and also the most known and published, is the one used in the Space Shuttle. Therefore, the Space Shuttle will be used as a reference for analysis and comparison of the new concept presented.

The Space Shuttle electric power is generated and managed by 3 alkaline hydrogen–oxygen fuel cells, each can provide an electric power of 7 kW continuously and a peak power of 12 kW for as long as 15 min. The Shuttle's mean power consumption is 14 kW, leaving 7 kW for the payloads [2]. Each fuel cell weighs 116 kg (255 lb) and its volume is 138 l (8400 in^3). The power reactants, hydrogen and oxygen, are stored in pairs of cryogenic, insulated, double-walled spherical tanks with vacuum between the walls. The number of pairs depends on the mission duration and the number of crew members. Maximum five pairs of hydrogen and oxygen tanks can be installed. The tanks include heaters to control the pressure. Besides the use for the fuel cells, oxygen is also supplied for the crew cabin. Data on the tanks are given in Ref. [8]. The hydrogen vessel inner wall diameter is 105.4 cm and the outer wall diameter 115.6 cm. Inner vessel volume is 610 l ($\pm$1%) and overall vessel volume is 800 l ($\pm$1%). Each tank contains 41.8 kg hydrogen and its empty (dry) mass is 98 kg, implying hydrogen mass fraction of 29.9% and an overall hydrogen density of 52 kg/m^3. The hydrogen is introduced at a temperature of 22 K, but is kept at supercritical conditions using a heater that controls the pressure at about 13.6–15.2 atm (the critical pressure of hydrogen is 12.8 atm, and the critical temperature is 33.2 K). The dimensions of the oxygen tank are 84.9 cm and 93.5 cm of the internal and external wall diameters, respectively, implying internal volume of 320 l and overall volume of 428 l. The oxygen mass within a vessel is 354.6 kg and the empty tank (dry) weighs 91.3 kg, implying oxygen mass fraction of 79.5%. The overall oxygen density is 830 kg/m^3. Similarly to the hydrogen, the oxygen in the tank is introduced at a cryogenic temperature of 97 K, but is kept at supercritical conditions at a pressure range of 55–58 atm. The critical point is: 154.6 K and 49.8 atm.

3. Fuel cell operating calculations

The chemical reaction in the fuel cells is:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{electric energy} + \text{heat energy} \tag{1}$$

Let's assume that the fuel cells operate at 50% efficiency (relative to the high heating value). It means that the fuel cell provides 71 MJ/kg H_2 (19.8 kWh/kg H_2) electric energy and 71 MJ/kg H_2 heat energy (if the chemical product is liquid water) or about 60 MJ/kg H_2 (if water vapor is produced). For the operation of a 7 kW fuel cell, approximately 0.35 kg H_2/h and 2.8 kg O_2/h should be supplied, producing besides electricity and heat 3.15 kg H_2O/h. For all three fuel cells operating together, producing 21 kW of electric power and 9.45 kg water per hour, 1.05 kg H_2/h and 8.4 kg O_2/h should be supplied. The average electric power generation of 14 kW requires an average supply of 0.7 kg H_2/h and 5.6 kg O_2/h, producing 6.3 kg water per hour.

4. Water management

Life support systems in human spacecraft include food and water supply, atmosphere and oxygen management, carbon dioxide removal, solid and liquid waste management, electric energy generation, heat and temperature conditioning, and more. Great efforts are invested in recycling different components and saving mass and volume.

Water is needed on board a spacecraft for the crew members and cooling system. The water can be generated by the fuel cells during the mission. In the Shuttle for example, the water is stored in four tanks pressurized with N_2, where only one of them is sterilized and contains filtered drinking water. Each tank stores about 75 kg (165 lb) water. When necessary, excess water is dumped from the Shuttle. Up to 95 kg water (210 lb) can be dumped, usually every 12 h [9].

Typical ranges of metabolic human values in spacecraft are presented in Table 1. See details in Refs. [9–11]. According to NASA publications [9], 76 kg (168 lb) drinking water must remain on-board the Shuttle at all times, supplying seven crew members for 96 h (assuming 6 lb/person-day).

The waste water accumulated during the mission is stored in one tank, physically identical to the other water tanks, also

Table 1
Typical metabolic values per person-day in spacecraft.

Parameter	Input/Output range [kg/person-day]	Representative value [kg/person-day]	Remarks
Oxygen Consumption	0.64–1.0	0.84	
CO_2 Production	0.73–1.23	1.0	
Drinking (Potable) Water	2.27–3.63	3.5	
Hygiene Water	1.36–9.0	3.5	
Food	0.5–0.66	0.62	
Urine Production	1.27–2.27	2.2	
Overall Metabolic Liquid Production	3–4	3.5	Including additional humidity in the cabin atmosphere
Metabolic Energy / Heat Load	7400–12,000 kJ/person-day	11,800 kJ/ person-day	Approx. 7400 kJ/person-day of sensible heat and 4400 kJ/person-day of latent heat