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Urine and aluminum as a source for hydrogen and clean energy

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ABSTRACT

This work suggests the use of a waste material, human urine, as a source of hydrogen via in-situ reaction with aluminum. It represents a compact and safe method of hydrogen production on-demand. A parametric investigation of hydrogen production is presented based on the reaction between urine and aluminum powder activated by an in-house patented process. Reaction rate and yield have been measured experimentally under different conditions. Depending on the operating conditions, hydrogen production rates in the range of 150–700 ml/min/g Al and a yield of about 90%, comparable to the results of the aluminum–water reaction, have been demonstrated. Furthermore, applying the hydrogen produced in a fuel cell reveals specific electric energy of up to 2200 Wh/kg Al, an order of magnitude higher than in batteries. This technology may provide means for energy production and storage where fresh water supply is limited and there is no access to the grid.

Introduction

Energy generation and storage is one of today's major challenges. The increasing demand for clean energy, in particular for mobile and stand-alone applications, has led to an extensive search for new technologies that will enable higher energy content per unit mass and volume while reducing pollution. One of the main solutions is the use of fuel cells which efficiently convert chemical energy into electric energy using hydrogen and oxygen. While oxygen is typically extracted from the air, hydrogen has to be supplied, and is usually stored in a gas or liquid state. Hydrogen storage is a challenging task; hydrogen gas has extremely low density (0.089 kg/m^3), so its compression to high pressure (200–700 bar) is essential for storage of sufficient amounts. Storage in liquid form (density 71 kg/m^3) at very low temperatures (20 K) is even more challenging, requiring investment of about one third of its energy. In addition, hydrogen poses safety issues, affecting the complexity and cost of its storage, transport, and fueling. Despite the mentioned disadvantages, hydrogen presents unique advantages: it has extremely high specific energy (energy per unit mass), tripled than that of fossil fuels, and its reaction does not cause pollution. Therefore much attention is paid towards alternative storage methods [1,2].

This research suggests the production of hydrogen on-demand, at the point of use, utilizing human urine and aluminum powder. It will convert a waste material to clean energy, and also overcome the hazardous storage of elemental hydrogen. It should be mentioned that the production of hydrogen from urine in a microbial electrolysis cell (MEC) [3]

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as well as the use of urine directly in Microbial Fuel Cells (MFC) [4–6], which are characterized by a low power density, have been explored. Nevertheless, there are no current techniques using urine for hydrogen production independently from a fuel/electrolysis cell. The hydrogen produced by the presented technology can be used in fuel cells as well as in other applications.

The work described here follows a previous study by the authors investigating the reaction between aluminum and water to produce hydrogen [7,8]:

$$Al + 3H_2O \rightarrow Al(OH)_3 + 3/2H_2 \quad (1)$$

Reaction (1) represents a compact storage of hydrogen, 11 wt% compared to the aluminum mass, much higher than the common alternatives [1,2]. To overcome the barrier of the thin aluminum oxide layer which typically covers aluminum surfaces and prevents interaction with the surrounding water, an original, patented thermo-chemical aluminum activation process [9] has been utilized. It uses a small fraction (typically 1–2.5 wt%) of lithium hydride (LiH), which causes diffusion of lithium atoms through the aluminum oxide layer into the aluminum lattice, making this layer non-protective and enabling a spontaneous reaction between the aluminum and water at room temperature. It was demonstrated that high reaction rates (200–600 ml/min/g Al) and high yields (about 90%) could be obtained with tap water, sea water, and purified water at different reaction conditions [7,8]. Further work demonstrated the combination of this method for in-situ hydrogen production and fuel cells for electric energy generation, revealing its high specific electric energy storage capabilities (i.e., electric energy per unit mass), up to an order of magnitude more than batteries [10].

We reveal that also waste water and urine can react very efficiently with the activated aluminum. Urine is composed of 97% water, which plays the active role in the reaction with aluminum.

The objective of this study is to present a parametric investigation of the reaction between urine and aluminum for hydrogen production and to demonstrate its electric energy generation and storage potential when combining with fuel cells.

Utilization of available urine, and gray water in general, as a source of hydrogen and electric energy can further promote the implementation of hydrogen fuel in additional specific applications: particular scenarios may be personal power kits in the field (substantially lighter than batteries), auxiliary power units (e.g., for cabin power in passenger aircraft, using available waste water), and energy supply in areas with scarce availability of fresh water and limited access to the grid.

Experimental

A parametric experimental study has been conducted in order to determine the influence of different parameters and conditions on the activated aluminum–urine reaction rate and efficiency. Effects of urine/aluminum mass ratio, initial urine temperature, and activator fraction have been investigated. A comparison between water–aluminum reaction and urine–aluminum reaction has also been conducted. The activator LiH and aluminum powder activation method were the same as applied for the study of the reaction between activated aluminum and water [7–9].

Batch type experiments were conducted in a glass reactor at atmospheric pressure. The aluminum powder was put in the reactor first, then urine was added and a spontaneous and exothermic reaction started. Hydrogen production rate and yield were measured by water displacement, as described in Ref. [8]. The temperature of the reaction and the temperature of the hydrogen produced were measured by a digital thermometer.

The tests applied aluminum powder of 9 μm mean particle size. The aluminum powder tested in most experiments was activated by 2.5 wt% of activator. Some experiments included different fractions of activator (1.25 wt%) as will be specified. In order to compare results of experiments conducted with different amounts of aluminum powder, the results are presented per unit mass (1 g) of aluminum.

The amount of hydrogen produced in the experiments was compared to the theoretical amount of the stoichiometric aluminum–water (urine) reaction (Eq. (1)), (approximately 1.24 L of hydrogen per 1 g of aluminum at standard conditions, 1 atm, 273 K). For the calculation of the actual yield, the hydrogen temperature and pressure at the experiment were accounted for. The typical composition of human urine is described in NASA Contractor Report [11], and the main components are summarized in Table 1. Since the amount of hydrogen containing materials (besides water) in urine is much lower than the water amount, they are not considered as an additional source of hydrogen. The uncertainty of the results was about 3% based on errors in measuring weight, temperature, and time. Error bars are presented in the figures.

Results

Urine–aluminum mass ratio

The influence of the mass ratio between urine and aluminum powder on the hydrogen production rate and volume was tested with 2 g of activated aluminum powder and different amounts of human urine (4, 6, 8, 10 ml). The stoichiometric mass ratio between urine (water) and aluminum is 2. However, excess urine may be required due to evaporation and some absorption by the aluminum hydroxide reaction product. Hence, larger ratios have been tested as well (up to 2.5

Table 1 – Main components of human urine (Data adapted from Ref. [11]).

Item	Formula	Amount [mg/liter]
Sodium chloride	$NaCl$	8001
Potassium chloride	KCl	1641
Potassium sulfate	K_2SO_4	2632
Urea	H_2NCONH_2	13,400
Creatinine	$C_4H_7N_3O$	1504
Ammonium hippurate	$NH_4C_6H_5CO\cdot NHCH_2\cdot CO_2$	1250

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