Session 3133

Performance of a PEM Fuel Cell System

Ahmad Pourmovahed, Professor
Mechanical Engineering Department
Kettering University
Flint, Michigan 48504

Abstract

A PEM fuel cell system was recently added to the *Energy Systems Laboratory* at Kettering University (formerly GMI). The educational objectives of this experiment are to familiarize the students with the principles and operation of a PEM fuel cell, to compare the power output efficiency of the fuel cell with that of an IC engine, to determine the effect of current density on stack and individual cell voltages, to determine the effect of hydrogen flow rate on the stack power output and to determine the effect of stack temperature on the stack power output. The apparatus used is the TVN RU-2100 Test Stand which uses a three-cell stack. The stack consists of three membrane and electrode assemblies (MEA's) in series. The maximum power output of this unit is about 25 Watts. It uses hydrogen and air to provide electrical power to a variable load. This system can be controlled and data can be acquired manually or through a computer. By using basic definitions as well as the first law of thermodynamics, current density, open-cell voltage and stack efficiency are determined for the fuel cell stack. This paper presents measured test data and analytical results obtained by using the principles of thermodynamics. Experimental results compare favorably with theoretical predictions and expectations.

Nomenclature:

A_t	total electrode area
A/F	air-fuel ratio
E	reversible open circuit voltage
e	charge on one electron (1.602×10^{-19} C)
F	Faraday constant (N_a .e = 96485 C/kmol)
h_{RP}	(lower) enthalpy of combustion of hydrogen (119,953 kJ/kg)
I	current
i	current density
N_a	Avogadro's number (6.022×10^{23} molecules/kmol)
$\dot{m}$	mass flow rate
P	power
V	voltage
V_c	individual cell voltage
x	excess air ratio
$\Delta \bar{g}_f$	change in Gibbs free energy of formation (molar)
η	stack efficiency
η_c	individual cell efficiency
μ_f	fuel utilization coefficient

Introduction:

A fuel cell is a power source that uses a fuel to provide electric current without combustion. Many different fuel cells have been developed and used in a variety of applications. All fuel cells function much like a battery, having an anode and a cathode that conduct current. Gaseous fuel enters the anode side while oxygen or air is introduced on the cathode side. On the anode side, electrons are separated from the fuel. The electrons flow from the anode through an external load to the cathode side. Of the fuel cells that have been researched and manufactured, the most widely used and promising include alkaline, molten carbonate, phosphoric acid and PEM fuel cells.

PEM fuel cells are becoming an industry standard for consumer applications. The defining characteristic is the electrolyte. Instead of phosphoric acid, PEM fuel cells use a polymer film as an electrolyte. With operating temperatures ranging from 30 to 100^{o}C, modern PEM fuel cell stacks are used in a variety of applications such as vehicles, mobile applications and for low power "combined heat and power" (CHP) systems. Currently, the most sought after use is to power electric motors for transportation vehicles. The future dubbed as ***"The Hydrogen Economy"*** will incorporate PEM fuel cells into all aspects of everyday life. Future applications of electricity created by PEM fuel cells will include anything from cell phones, laptops and other portable devices to larger applications such as to power large buildings as well as residential homes independent of large power grids.

Having low operating temperatures, PEM fuel cell stacks can be used in mobile applications. The solid flexible electrolyte makes it possible to avoid cracks and leaks. Emissions from PEM fuel cells are very clean. Automotive companies can lower carbon dioxide output from vehicles by implementing PEM fuel cell stacks. Output from the fuel cell will only be water and excess hydrogen and air. Fuel cells produce a small amount of voltage individually. Stacks of cells are used and their output to an inverter can provide a usable constant voltage. PEM fuel cells are expensive to manufacture and platinum catalysts are not cheap. Fuel must be processed before hydrogen gas can be input to the system. If impure hydrogen is used, carbon monoxide will quickly contaminate the polymer membrane electrolyte. Additionally, since the electrolyte is a thin film, constant and equal pressure must be applied to each side of the membrane or it will balloon and burst.

The basis for operation of a PEM Fuel Cell is hydrogen and oxygen creating a voltage at two poles by reacting to form water. The basic fuel cell is composed of a membrane and electrode assembly known as an MEA, flow field plates, current collectors, and endplates (Figures 1 and 2). Heating or cooling plates may also be contained in the fuel cell. Hydrogen and oxygen react on opposite sides of the MEA to produce water, electricity, and heat. In order to accomplish this, the hydrogen and oxygen half reactions are separated by a solid polymer electrolyte (known as either a **proton exchange membrane** or a **polymer electrolyte membrane**). This electrolyte separates the two reactant gases while providing an ionic connection through which the protons may pass. The electrolyte has a catalytic electrode layer on each side to speed the reaction rate and provide electrical contact for the conduction of electrons. The reactant gases flow through channels cut into the flow field plates. While the gas flows parallel to the MEA the gas can diffuse the catalyst layer of the MEA to react. The product water is wicked out to the flow field, where it is swept away by the excess gas flow. The electrical potential is transferred to the current collectors, which can be connected to a load to perform electrical work. Electrochemical reactions in a PEMFC are shown schematically in Figure 3.

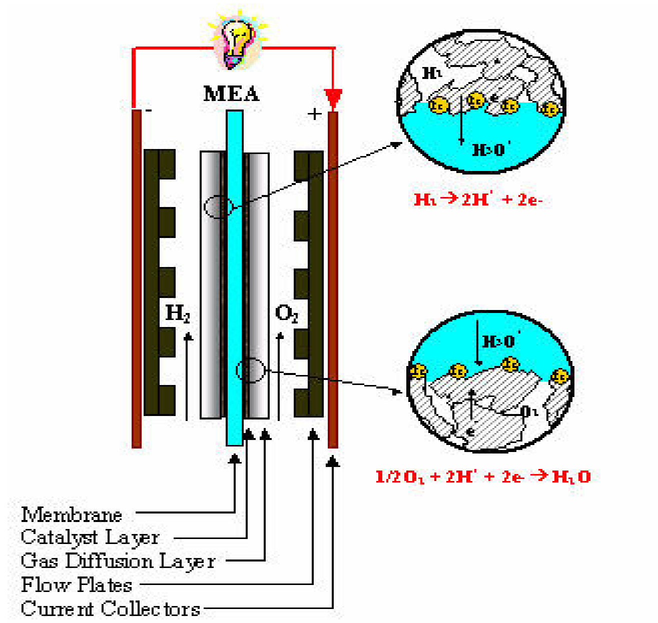

Figure 1: Schematic diagram of a PEM fuel cell [2]

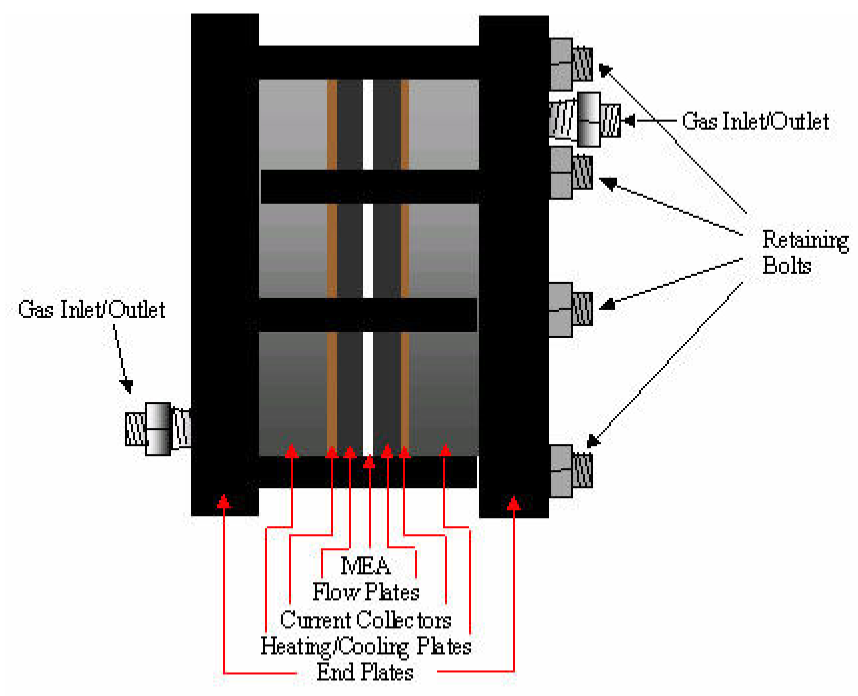

Figure 2: Schematic diagram of a single PEMFC assembly [2]

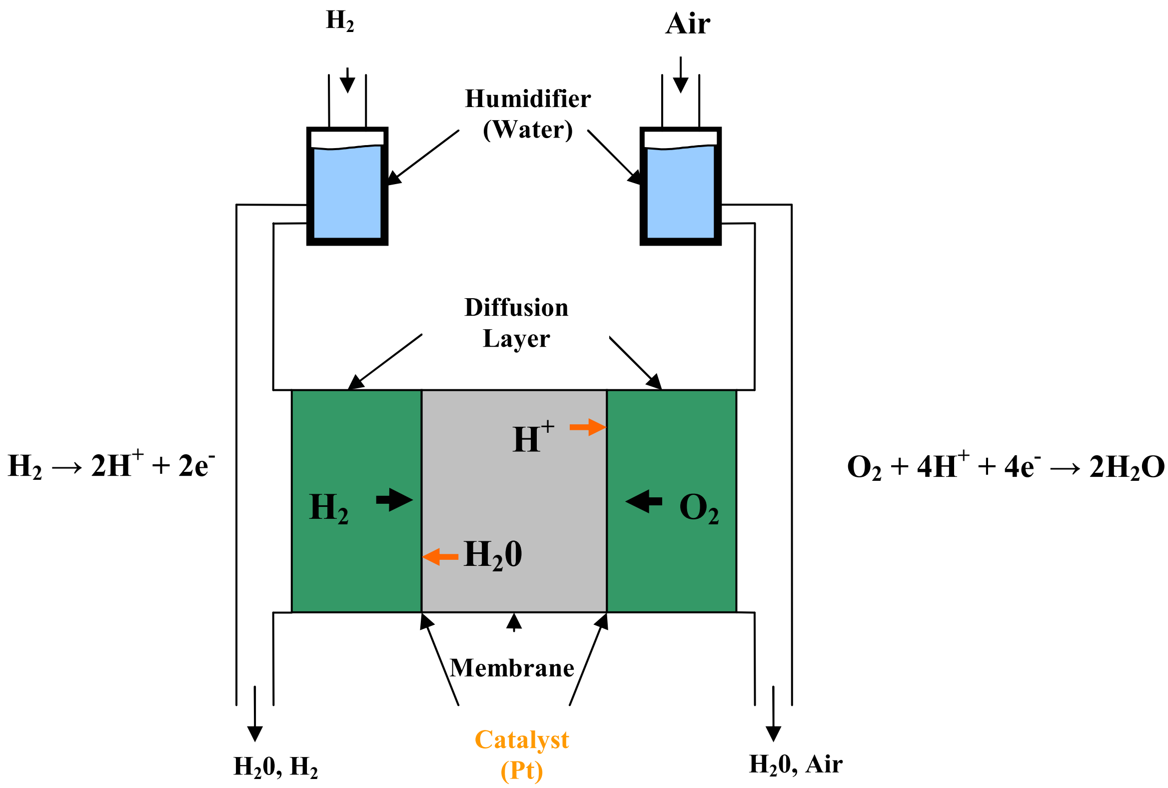

Figure 3: Electrochemical reactions in a PEMFC

Educational Objectives:

The *PEM Fuel Cell Performance* experiment at Kettering University has the following objectives:

1. To familiarize the students with the principles and operation of a PEM fuel cell.
2. To compare the power output efficiency of the fuel cell with that of an IC engine.
3. To determine the effect of current density on stack and individual cell voltages.
4. To determine the effect of hydrogen flow rate on the stack power output.
5. To determine the effect of stack temperature on the stack power output.

Definitions and Theoretical Analysis:

Current density is the amount of current supplied by the fuel cell divided by the total area of the fuel cell electrode. This is analogous to the power to weight ratio of a car engine. The current density of a fuel cell is defined as

$$i = \frac{I}{A_t} \tag{1}$$

and is usually expressed in (A/cm^2). Current density is used to compare one fuel cell stack to another. For example, in automotive applications, it is important to optimize this number such that the overall size of the fuel cell stack is reduced for any given output.

Electrical power output of the fuel cell (usually expressed in Watts) is easily found from

$$P = VI \tag{2}$$

Specific Power and **Power Density** are defined as

$$Specific\ Power = \frac{power}{mass} \quad (W/kg) \tag{3}$$

$$Power\ Density = \frac{power}{volume} \quad (W/m^3) \tag{4}$$

The reversible **open circuit voltage (OCV)** of a fuel cell using pure hydrogen and oxygen at standard pressure (0.1 MPa) is given by (Larminie and Dicks, 2003) [1]:

$$E = \frac{-\Delta \bar{g}_f}{2F} \tag{5}$$

where $\Delta \bar{g}_f$ is the Gibbs free energy released and F is the Faraday constant (96485 C/kmol). The values of $\Delta \bar{g}_f$ for the simple reaction $H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$ at various temperatures are shown in Table 1.

Table 1 $\Delta \bar{g}_f$ **for the reaction** $H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$ **at various temperatures** [1]

Phase of Water Produced	Temperature, °C	$\Delta \bar{g}_f$ (kJ/kmol)
liquid	25	-237.2
liquid	80	-228.2
vapor	80	-226.1
vapor	100	-225.2
vapor	200	-220.4
vapor	400	-210.3
vapor	600	-199.6
vapor	800	-188.6
vapor	1000	-177.4

The cell potential (voltage) drops as current is drawn from a fuel cell. This is shown in Figure 4. The voltage drop is caused by four factors:

1. Activation losses
2. Fuel crossover and internal currents
3. Ohmic losses
4. Mass transport or concentration losses

Detailed discussion of these factors can be found in Larminie, J. and Dicks, A. (2003) [1].

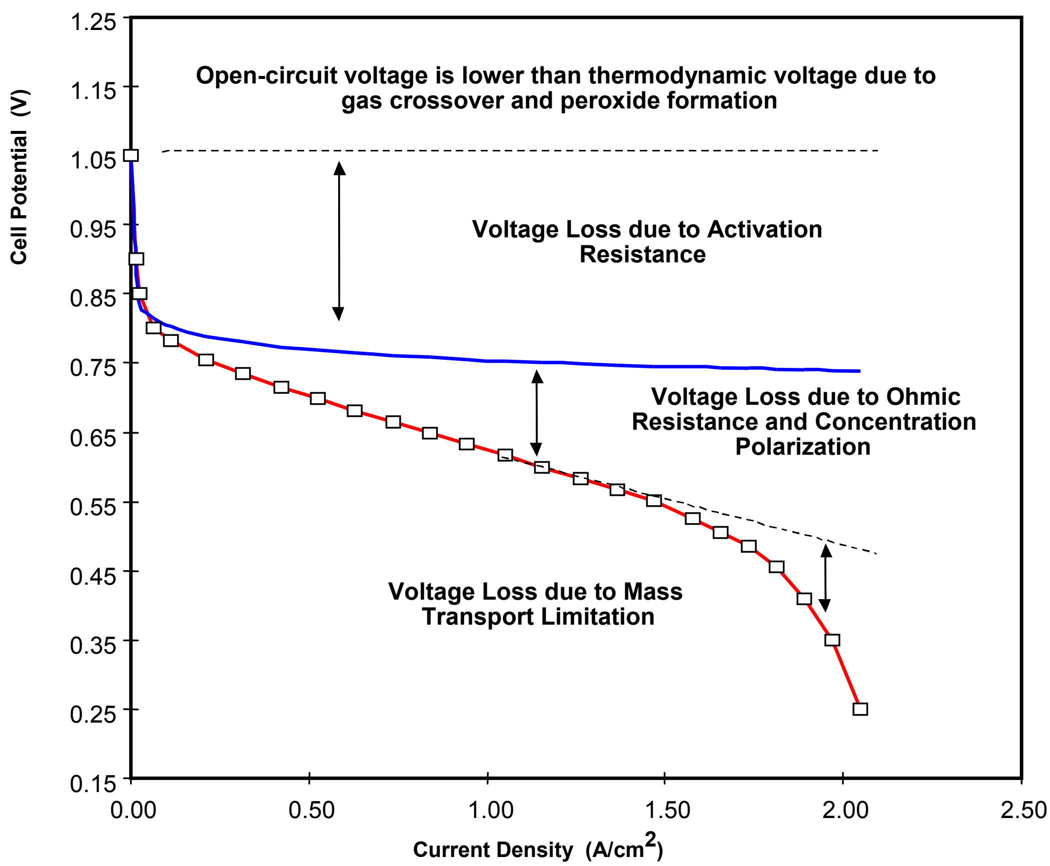

Figure 4: Cell potential versus current density for a PEMFC [2]

One way to define **fuel cell stack efficiency** is to compare the energy output from a fuel cell to the lower enthalpy of combustion of hydrogen (Figure 5).

$$\eta = \frac{VI}{\dot{m}_{H_2}\mathrm{h}_{RP}} \tag{6}$$

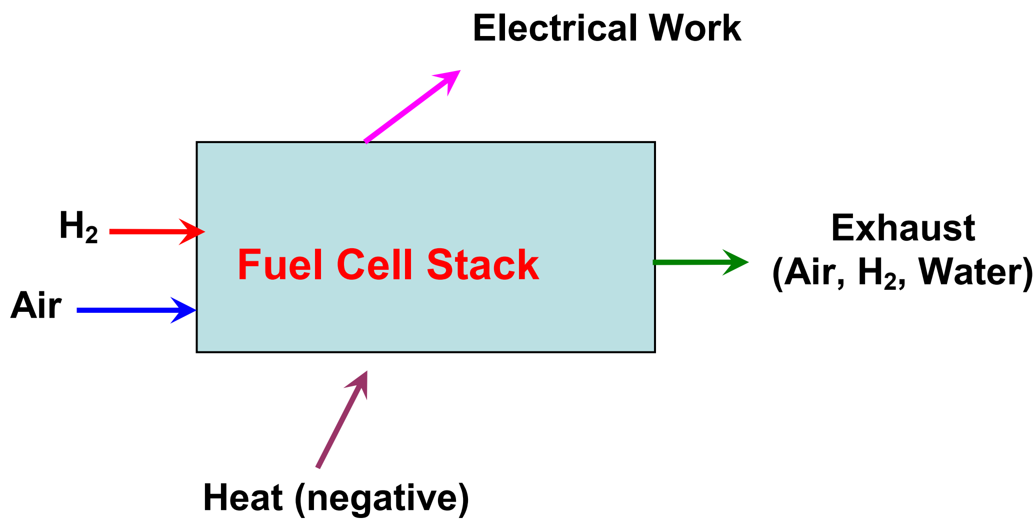

Figure 5: Fuel cell stack as a control volume (open system)

This definition provides a method for comparing the power output of a fuel cell stack to that of an internal combustion engine utilizing the same fuel (hydrogen) with water vapor in the combustion products.

The **efficiency of an individual cell** has been derived by Larminie, J. and Dicks, A. (2003, p. 35) [1] as

$$\eta_c = \mu_f \frac{V_c}{1.48 \; or \; 1.25} \tag{7}$$

Where 1.48 is the number to be used in conjunction with the "higher heating value" and 1.25 corresponds to the "lower heating value" of hydrogen. The fuel utilization coefficient, μ_f, is usually taken to be 0.95.

Stoichiometric reaction is a complete reaction where the quantity of oxidizer is the precise amount needed to completely consume a quantity of fuel. Consider stoichiometric reaction of hydrogen with air inside the fuel cell stack,

$$\mathbf{H_2 + \frac{1}{2}\,[O_2 + 3.76\,N_2] \rightarrow H_2O + 1.88\,N_2} \tag{8}$$

$$(A/F)_{stoich.} = \frac{0.5[32 + 3.76(28)]}{2(1)} = \mathbf{34.32} \tag{9}$$

$$(A/F)_{actual} = \frac{\dot{m}_{Air}}{\dot{m}_{H_2}} \qquad (10)$$

Define excess air ratio (x) as

$$x = \frac{(A/F)_{actual}}{(A/F)_{stoich.}} \qquad (11)$$

For example, if $x = 2$, we have 100% **excess air** or 200% **theoretical air** (double the amount of air required for complete reaction of hydrogen and oxygen).

The **actual reaction** is

$$\mathbf{H_2 + \frac{x}{2}\,[O_2 + 3.76\,N_2] \rightarrow H_2O\ (liquid) + (1.88\,\mathit{x})\,N_2 + \frac{x-1}{2}\,O_2} \qquad (12)$$

The minimum (stoichiometric) reactant flow rate required for current generation at standard pressure and temperature may be determined as follows. The stoichiometric reaction of hydrogen and pure oxygen to form water can be written as

$$
\begin{array}{ll}
H_2 \rightarrow 2H^+ + 2e^- & (a) \\
\tfrac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O & (b) \\
\textit{which combine to}: & \\
H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O & (a+b)
\end{array}
$$

At standard temperature and pressure (STP), **1 kmol** of any gas (such as hydrogen) occupies 22.41 liters and consists of 6.022×10^{23} molecules (Avogadro's number, N_a). The charge on one electron is $e = 1.602 \times 10^{-19}$ C. For each kmol of hydrogen that reacts, 2 electrons are released. The electric charge produced is $2\,N_a\,e = 2F = 192{,}970$ C. Therefore, a hydrogen volumetric flow rate of 22.41 liters/s (at STP) corresponds to an electric current of 192,970 C/s (or Amps). To produce 1 Amp, the minimum volumetric flow rate of hydrogen at STP is 22410/192970 = 0.11613 ml/s = 6.97 ml/min ≈ 7 ml/min.

For every oxygen molecule, two hydrogen molecules are needed. This will result in a 2:1 ratio for hydrogen/oxygen volumetric flow rates. If air is used instead of pure oxygen, since air is comprised of 21% oxygen and 79% nitrogen by volume, the volumetric flow rate of air would have to be ≅ 4.76 times greater than that of oxygen to react with the same amount of hydrogen.

Table 2 shows the stoichiometric (minimum) reactant flow rates required for current generation at STP.

Table 2 Stoichiometric reactant flow rate required for current generation at standard temperature and pressure , STP [2]

Current (A)	H_2 (ml/min)	O_2 (ml/min)	Air (ml/min)	Current (A)	H_2 (ml/min)	O_2 (ml/min)	Air (ml/min)
0.5	3.5	1.7	8.3	10.5	73.1	36.6	174.1
1	7.0	3.5	16.6	11	76.6	38.3	182.4
1.5	10.4	5.2	24.9	11.5	80.1	40.0	190.7
2	13.9	7.0	33.2	12	83.6	41.8	199.0
2.5	17.4	8.7	41.5	12.5	87.1	43.5	207.3
3	20.9	10.4	49.7	13	90.5	45.3	215.6
3.5	24.4	12.2	58.0	13.5	94.0	47.0	223.9
4	27.9	13.9	66.3	14	97.5	48.8	232.2
4.5	31.3	15.7	74.6	14.5	101.0	50.5	240.4
5	34.8	17.4	82.9	15	104.5	52.2	248.7
5.5	38.3	19.2	91.2	15.5	108.0	54.0	257.0
6	41.8	20.9	99.5	16	111.4	55.7	265.3
6.5	45.3	22.6	107.8	16.5	114.9	57.5	273.6
7	48.8	24.4	116.1	17	118.4	59.2	281.9
7.5	52.2	26.1	124.4	17.5	121.9	60.9	290.2
8	55.7	27.9	132.7	18	125.4	62.7	298.5
8.5	59.2	29.6	141.0	18.5	128.8	64.4	306.8
9	62.7	31.3	149.2	19	132.3	66.2	315.1
9.5	66.2	33.1	157.5	19.5	135.8	67.9	323.4
10	69.6	34.8	165.8	20	139.3	69.6	331.7

Experimental Apparatus and Instrumentation:

The TVN RU-2100 Test Stand (Figures 6 and 7) uses a three-cell fuel cell stack. The stack consists of three Membrane and Electrode Assemblies (MEA's) in series. The maximum power output of this unit is about 25 Watts. It uses hydrogen and air to provide electrical power to a variable load. This system can be controlled and data can be acquired manually or through a computer.

Figure 6: The TVN RU-2100 fuel cell system [2]

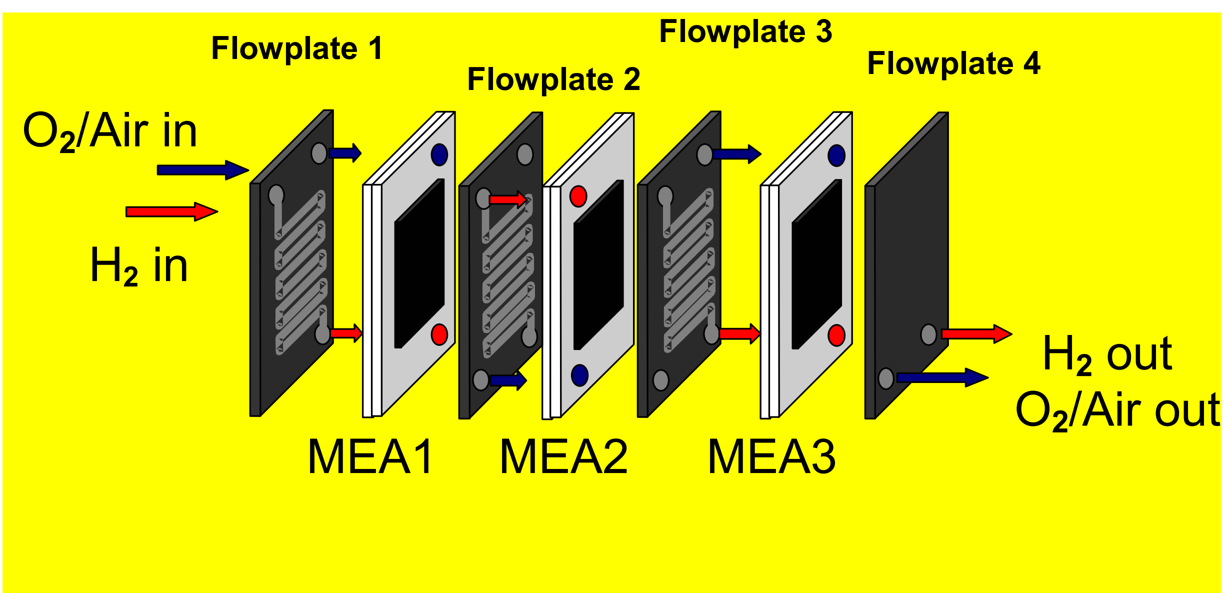

Figure 7: Series gas flow pattern for the three-cell stack [2]

Experimental Procedure:

1. Follow the "Start-up Procedure" and warm up the fuel cell stack. Make sure that the **H_2 and air supply pressure regulators are set at 20 psig**. The H_2 and air back pressures must be set at 0 psig.

2. Set the stack temperature at 50 ºC, the hydrogen humidifier at 30 ºC, and the air humidifier at room temperature.

3. Set the air flow rate at 1000 ml/min and the H_2 flow rate at 150 ml/min. Use the electric current control knob to vary the current from zero to maximum in 10 approximately equal increments. Record your data on the attached "Observed Data Sheet".

4. Set the air flow rate at 1000 ml/min and the H_2 flow rate at 600 ml/min. Use the electric current control knob to draw 10 amps from the fuel cell stack. Vary the H_2 flow rate from 600 to 50 ml/min in 50 ml/min increments. Record individual cell voltages, the stack voltage and the current for each H_2 flow rate. **Do not change the position of the current control knob (fixed load).**

5. Set the air flow rate at 1000 ml/min and the H_2 flow rate at 50 ml/min. Set the stack temperature at 50 ºC. Use the electric current control knob to draw 2 amps from the fuel cell stack. For five different stack temperatures, record the stack voltage and current. **Do not change the position of the current control knob (fixed load).**

Graphical Results:

1. Using the data from Part 3 of the Experimental Procedure, plot the stack voltage and stack efficiency versus current density (A/cm^2).

2. Using the data from Part 3 of the Experimental Procedure, plot the voltage for individual cells versus current density (A/cm^2).

3. Using the data from Part 4 of the Experimental Procedure, plot the stack power output (Watts) versus H_2 flow rate (fixed load).

4. Using the data from Part 5 of the Experimental Procedure, plot the stack power output (Watts) versus stack temperature (fixed load).

Discussion:

1. Discuss the variation of the stack voltage with current density. Compare the open-circuit stack potential with the maximum theoretical value (Eq. 5). Discuss the losses associated with the voltage drop.

2. Compare the efficiency of the fuel cell stack with that of an IC engine.

3. Comment on the cell-to-cell voltage variations with current density.

4. Discuss the variation in the power output with H_2 flow rate for a fixed load.

5. Discuss the variation in the stack power output with stack temperature for a fixed load.

6. For one case from Part 4 of the Experimental Procedure (use H_2 flow rate = 100 ml/min), estimate the **minimum theoretical** volumetric flow rate of hydrogen required at the given supply pressure (ml/min). What is the **estimated** rate of water production in the fuel cell stack (grams/min) for this case?

Experimental Results:

The maximum measured efficiency of the fuel cell stack was 18% (Figure 8). The max thermal efficiency of an IC engine measured in a separate experiment is about 30%. Since the stack tested has only 3 cells and is constructed for educational purposes, it is not surprising that its efficiency is low compared to a full size 6-cylinder IC engine. Figure 8 also shows the drop in stack voltage is the output current is increased. This is due to various losses discussed above (Figure 4).

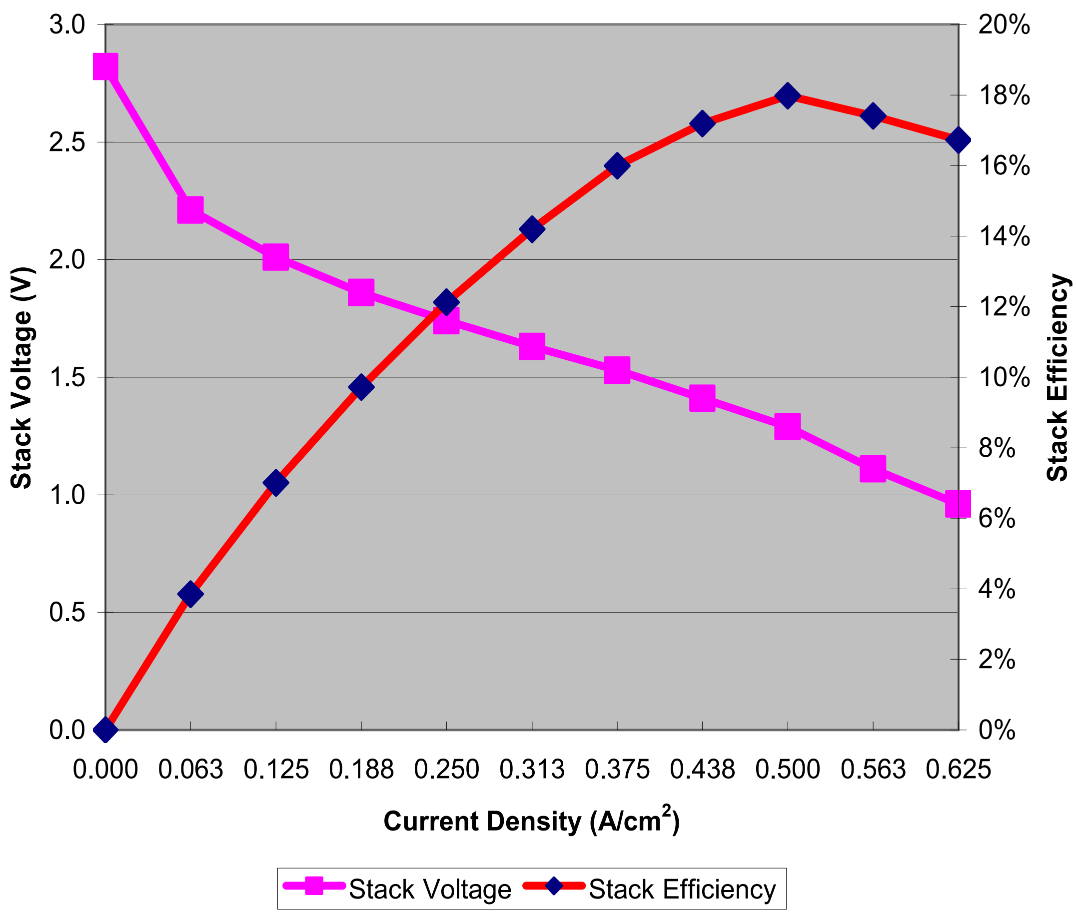

Figure 8: Stack voltage and efficiency versus current density

The cell-to-cell voltage variation was nearly zero across the stack at zero current (Figure 9). As predicted, as current density increased, the third cell began to become starved. This is due to the current density rising without increasing the flow rate of hydrogen. Thus at higher current densities more hydrogen was used by the first two cells. This left the third cell without enough hydrogen to produce the same potential.

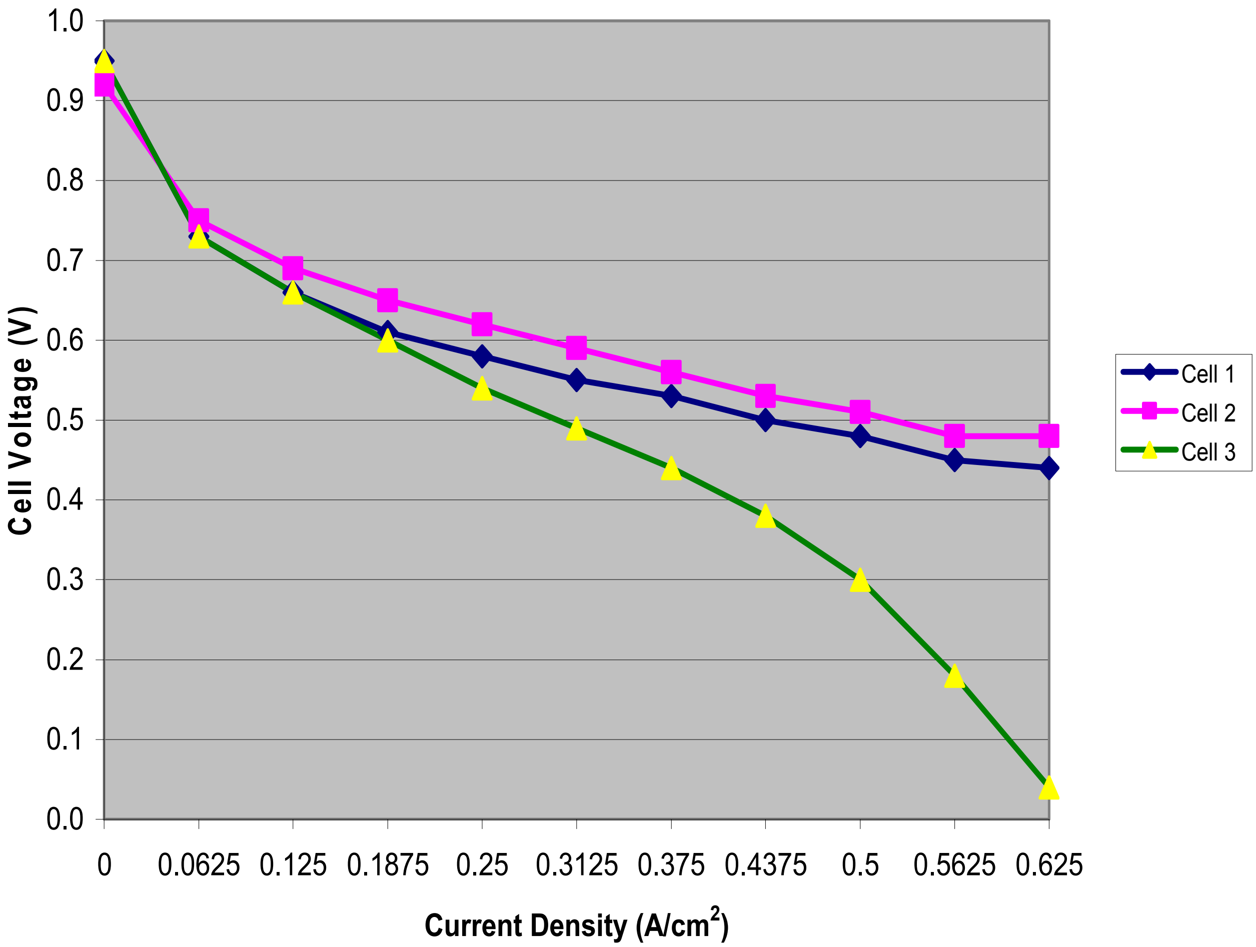

Figure 9: Cell voltage versus current density

Figure 10 clearly shows that adding large amounts of hydrogen will not necessarily increase the power output of a fuel cell. The cell can only utilize a certain amount of hydrogen and the rest is just exhausted into the atmosphere. Under the test conditions, the ideal volumetric flow rate of hydrogen into the fuel cell is approximately 200 ml/min.

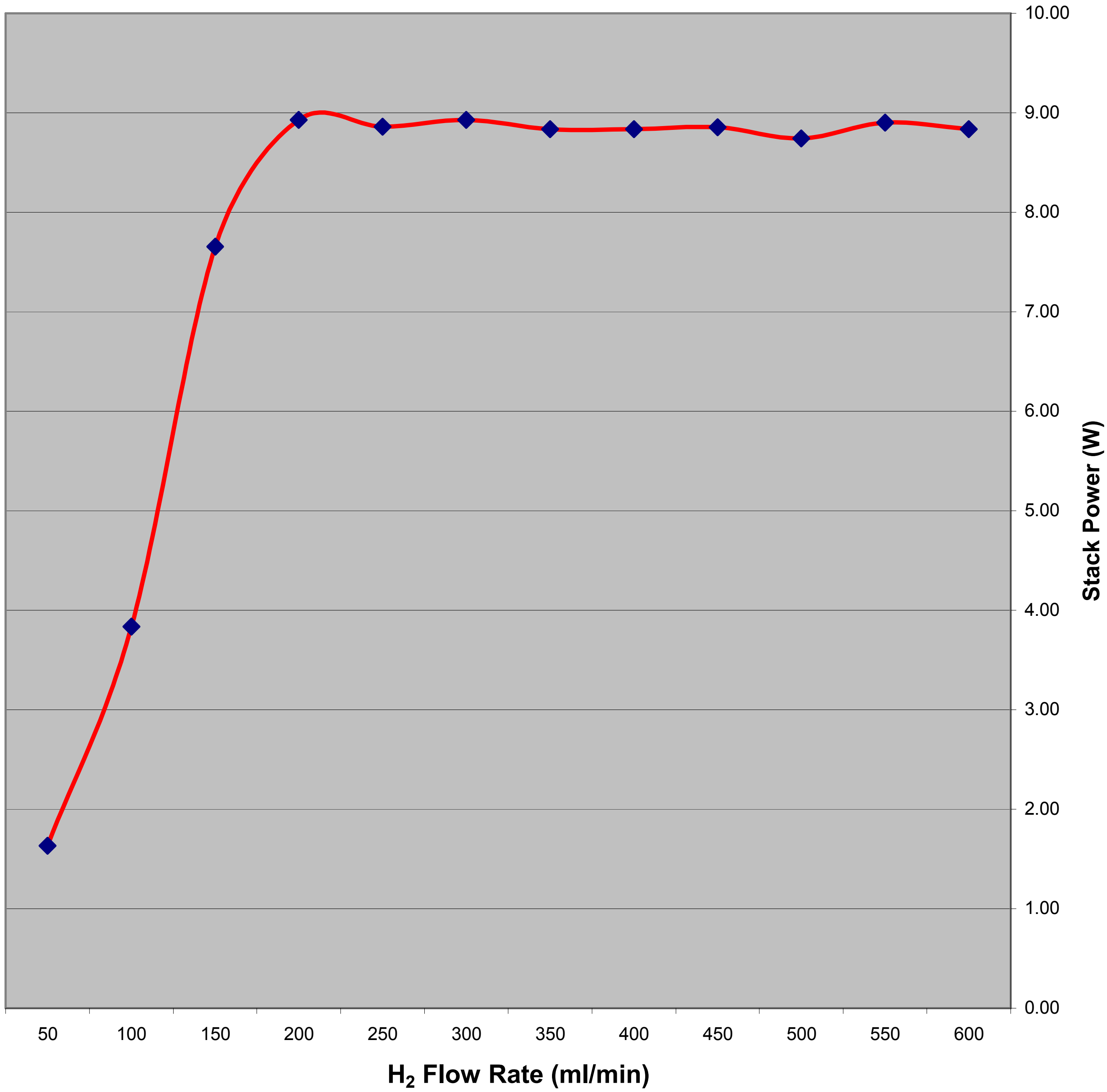

Figure 10: Stack power versus H_2 flow rate

Figure 11 shows the variation in the stack power output with stack temperature for a fixed load. The stack power decreased about 29% as the stack temperature varied from 45°C to 80 °C. This is primarily caused by a drop in humidity at higher temperatures. When the membranes get dry, the power output drops as expected. A secondary cause of the reduction in power is the drop in $\Delta\overline{g}_f$ at higher stack temperatures (Table 1).

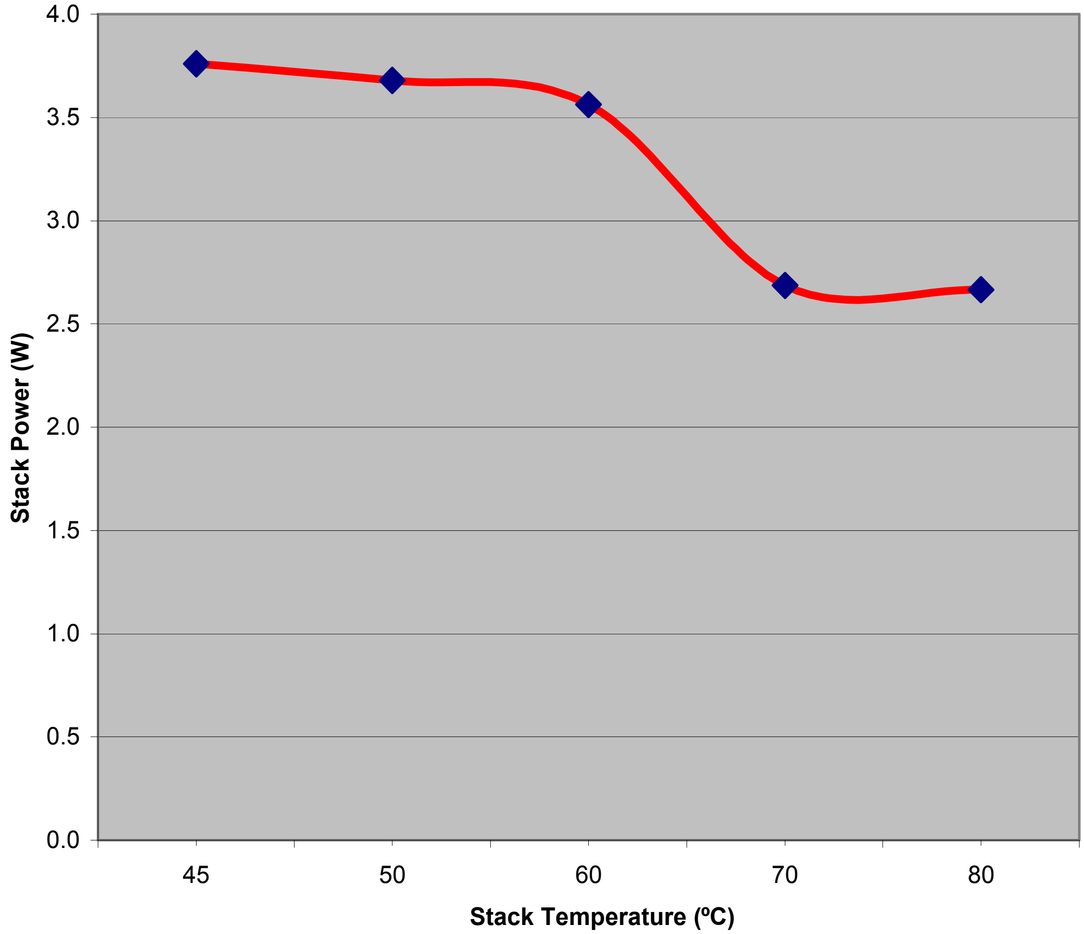

Figure 11: Stack power versus stack temperature

Conclusions:

The *TVN RU-2100 PEM Fuel Cell Test Stand* was successfully implemented in the *Energy Systems Laboratory* at Kettering University. Experimental results are reported and discussed in this article. The maximum stack efficiency (about 18%) was well below the actual electrical efficiency of industrial fuel cells (about 45%) and that of internal combustion engines (about 32%) due to the small size of this educational stack. This system has proven to be a valuable educational tool. Experimental results obtained from this fuel cell stack agree well with students' expectations and their calculated results. This laboratory experiment integrates well with Kettering University's world class fuel cell engineering curricula. It provides an opportunity for about 250 mechanical engineering students per year to become familiar with the operation of a PEM fuel cell stack and apply the principles of thermodynamics to this power source.

References:

1. Larminie, J. and Dicks, A. **(2003),** *Fuel Cell Systems Explained,* 2nd ed., Wiley.

2. TVN Systems **(2004)**, http://www.tvnsystems.com

AHMAD POURMOVAHED
Ahmad Pourmovahed is a Professor of Mechanical Engineering at Kettering University. He received his Ph.D. in Mechanical Engineering (1985) and an M.S. in Mechanical Engineering (1979) both from the University of Wisconsin-Madison. After graduation, he worked at General Motors Research Laboratories and Lawrence Technological University. In 1990, he joined Kettering University where he teaches courses in thermal sciences, mechanics, and engineering design and serves as the Director of Energy Systems Laboratory.