Journal of Power Sources 332 (2016) 111–117

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Improved low-cost, non-hazardous, all-iron cell for the developing world

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HIGHLIGHTS

- Low-cost non-hazardous all-iron cell is improved using commercial materials.
- Maximum discharge power of 40 mW cm^{-2} was observed.
- Ferric iron utilization of 88% is achieved.
- Demonstrated prototype LED lighting product that consumes inexpensive iron materials.

ARTICLE INFO

Article history:
Received 23 August 2016
Received in revised form
14 September 2016
Accepted 17 September 2016
Available online 28 September 2016

Keywords:
Redox flow
All-iron
Developing world
Portable power

ABSTRACT

A low-cost, non-hazardous personal-power system based on an aqueous all-iron electrochemical cell is demonstrated. The system is intended to be assembled and operated by developing-world households that lack sufficient access to electricity, thereby enabling LED lighting or mobile phone charging on demand. Lab-scale hardware is used to assess the performance of individual cell components. It is found that coffee filter paper is an effective low-cost separator. Carbon felt is a low-cost electrode material, and its performance and wetting by the electrolyte solution is greatly improved by pre-treatment with sulfuric acid. The carbon felt does not degrade after a week of daily use. By using these components, performance of the system is significantly improved over the previous baseline, with power density more than doubling to 40 mW cm^{-2}, and iron utilization improving from 78% to 88%. The operating cost is estimated to be less than US$0.03 per mobile phone charge. Based on the lab-scale results, a stand-alone prototype consumer product is designed, fabricated, and tested. It successfully provides 2.5 h of LED illumination while consuming 200 mL of electrolyte solution via gravity feed. We anticipate these results will enable deployment of this innovative system to energy-impoverished individuals in the developing world.

1. Introduction

Insufficient access to modern electrical power is prevalent throughout the developing world [1]. 500 million households rely on kerosene-lamp lighting, which provides low-quality light; it is unsafe due to indoor air pollution, kerosene ingestion, and fire hazard [2], and is expensive with typical household fuel costs around $4 per month [3]. Cellphone ownership is common throughout the developing world, although access to electricity to charge the phones is scarce. In sub-Saharan Africa, roughly 80% of adults own cellphones [4], yet electrification rates are only 59% of urban and 17% of rural households [5]. Charging mobile phones at pay-per-charge kiosk businesses costs about $0.25 per charge.

To address this need, we previously introduced a concept for a low-cost, non-hazardous iron-based battery in which the active materials are assembled by the end-user, and can be spilled on the ground after use without impacting environmental or human health [6]. The vision is a compact, low-cost power source that allows end-users to produce small amounts of power suitable for LED lighting and phone charging in their home, on demand. The user will initially purchase a durable product containing a cell housing, electrical circuitry, LED lamp and USB receptacle (for

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http://dx.doi.org/10.1016/j.jpowsour.2016.09.098
0378-7753/

phone charging). Fig. 1 shows the configuration of the active electrochemical components, including a porous carbon (+) electrode, paper separator, and iron-foil (−) electrode. For ongoing lighting and phone charging sessions, the user will purchase small prepackaged quantities of consumable cell materials (carbon electrode, paper separator) and active materials (iron and supporting electrolyte salt powder, and iron or steel foil). The user dissolves active iron salt ($Fe_2(SO_4)_3$) and supporting electrolyte (NaCl) in locally-available water, and this solution is fed into the (+) electrode by gravity. The product will provide the user with clear instructions on how much water to mix with the dry chemical (for example fill lines on the product inlet tank or separate mixing cup). During discharge of the cell to produce power, the Fe^{3+} is reduced and the iron foil is oxidized, according to

$$\text{Cathode}: \quad 2Fe^{3+}(aq) + 2e^- \rightleftharpoons 2Fe^{2+}(aq) \quad E^0 = 0.77\ V\ vs.\ SHE \tag{1}$$

$$\text{Anode}: \quad Fe^0(s) \rightleftharpoons Fe^{2+}(aq) + 2e^- \quad E^0 = -0.44V\ vs.\ SHE \tag{2}$$

$$\text{Overall}: \quad 2Fe^{3+}(aq) + Fe^0(s) \rightleftharpoons 3Fe^{2+}(aq) \quad E^0 = 1.21V \tag{3}$$

In the initial proof-of-concept work, the electrolyte solution species ($Fe_2(SO_4)_3$ and NaCl) were selected for low cost, high performance, solubility, and non-toxicity [6]. Porous carbon paper (Sigracet 10AA) showed the highest performance of several carbon papers tested, and was found to be a significant contributor to total system cost. Office paper was demonstrated to be an acceptable and very low-cost separator, and provides open circuit voltage (OCV) of about 1.0 V. Low carbon steel was selected as the (−) electrode iron source, as high-purity iron is not required. In the present work, we dramatically increase the cell performance in lab testing hardware by selecting improved paper separator and carbon porous electrode materials. One design goal is to minimize the size of the device by maximizing cell power. This helps to minimize up-front purchase price which for users in extreme poverty is a more difficult barrier than ongoing consumables cost. Our previous work indicates that power (and energy) are maximized for discharge at 0.55 V [6], so that is adopted as the standard test condition here. The cell materials selected in lab-hardware tests are then demonstrated in a proof-of-concept stand-alone consumer product prototype fabricated in plastic for low cost and designed for ease of use by the end-user.

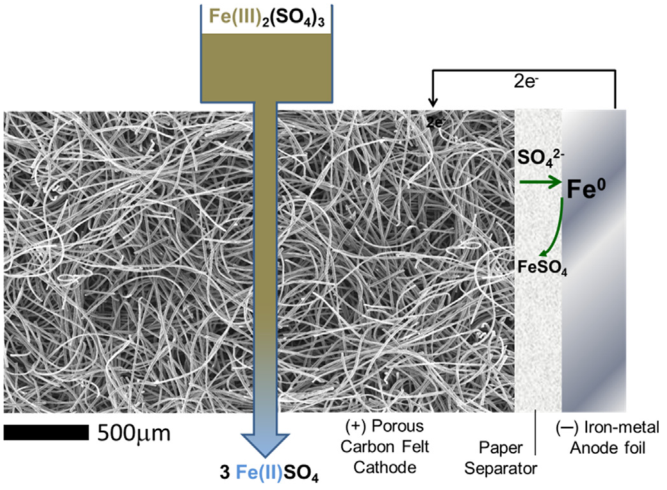

Fig. 1. Schematic of the all-iron flow cell. The horizontal axis in the image is to scale. The iron sulfate solution is introduced by gravity feed from an inlet reservoir, and flows through the entire thickness of the porous carbon cathode.

2. Experimental methods

Electrolyte solutions (0.25 M iron sulfate and 1.2 M sodium chloride) were prepared by mixing de-ionized water with $Fe_2(SO_4)_3$ (Sigma Aldrich analytical grade) and NaCl (BDH analytical grade). Low-carbon steel (−) electrode sheets were provided by McMaster-Carr. Sheets were cleaned with acetone and polished lightly with sand paper before cell assembly to eliminate surface oxidation or machine oil contamination. Carbon porous electrode papers were provided by SGL (Sigracet 10AA) or CeraMaterials (all others listed in Table 1). Pre-treated carbon felt electrodes were soaked in concentrated sulfuric acid (Sigma Aldrich) for 1.5–20 h at room temperature. Treated felts were washed thoroughly with deionized water before cell assembly. Various paper separators were tested including office paper (printer and copier paper, Boise Cascade), laboratory filter paper (GE Whatman), and coffee filter paper (Melitta, If You Care, and generic).

Cells were assembled in standard fuel-cell-testing hardware (Fuel Cell Technologies) with 10 cm^2 active area. Flow-through Niobium flowfields were used on the positive side to avoid carbon oxidation or metal corrosion (Treadstone Technologies, Inc.). The carbon porous electrode and iron electrode were inserted in window-frame shape Teflon gaskets, the thickness of which was selected to compress the carbon porous electrode to the intended thickness, which varied between 35 and 85% of the original thickness. The iron thickness (0.15 mm) was selected to be significantly thicker than necessary, so that consumption of iron metal did not limit cell capacity. Electrolyte solution was provided by a syringe pump at 1 mL min-1 or by gravity feed (as indicated in the figure captions) and was not recirculated from the cell exit. The pump flowrate was chosen to mimic the flowrate typically observed with gravity feed.

Cells were tested at room temperature with a VMP-3 (BioLogic) potentiostat. Constant-voltage discharge at 0.55 V immediately followed cell assembly and solution introduction. Cell OCV was in the range 0.98–1.05 V in the several seconds before discharge commenced. Fe^{3+} utilization was determined from coulometry during cell operation. Efficiency was determined as the ratio of applied external current capacity (mAh) to total electrochemical activity (including applied current, self-discharge, corrosion, and any other side reactions that consume iron metal) assessed by weight loss of the iron foil.

Carbon felt re-usability was determined by testing and disassembling a cell, recovering the carbon felt, letting it dry 24 h in ambient conditions, and re-using it in another cell assembled with fresh paper, iron foil, and electrolyte solution. This was repeated for 7 total uses of the carbon felt.

A stand-alone prototype was designed with CAD software (SolidWorks), and fabricated using a 3D printer (Series 1 Pro, Type A Machines). A viton o-ring was used as a seal between the two halves of the screw-cap cell housing. The two cells were attached in series and connected to a printed circuit board (PCB) containing a white light-emitting diode (LED, Seoul Semiconductor STW8T16C) and LED-driver (Zetex ZXLD383).

3. Results and discussion

3.1. Carbon porous (+) electrode

Previous work with Sigracet 10AA carbon paper electrode demonstrated porous carbon to be an effective electrode for this system [6]. Here, a range of lower-cost highly porous carbon felts provided by CeraMaterials are examined. The felts are produced