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News and Views

Design of a proton exchange membrane portable fuel cell system for the 1st international association for hydrogen energy design competition

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A B S T R A C T

A portable hydrogen fueled proton exchange membrane fuel cell (PEMFC) system was designed to meet the design constraints of the 1st International Association for Hydrogen Energy Portable Fuel Cell Design Competition that could be used to supply power to portable devices. The portable PEMFC stack has a physical dimension of 5.95 × 5.95 × 1.95 cm and 0.275 kg in mass. The PEMFC stack has a continuous output power of 12.5 W with a peak power output of 17 W. The fuel cell stack is an open cathode design which uses an external fan for both cooling and air supply. The fuel cell system includes an external fan along with power and control electronics that powers the fan and provides steady 5 V and 12 V outputs. The system also includes a standard USB connector for charging portable devices such as cellular phones and portable media players. A detailed description of the fuel cell stack and system design is presented along with experimental data demonstrating the stack and system performance.

1. Introduction

Recently, portable electronic devices such as notebook computers and cellular phones have experienced a boom in popularity and are now commonly owned by most people in the developed world. However, power requirements for these devices are increasing as demand for more power and longer runtime are increasing. Portable electronic devices are typically powered by batteries which often are characterized by a low energy density and must be frequently recharged. Another, and much less common, option for powering portable devices is the use of fuel cells. It has been shown that fuel cells have the ability to provide greater energy density and longer operating time than batteries in some applications [1]. Fuel cells also provide the advantage of not needing to be recharged for long periods of time and instead can be easily and quickly refueled. Although portable fuel cells are an attractive alternative to batteries for portable devices, they are often more complex due to ancillary devices such as fans or pumps and power and control electronics. This increased level of complexity creates significant design challenges when developing a portable fuel cell system.

In order to aid in the development of such portable fuel cell systems, the International Association for Hydrogen Energy (IAHE) chapter at Oakland University (OU) has designed, constructed, and tested a hydrogen fueled portable Proton

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Exchange Membrane (PEM) fuel cell stack in accordance with the 1st Annual International Association for Hydrogen Energy Competition for the Portable Fuel Cell guidelines for participation of the competition. The fuel cell created by the OU IAHE chapter is 5.95 × 5.95 × 1.95 cm in size, 0.275 kg in weight, and can produce up to 12.5 W of power continuously with a peak power output of 17 W. The fuel cell can be fueled by any source of pure dry hydrogen at 2 to 3 psig. The total fuel cell system includes the portable fuel cell stack, an electrical fan with controller, and a 5 V and 12 V DC–DC boost converters.

This paper addresses the design of the fuel cell system with the main focus on the portable fuel cell stack. The paper also presents the experimental results and performance of the fuel cell and accompanying devices.

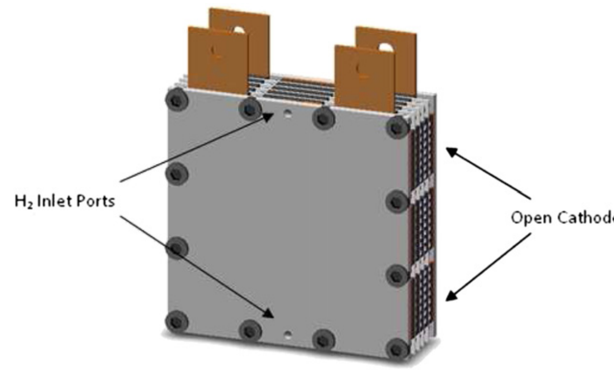

Fig. 1 – CAD model used for design of the fuel cell stack.

2. Portable fuel cell design

2.1. *Goals and objectives*

The objectives of the fuel cell system design was for the system to be simple, self-contained, and to achieve optimal performance with respect to cost and size. The complete system includes the fuel cell stack, fan, and accompanying electronics. However, not included in the system design is the hydrogen storage device or hydrogen fuel pressure regulator. The goal of the competition set by the IAHE was to produce the greatest measured sustained power from the stack given the following dimensional constraints: 2 cm high or less (excluding fittings, power tabs, and fasteners), and a maximum of 6 cm × 6 cm in length and width. The type of fuel cell that could be used for the competition was not restricted to any specific technology.

2.2. *Fuel cell stack concept and design*

While the Direct Methanol Fuel Cell (DMFC) or the Direct Borohydride Fuel Cell (DBFC) is commonly used for portable power applications, the type of fuel cell chosen for this work was a hydrogen fueled PEM fuel cell as it provides a high power density and does not suffer from adverse effects such as fuel crossover and hydrolysis [1–4]. The advent of portable metal-hydride canisters has allowed the gaseous fuel, hydrogen, to be stored in small spaces for long periods of time making hydrogen fueled fuel cells a practical option for portable devices.

The hydrogen fueled portable fuel cell stack designed in this project contains four individual cells, each having a 25 cm^2 active area. The stack is ambient air breathing and uses a fan to provide air for the reduction reaction on the cathode and for stack cooling. All four of the cells are stacked in a series configuration with current collectors placed on the anode and cathode sides. Due to the fuel cell stack being an open air design, the cathode side of the cell is open on two sides to allow for the attachment of the external fan. An image of the CAD model used for fuel cell stack design is show in Fig. 1. The components considered in the volume size restriction are the endplates, current collectors, bipolar plates, all sealing materials, and the membrane electrode assemblies (MEA). The dimensions of these components are 5.95 × 5.95 × 1.95 cm when the stack is fully assembled and compressed. The components not included in this volume are the fasteners, hose fittings, and the current collector tabs. Images of the fuel cell stack are shown in Fig. 2.

2.2.1. *Membrane electrode assemblies*

The MEAs have an active area of 25 cm^2 providing a total active area of 200 cm^2 for the entire fuel cell stack. The MEAs were selected based on both the characteristics of performance and simplification of the system design. The electrolyte used was self humidifying Nafion™ N-112 type ionomer membrane. A self humidifying membrane was used because it greatly simplifies the overall system design by eliminating the need for an external humidifier. The catalyst loadings on the anode and cathode side were 0.2 mg Pt/cm^2 and 1.0 mg Pt/cm^2, respectively, to minimize activation losses without significantly increasing cost. A carbon cloth type gas diffusion layer was used for both the anode and cathode sides of the MEAs.

2.2.2. *Bipolar plates*

The bipolar plates of the fuel cell stack were constructed out of 0.095 inch thick Graphtek LLC GR-940™ composite graphite material. This material was chosen because it provides adequate thermal and electrical conductivity while having very low hydrogen permeability. The CAD models of both the anode and cathode bipolar plates are shown in Fig. 3.

The cathode flow channel design provides access to ambient air on the left and right sides of the fuel cell stack. An external fan is connected to the right side of the fuel cell stack to provide airflow through the cathode flow channels. The anode flow channels consist of straight vertical flow paths covering the entire active area of the MEAs. This design was chosen because it is simple, low cost in terms of time of manufacturing, and provides adequate contact resistance and fuel delivery. Because the anode sections of the stack are "dead ended" there is no concern about maintaining proper concentration gradients or issues with fuel flow.

2.2.3. *Current collectors*

The current collectors used are constructed out of 1 mm thick plates of 101 alloy high conductivity copper machined with the same planar profile as the bipolar plates. Also included with the current collectors are two tabs per collector, which are used for attaching power leads and voltage sensing leads for testing.

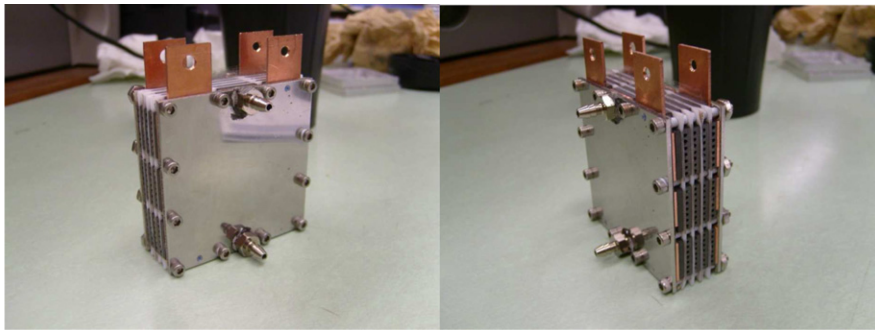

Fig. 2 – Images of PEM Fuel Cell Stack.

2.2.4. *End plates*

The endplates of the fuel cell stack consist of two 1.5 mm thick 316 alloy stainless steel sheets with a 12-hole bolt pattern designed to accept M3 type fasteners. The end plate located on the anode side, or the fuel inlet side, of the stack contains two ports for hose fittings to supply each of the cells with hydrogen. Two ports were included instead of one because it allows the cell to be purged of water and air.

2.2.5. *Gaskets/sealing*

Due to the effusion characteristics of hydrogen, a significant amount of study and focus was required for the design of sealing the fuel cell stack. In order to prevent hydrogen from leaking from the gas inlet fittings to the manifolding in the bipolar plates an "x-ring" was placed between the fittings, through the current collector, and to the first flow channel plate. An x-ring type seal was used as it provides more points of contact than an o-ring giving a better probability of a good seal.

In order to prevent hydrogen from leaking from the perimeter of the flow channel plates, two separate gaskets were used. A 150 μm thick adhesive backed Teflon coated fiberglass gasket was placed around the perimeter of the flow channel plate on the anode side of each cell. A 250 μm Teflon gasket was used to provide sealing on the cathode side of the flow plates to prevent hydrogen crossover and to protect the Nafion of the MEAs from damage. An image of the CAD model used for these gaskets is shown in Fig. 4.

2.3. *Power electronics*

A fuel cell, similar to all other electrochemical devices, does not create a constant voltage output with varying current density like most portable electronic devices demand. Because of this, the DC power output from the fuel cell must be converted to a usable voltage. For the fuel cell system developed in this work, two DC–DC boost converters were used to convert the output of the fuel cell to a constant 5 V and 12 V. The 5 V converter not only provides a 5 V output to the system load but also provides a constant 5 V to the 12 V boost converter, a fan controller, and to itself (after startup). The 12 V boost converter provides power to the system output and to the fan controller which powers the fan that provides air to the fuel cell stack. A block diagram showing the complete fuel cell system is shown in Fig. 5.

The fan controller controls the speed of the fan by varying the voltage across it (10–12 V) based on the voltage output of the fuel cell stack. At lower cell voltages, the fan speed increases to maintain oxygen concentration and cooling, and vice-versa for higher voltages. A schematic of the fan controller and power electronics is shown in Fig. 6.

The 12 V boost converter was designed to supply a maximum of approximately 500 mA of current at a peak efficiency of about 90%. The power required by the external fan is not included in this value, yielding a 12 V system output current of about 300 mA. The 5 V boost converter was designed to produce approximately 1A of maximum current output, not taking into account power to other system devices at a maximum efficiency of about 90%. This yields a practical 5 V maximum voltage output from the system of about 850 mA.

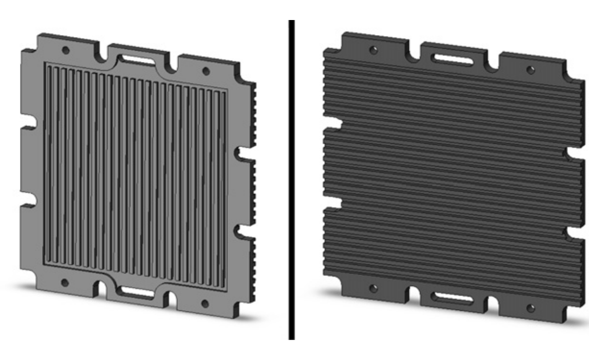

Fig. 3 – Bipolar plate anode flow channel design (left) and cathode flow channel design (right).

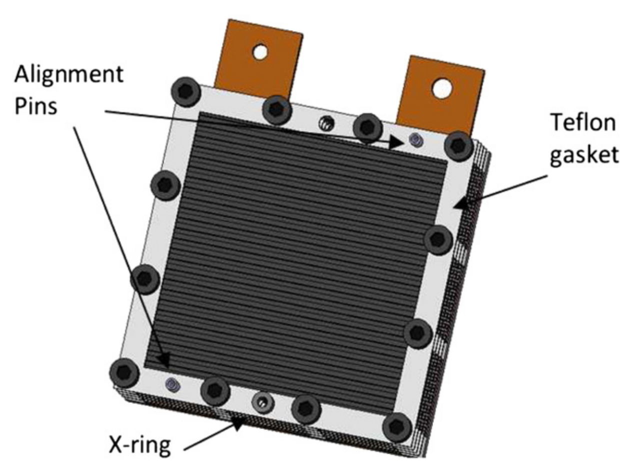

Fig. 4 – CAD model for Teflon gaskets on the cathode side.

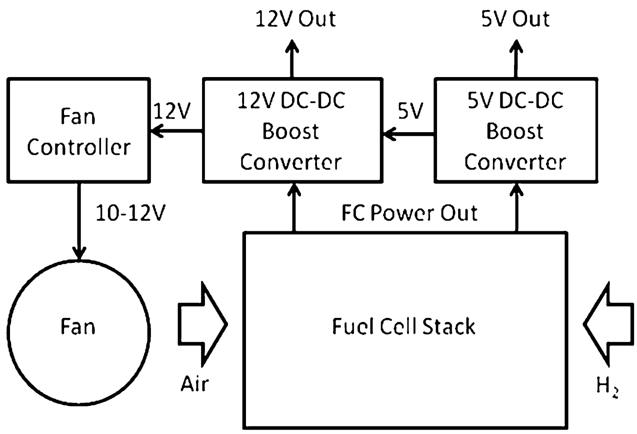

Fig. 5 – Block diagram of entire fuel cell stack power system (excluding hydrogen storage device).

The fuel cell system contains a USB jack for powering small portable devices that could normally be powered or recharged from a computer, such as cellular phones and portable media players. Given that the normal maximum current output from a PC's USB port is 300 mA at 5 V, the 850 mA output of the fuel cell system should be sufficient for powering most USB compatible devices. Images of the entire fuel cell system, including fuel cell stack, power electronics, and fan, are shown in Fig. 7.

3. Experimental testing

The University Model Test Station by the Fuel Cell Technologies Inc. was used to accurately measure the current density and voltage during testing of the fuel cell stack. The same test bench along with two Agilent 34401A digital multimeters with data logging. Ultrapure (99.99999%) hydrogen is supplied from a hydrogen tank through an adjustable regulator operated at a constant 3 psig. Air was supplied through the radial type system fan connected to one side of the fuel cell stack. Fuel cell stack temperature was measured at the cathode backplate surface and maintained between a temperature range of 25–30 °C.

4. Results and discussion

The fuel cell stack was found to have a steady state power output of approximately 12.5 W; however it was found that a power output in excess of 17 W could be maintained for periods of a few minutes. The reason for the inability to maintain this high power output is believed to be caused by a lack of oxidant delivery due to an undersized fan used to deliver air to the fuel cell stack along with the restrictive geometry of the cathode flow channels. The lack of air, or "choking", of the cathode is also believed to be the root source of system inefficiency or power loss. Fig. 8 shows the polarization curve obtained from the fuel cell stack under steady state operating conditions (output greater than 1 h).

Based on the polarization curve shown above in Fig. 8, a maximum power output of 12.5 W was obtained at a current density of 0.28 amps/cm^2 (7 amps) with an efficiency of ~38.5%. It was calculated that the fuel cell stack would consume approximately 11.7 LSTD of H2 every hour at this operating condition. Using this value for the maximum power output of the fuel cell, the cell was operated for approximately 2 h under steady state at a constant 0.28 amps/cm^2 (for each cell) under practical portable fuel cell operating conditions to

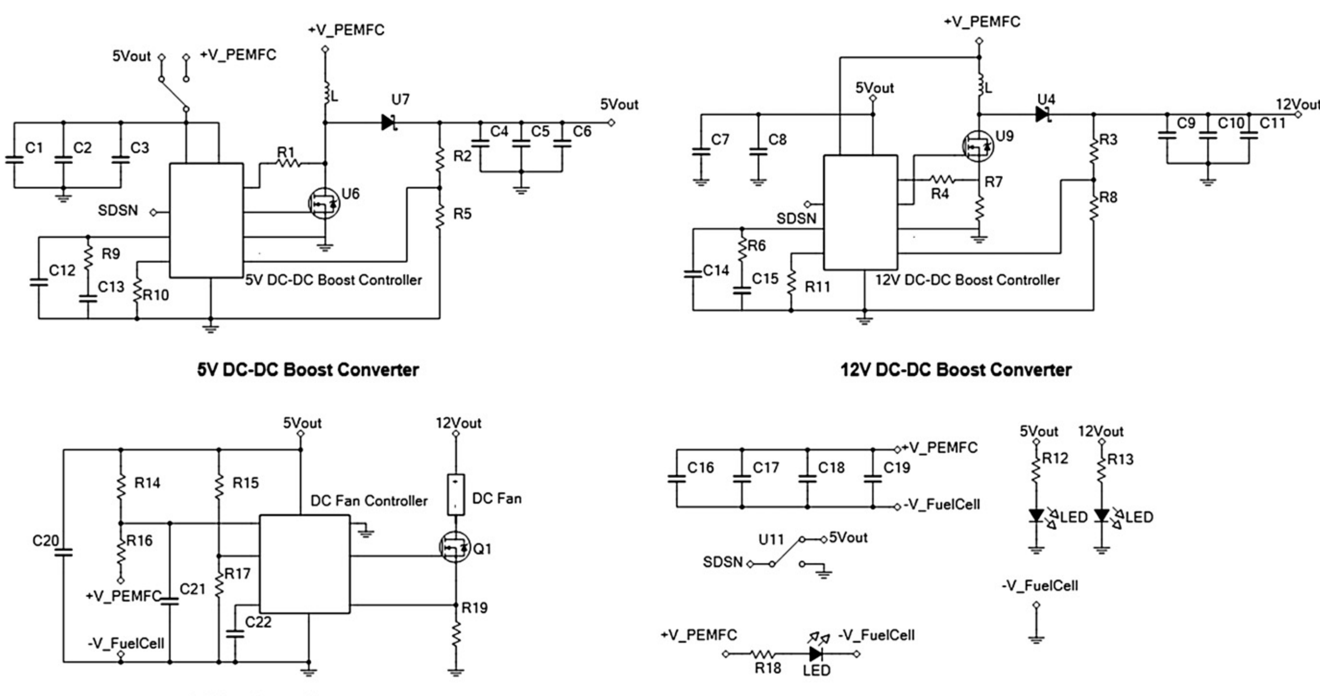

Fig. 6 – Schematic of Power Electronics and Fan Controller.

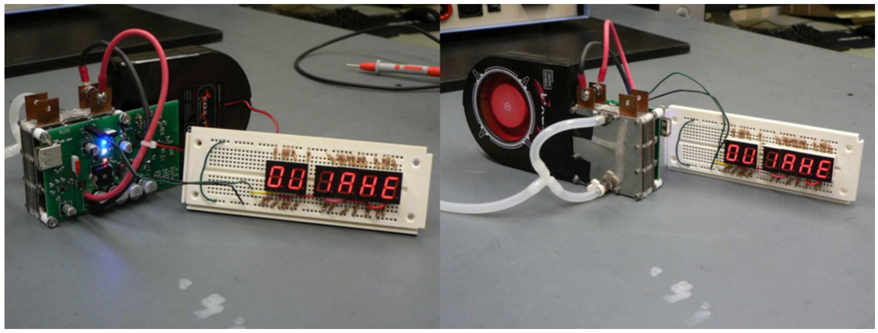

Fig. 7 – Images of the Portable Fuel Cell System in Operation.

confirm that this level of power output was sustainable for long periods of time. Fig. 9 shows a plot of the voltage, current, and power output of the fuel cell stack for a 1 h period.

As shown in Fig. 9, the power output of the fuel cell stack is relatively steady with a slight increase in voltage with operating time. This test is believed to confirm that the fuel cell stack is capable of delivering the maximum power output for extended periods of time.

In order to determine the maximum output power and efficiency of the entire fuel cell power system, the other ancillary devices must be taken into account. These devices include the fan and fan controller which provide air to the cells and the power converters. Fig. 10 shows a power summary of the entire fuel cell system showing what forms of energy the hydrogen chemical energy is ultimately converted to.

From Fig. 10, it can be seen that under full load, only about one quarter of the chemical energy provided by the hydrogen fuel is being used to generate useful electrical work. The majority of the chemical energy is converted into heat due to the irreversible processes which take place inside the PEM fuel cell. The remaining losses are generated by the power electronics and fan. The power consumed by the power electronics and the fan make up a large portion of the losses, comparable to the heat generated by the fuel cell, at lower power output. These losses increase only slightly as the power output increases and at higher power output become less significant as losses due to heat generation from the fuel cell dominate. As the power output of the system increases beyond 4.25 W, this trend would likely increase and the efficiency of the fuel cell and not the system overhead would have a greater influence on the total efficiency of the system. However, the 5 V DC–DC boost converter was designed to provide a power output comparable with most USB compatible devices with a peak efficiency at 3.5 W with a current of 700 mA. At total current outputs (5 V output plus system consumption) greater than 1A the boost converter begins to dropout and can no longer sustain a 5 V output.

It should be noted that the system requires a minimum output of the fuel cell of approximately 2.5 W just to activate the system. Because of this, the system is always consuming fuel even if the system is not providing any usable output power. Similar to a conventional thermal engine which must be constantly idling and consuming fuel when no useable work is being generated, the PEM fuel cell system must constantly be consuming fuel to power the fan and other ancillary devices. In this aspect, batteries can provide a significant advantage over portable fuel cell systems in applications where the portable devices require a large dynamic range of power consumption over long periods of time. However when not activated, fuel cell systems do not suffer from any type of "self-discharge" mechanisms which batteries do. This can be further understood by observing the hydrogen fuel consumption with respect to power output as

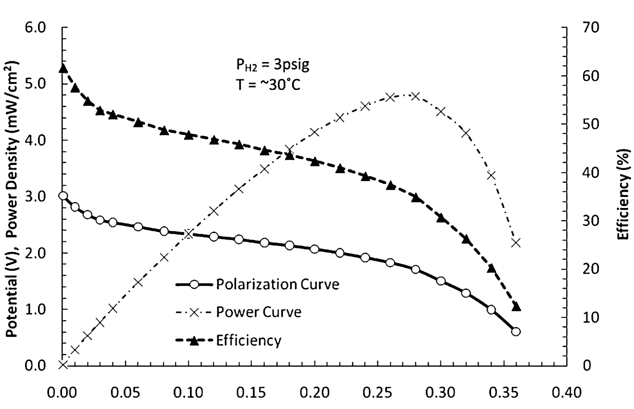

Fig. 8 – Polarization curve of the IAHE-OU fuel cell stack for steady state operating conditions.

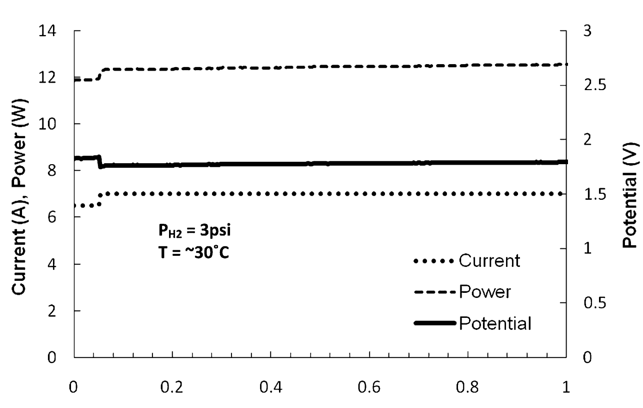

Fig. 9 – Fuel cell stack performance for approximately 1 h of constant operation.

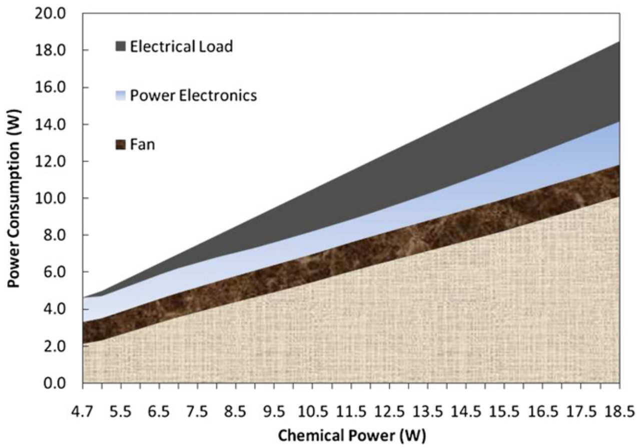

Fig. 10 – Power summary of portable fuel cell system with only a 5 V load varying from 0 to 4.25 W.

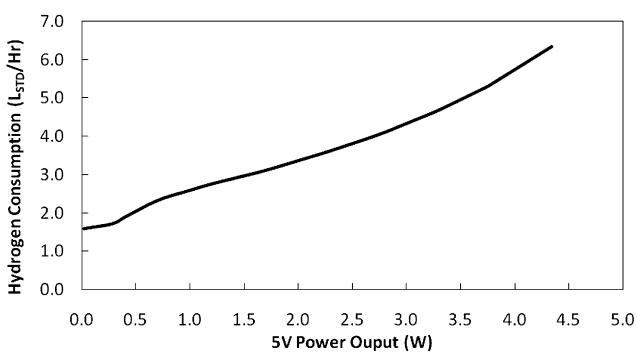

Fig. 11 – PEM Fuel Cell System hydrogen consumption with respect to power output.

shown in Fig. 11. As shown in Fig. 11, when the fuel cell system is providing no output power, $1.6L_{STD}$ of hydrogen are consumed per hour. As expected, consumption of fuel increases relatively linearly with power output.

To better understand the system characteristics, the efficiencies for the system including the system overhead

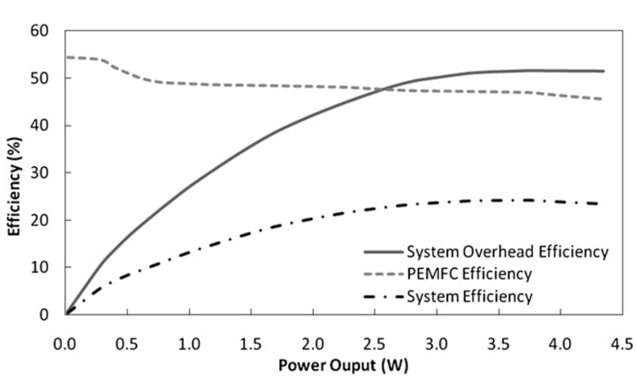

Fig. 12 – Power and efficiency curves for fuel cell stack and total power system with a varying 5 V load from 0 to 4.25 W.

(includes power electronics and fan) and the PEM Fuel Cell along with the total system efficiency is plotted with respect to the output power of the 5 V rail of the system. A plot representing these efficiencies is shown in Fig. 12. As can be seen from Fig. 12, the total system has a peak efficiency of approximately 25% at a power output of about 3.75 W. This peak output efficiency is due to a steady decrease of the fuel cell efficiency coupled with an increasing system overhead efficiency of the fan and power electronics. From these results it can be seen that significant increases in total system efficiency can be achieved by reducing system overhead. For example, a more efficient way of delivering air to the fuel cell by using a more efficient fan along with more open cathode flow channel geometry could reduce fan size and power consumption and thereby reducing system overhead. Further, better DC–DC boost converter topology could be used to provide a more efficient power output under a wide range of load demands.

5. Conclusions

A portable PEM fuel cell system was designed, constructed, and experimentally tested, which has a continuous power output of 12.5 W at an efficiency of 38.5% and a peak power output of 17 W. This fuel cell was coupled with two DC–DC boost converters, a fan, and a fan controller, creating a completely self-contained portable fuel cell system with the exception of a hydrogen storage device. The total system is capable of continuously outputting up to 4.25 W of electrical power at 5 V and was designed for powering and recharging USB compatible devices. The total system has a peak efficiency of approximately 25% at a power output of 3.75 W.

The results of testing and analysis reveal that significant improvements can be made to future designs to greatly improve performance and efficiency. The polarization curve of the fuel cell indicates significant concentration losses at higher power densities which also reduce the efficiency of the fuel cell. The fuel cell is also the greatest contributor to power loss in the entire system. Therefore, the most significant improvements can be made from a more efficient design of the cathode flow channel geometry and the use of a more efficient, and a more properly sized, DC fan which would also allow for a greater gravimetric power density and total output power. Further, a more effective fan controller along with more advanced DC–DC boost converter topologies could be used to increase the efficiency of the power electronics. This would reduce the amount of fuel consumed when the fuel cell system is at idle and when operating at low power output.

Acknowledgments

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Nomenclature

PEMFC	Proton Exchange Membrane Fuel Cell
MEA	Membrane Electrode Assembly
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
DBFC	Direct Borohydride Fuel Cell
USB	Universal Serial Bus

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