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Micro fuel cell utilizing fuel cell water recovery and pneumatic valve

S. Eickhoff [a,b,*], C. Zhang [b], T. Cui [a]

[a] Department of Mechanical Engineering, University of Minnesota, 111 Church Street SE, Minneapolis, MN 55455, USA
[b] Honeywell International, Automation and Control Solutions Research Laboratory, Plymouth, MN 55441, USA

HIGHLIGHTS

- MFC utilizes vapor hydrolysis, water recovery, and a pneumatic valve.
- Integrated MFCs were developed and tested, and achieved 987 Wh L^{-1}.
- Energy density greater than 2000 Wh L^{-1} should be possible in optimized MFCs.

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ABSTRACT

Micro fuel cells (MFCs) defined by an average power output of less than 10 W offer the potential to improve the runtime and performance of portable devices by providing significantly higher energy density (energy per unit volume) than batteries. However, despite several decades of intense research and development, MFCs have yet to realize this potential, and no MFC technology has achieved broad market adoption. We report in this article an MFC which utilizes water-vapor-driven hydride hydrolysis, fuel cell water recovery, and a self-regulating pneumatic valve to achieve higher energy density than conventional batteries. Integrated MFC prototypes were developed and tested, and achieved 987 Wh L^{-1}. Further improvements in energy density are possible by optimizing the fuel pellet configuration (density, geometry, particle size and distribution, etc.). Energy density greater than 2000 Wh L^{-1} may be possible in optimized MFCs discharged at low power.

1. Introduction

The design of portable electronic devices reflects a compromise among a range of competing interests including size, performance, and battery lifetime. While the performance of portable devices as defined by disk space, CPU speed, and available RAM continues to advance at an exponential rate approximating Moore's Law, battery performance as defined by energy density (energy per unit volume) is increasing linearly (Fig. 1), creating an ever-widening gap between the potential and actual performance of portable devices [1]. Micro fuel cells (MFCs) (defined here as fuel cells producing $<$10 W average power) offer the potential to bridge this gap by providing a 5–10× increase in energy density vs. batteries. However, despite several decades of intense research and development, MFCs have yet to realize this potential, and no MFC technology has achieved broad market adoption.

Although many MFC approaches have been attempted as described elsewhere [2], among the most promising are those that store hydrogen in chemical hydrides, release the hydrogen via water vapor hydrolysis, and convert the hydrogen to electrical energy in a hydrogen–air proton exchange membrane (PEM) fuel cell. This approach is considered favorable because chemical hydrides have inherently high energy density, water vapor–hydrolysis reactions are relatively easy to regulate and have high yield, and PEM fuel cells are simple to construct, amenable to scaling, and capable of high chemical-to-electrical conversion efficiency.

The advantages of using water vapor (instead of liquid water) to carry out the hydrolysis reaction are well documented. Kong et al. carried out hydrolysis reactions with several commercially available hydrides (CaH_2, LiH, $LiAlH_4$, $NaAlH_4$) using both liquid water and water vapor, and found that the hydrolysis reactions were more controllable and generally had higher reaction yield when carried out with water vapor [3].

* Corresponding author. Department of Mechanical Engineering, University of Minnesota, 111 Church Street SE, Minneapolis, MN 55455, USA. Tel.: +1 763 954 2380; fax: +1 763 954 2504.
E-mail addresses: steven.eickhoff@honeywell.com, steveneickhoff@yahoo.com (S. Eickhoff).

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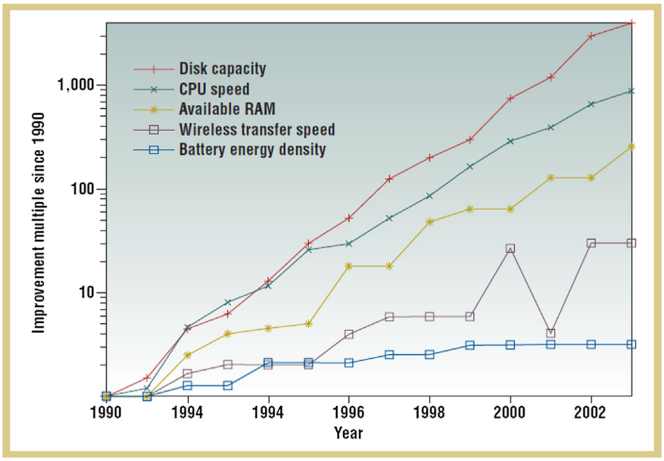

Fig. 1. Improvements in portable electronic device components from 1990 to 2003 [1].

Several MFCs using hydride hydrolysis with water vapor have been reported in the literature. Wood et al. reported an Electrical Power Generator using a water vapor generator comprised of a liquid water reservoir and vapor-permeable liquid-impermeable membrane, coupled to a hydride bed to generate hydrogen, and a miniature PEM fuel cell [4]. This Electrical Power Generator utilizes a micro controller, sensors, and an electrically controlled valve to regulate the power output of the system by controlling water vapor transport from the water vapor generator to a hydride bed. No experimental data or performance projections were provided, however the complexity of the balance of plant (sensors, valve, micro controller) would likely limit energy density. Rezachek et al. report an MFC with a passive pneumatic valve to regulate water vapor transport from a liquid water source to a hydride fuel, based on the pressure difference across a diaphragm [5]. This approach is an improvement over Wood et al. in that it eliminates much of the BOP, which should improve system energy density. Moghaddam et al. report a similar passive regulation scheme, however it differs from Rezachek et al. in that they utilized a membrane that deflects based on the pressure difference across a diaphragm, which blocks a water port and stops hydrogen generation [6,7]. Each of the MFCs described above have an on-board liquid water reservoir which generates the water vapor used in the hydrolysis reaction, and these reservoirs typically occupy >50% of the total volume of the MFC. If a means could be found to eliminate the water reservoir, the energy density of these MFCs could more than double.

This author first demonstrated an MFC without a water reservoir, replacing it with water vapor recovered from the fuel cell [8]. Water vapor generated at the fuel cell cathode permeates the PEM from cathode to anode, driven by a water vapor concentration gradient in the PEM, with is created by closely positioning the hygroscopic hydride to the fuel cell anode. MFCs utilizing water vapor recovery were built, and very high energy densities (>2000 Wh L^{-1}) were demonstrated [9]. Water vapor recovery using this method was subsequently reported by Zhu et al., although their reported energy density was much lower (313 Wh L^{-1}) due in part to the large fraction of the device volume that was occupied by packaging [10].

The power output of MFCs using water recovery is highly sensitive to ambient humidity as described by Zhu et al., due to the inherent requirement that the humidity at the fuel cell's cathode remains in equilibrium with the ambient environment. This humidity sensitivity, coupled with the unregulated nature of early MFCs using water vapor recovery, makes them unsuitable for portable devices in their current form. A means of regulating these water-recycling MFCs is required to make them practical for portable devices.

This paper describes an MFC utilizing water recovery and a pneumatic valve to regulate the hydrogen generation rate. It includes a detailed discussion of the MFC design, fabrication process, and testing methodology, as well as performance data for the MFC components and integrated device.

2. Experimental

The MFC (Fig. 2) is 14 mm in diameter and 50 mm in height, and has a total volume of 7.7 cc. The MFC has a nominal operating potential of 1.5 V, however because it uses two hydrogen–air PEM fuel cells in a series electrical configuration, the open circuit potential is ~1.9 V. The two circumferentially perforated bands in the metal case provide air access to the fuel cells. The cylindrical portion of the metal case acts as the MFC's cathode electrode, while the circular metal plate at the bottom acts as the anode.

2.1. Operating principle

The MFC shown schematically in Fig. 3 is comprised of a hydrogen–air PEM fuel cell coupled to a self regulating hydrogen generator. Hydrogen produced by the hydrogen generator and oxygen from ambient air react at the fuel cell, generating electrical energy, water vapor, and waste heat (not shown) by the following reactions:

$$\text{Fuel cell anode reaction}: \quad 4H_2 \rightarrow 8H^+ + 8e^-$$

$$\text{Fuel cell cathode reaction}: \quad 2O_2 + 8H^+ + 8e^- \rightarrow 4H_2O$$

$$\text{Overall reaction}: \quad 4H_2 + 2O_2 \rightarrow 4H_2O + \text{Energy} \tag{1}$$

Water vapor generated at the fuel cell cathode back-diffuses through the PEM and reacts with the chemical hydride to generate hydrogen by the following reaction:

$$LiAlH_4 + 4H_2O \rightarrow 4H_2 + \text{Solids} \tag{2}$$

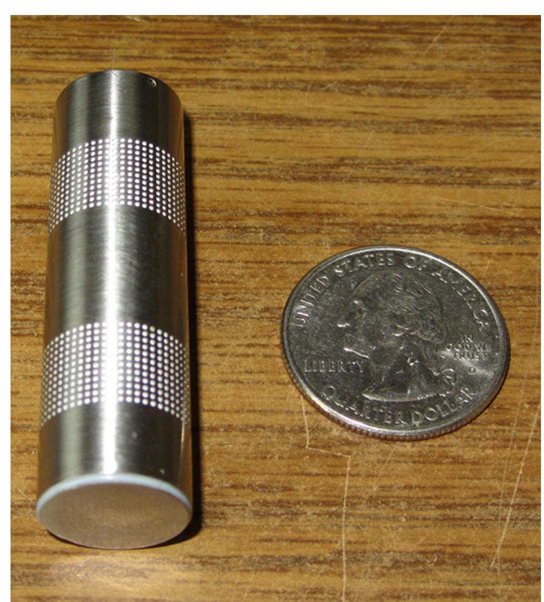

Fig. 2. Photograph of an MFC next to quarter for reference.