Exergy Analysis of a 1.2 kWp PEM Fuel Cell System

A. Yilanci[1], H.K. Ozturk[1], O. Atalay[1], I. Dincer[2]

[1]Pamukkale University, Faculty of Engineering, Denizli, Turkey
e-mail: ayilanci@pau.edu.tr http://www.pamukkale.edu.tr
[2]University of Ontario Institute of Technology, Faculty of Engineering and Applied Science, Oshawa, Ontario L1H 7K4, Canada

Abstract

Recently, interest in fuel cells has increased sharply and progress towards commercialization has accelerated. As a result, practical fuel cell systems are now becoming available and are soon expected to take a growing share of the markets for automotive power and generation equipment once costs fall to competitive levels. Proton Exchange Membrane (PEM) fuel cells using pure hydrogen as fuel is employed to produce electricity due to some advantages, e.g., simplicity, effectiveness, low operating temperature, easy maintenance, etc. In this paper, we conduct a thermodynamic analysis, in terms of energy and exergy, of a 1.2 kWp Nexa PEM fuel cell system in order to investigate its performance in terms of energy and exergy efficiencies at different operating conditions.

Keywords: *PEM Fuel Cell, Energy, Exergy, Efficiency, Thermodynamics.*

1 Introduction

The conventional fossil fuel energy sources such as petroleum, natural gas, and coal which meet most of the world's energy demand today are being depleted rapidly. Also, their combustion products are causing global problems such as the greenhouse effect and pollution which are posing great danger for our environment and eventually for the entire life on our planet. Therefore, a movement towards environmentally friendlier, more efficient power production sources over the world. The utilization of renewable energy resources such as solar, wind and geothermal energy requires some form of energy storage. It is widely accepted that hydrogen can operate as a storage and carrying medium of these primary energy sources. Recently most of the studies based on the utilization of hydrogen are their integration with renewable sources of energy. A Hydrogen-based energy system is regarded as a viable and advantageous option for delivering high-quality energy services in a wide range of applications in an efficient, clean and safe manner while meeting sustainability goals. Producing hydrogen from renewable energy sources such as solar energy would drive its production system toward a sustainable trajectory in the long term. Hydrogen also provides an ideal complement to electricity. Proton Exchange Membrane (PEM) fuel cells could be used produce electricity from stored hydrogen when needed. PEM fuel cell, where pure hydrogen needed is one of the most promising fuel cells because of its some advantages such as its simplicity, low operating temperature, and easy maintenance.

During the past decade there has been increasing attention to the energy and exergy analyses of hydrogen and fuel cell systems for better performance. In this regard, we aim to investigate the performance of a 1.2 kWp Nexa PEM fuel cell unit, as a key part of the solar-hydrogen system installed in Denizli, through energy and exergy efficiencies for comparison purposes. This is just an early phase of this large-scale project in terms of system analysis and performance improvement.

2 Experimental System

Here we first look at the general system and second the fuel cell system as the main focus for the performance analysis through energy and exergy efficiencies. A comprehensive solar-hydrogen system which has PEM fuel cell modules was installed in February 2007 at Pamukkale University in Denizli, Turkey. In this system, solar energy is converted into electricity directly by using photovoltaic arrays. Electricity which comes from PVs is delivered to charge regulators for appropriate voltage of batteries, and then went to DC/AC inverter for utilization. Excess electricity energy from PVs is used to electrolyze water within an electrolyzer. Producing hydrogen is then stored as a solid form in metal hydride tanks. Whenever needed the electricity, hydrogen from storage canisters and oxygen from air react in two Nexa PEM fuel cell modules. A schematic view of the solar-hydrogen system installed at the campus of Pamukkale University in Denizli is shown in Fig. 1.

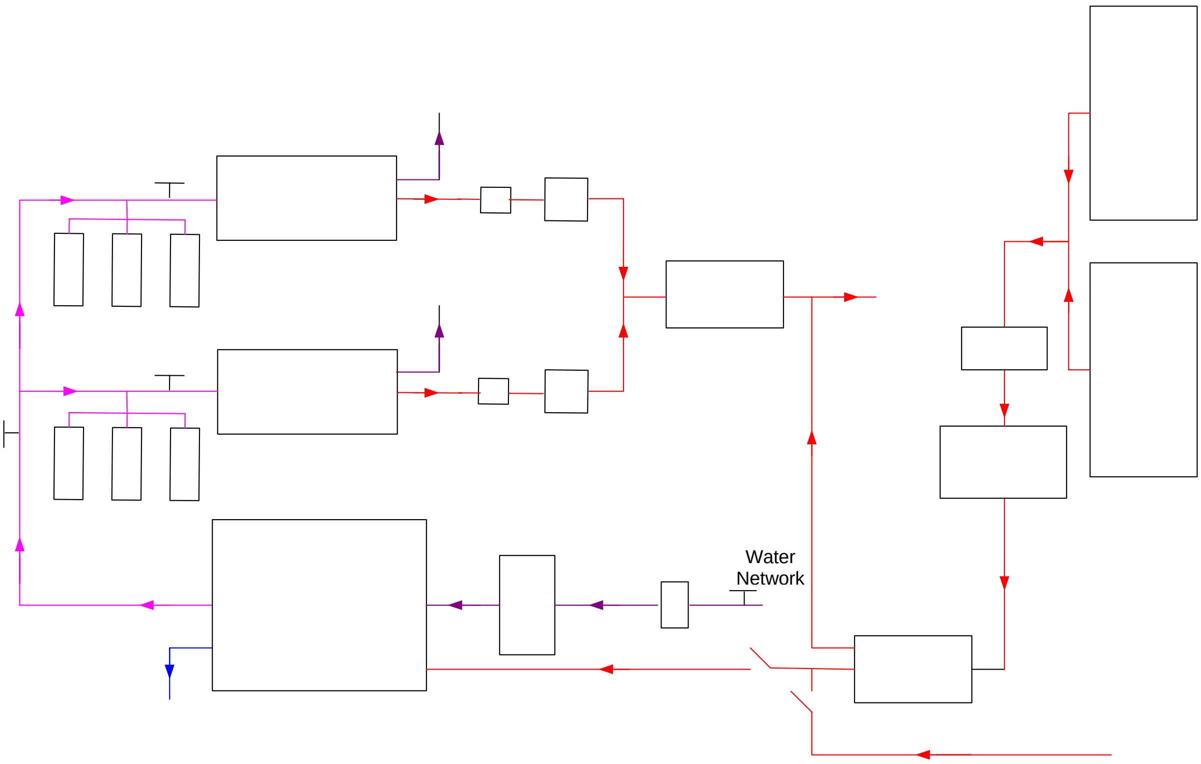

Fig. 1. *A schematic view of the solar-hydrogen system at the campus of Pamukkale University in Denizli.*

Here we will investigate the performance of the PEM fuel cell system, known as the Nexa power module commercially, which was first introduced in 2001. It is the world's first volume produced PEM fuel cell designed for integration into a wide variety of stationary and portable power generation applications. It enables original equipment manufacture products to be used to generate power in an indoor environment not possible with the conventional internal combustion engine generators. The Nexa power module used in this system provides up to 1.2 kW of unregulated DC power at a nominal output voltage of 26 VDC. With the use of an external fuel supply, its operation becomes continuous, limited only by the amount of fuel storage [1]. The Nexa power module can be seen in Fig. 2.

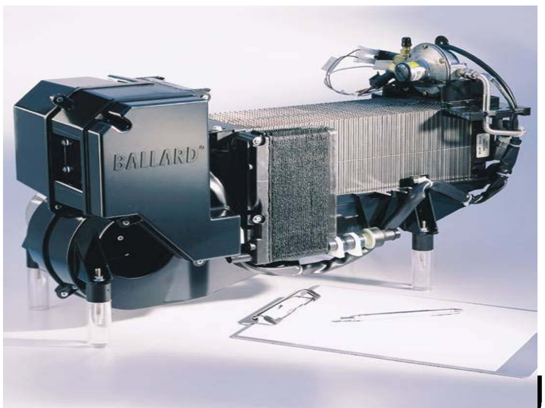

Fig. 2. *The Nexa power module* [1].

The Nexa power module is a fully integrated system that produces unregulated DC power from a supply of hydrogen and air. It contains a Ballard fuel cell stack, as well as all the ancillary equipment necessary for fuel cell operation. Ancillary subsystems include hydrogen delivery, oxidant air supply and cooling air supply. Onboard sensors monitor system performance and the control board and microprocessor fully automate operation. The Nexa system is also equipped with the appropriate safety/control systems for indoor operation.

Fig. 3 illustrates the schematic illustration of the Nexa system. Hydrogen, oxidant air, and cooling air are required for its operation, as shown in Fig. 3. The exhaust air, product water and coolant exhaust are emitted. The Nexa power module produces unregulated DC power for interfacing with external power conditioning equipment. Without going through the electrochemical fuel PEM cell operation, the Nexa fuel cell consists of a stack of multiple thin, fuel cell elements sandwiched together in series to provide the required electrical power. A single fuel cell element produces about 1 volt at open-circuit and about 0.6 volts at full current output. The Nexa fuel cell stack has a total of 47 fuel cells in series. The geometric area of the cell is 120 cm^2. The fuel-cell diagnostic system can monitor the performance of individual fuel cell elements and detect the presence of a poorly performing cell [2]. Main specifications of the fuel cell module are summarized in Table 1.

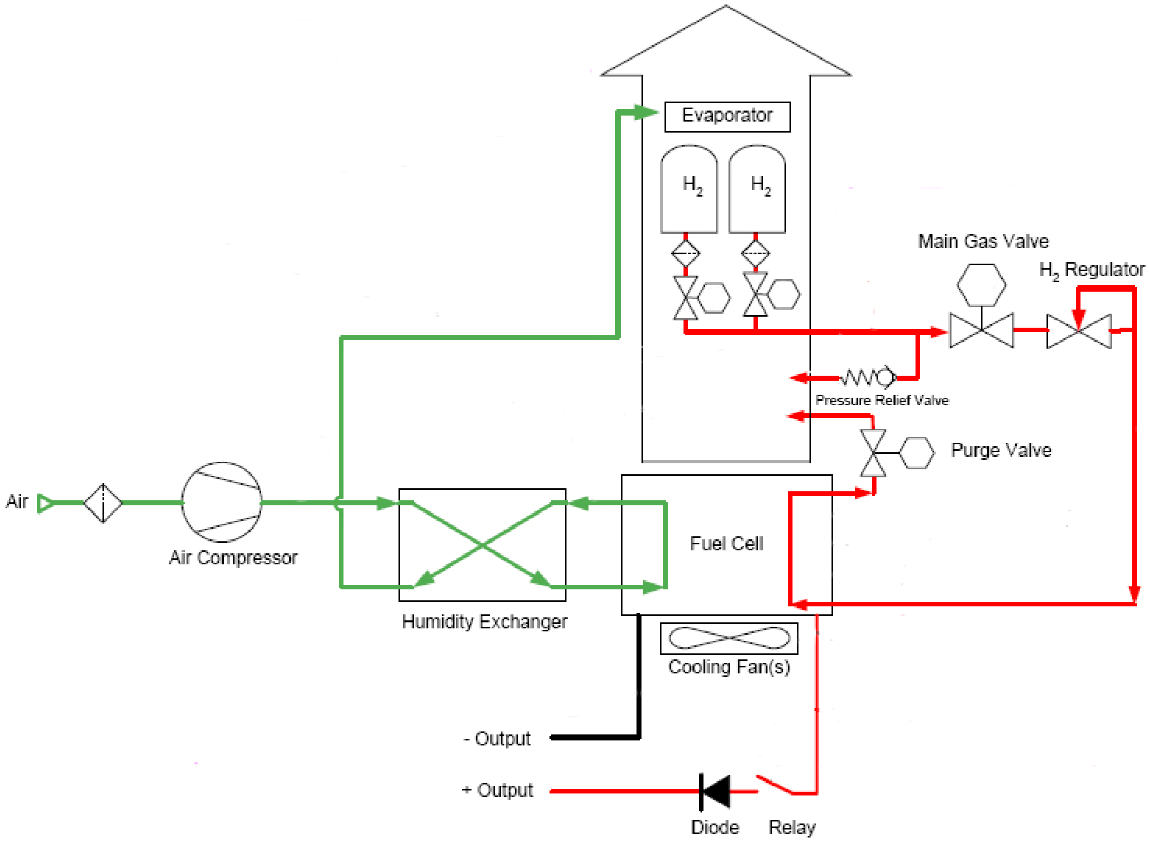

Fig. 3. *Flow diagram of the fuel cell system* [1].

Table 1. *Some Technical Specifications of* ***the*** *Nexa Fuel Cell Module.*

Performance	* Rated net output power * Heat dissipation * Current * Voltage * Lifetime	1200 Watts 1600 Watts (at rated net output) 46 Amps DC (at rated net output) 26 Volts DC (at rated net output) 1500 hours
Fuel	* Gaseous hydrogen * Supply pressure	99.99%, dry 7 to 17.2 bar
Operating Environment	* Ambient temperature * Humidity	3 to 40°C 0% to 95% non-condensing
Emissions	* Pure water (vapor and liquid) * CO, CO_2, NOx, SO_2 particulates * Noise	Maximum 870 ml/h (at rated net output) 0 ppm 72 dBA @ 1 m
Physical	* Dimensions * Weight	56 x 25 x 33 cm 13 kg

Source: Ref. [1].

The Nexa fuel cell system is designed for operation on pure gaseous hydrogen. No fuel humidification is required. Hydrogen can be supplied at pressures ranging from 0.7 to 17 bars (gauge). The pressure regulator continuously replenishes hydrogen, which is consumed in the fuel cell's electrochemical reaction. Nitrogen and product water in the air stream slowly migrates across the fuel cell membranes and gradually accumulates in the hydrogen stream and causes an accumulation of nitrogen and water at the anode, i.e., the negative terminal. These results in the steady decrease in performance of certain "key" fuel cells, which are called "purge cells." In response to the purge-cell voltage, a hydrogen purge valve at the stack outlet is periodically opened to flush out inert constituents at the anode to restore performance. Only a small amount of hydrogen is purged from the fuel cell system, less than one percent of the overall fuel consumption rate. Purged hydrogen is discharged into the cooling airstream before it leaves the Nexa power module. The purged hydrogen quickly diffuses into the cooling airstream and is diluted to levels many times less than the lower hydrogen flammability limit. The hydrogen leak-detector is situated in the cooling exhaust and insures that the flammability limits for hydrogen are not reached. This feature permits safe, indoor operation of the Nexa power module. The lower flammability limit (LFL) of hydrogen is the smallest amount of hydrogen that will support a self-propagating flame when mixed with air and ignited. At concentrations less than the LFL, there is insufficient fuel present to support combustion. The LFL of hydrogen is 4% by volume, respectively.

A small air compressor provides excess oxidant air to the fuel stack in order to sustain the fuel cell electrochemical reaction. An intake filter protects the air compressor and downstream components from particulates in the surrounding air. The compressor speed is controlled to suit the DC current demands of the fuel cell stack. Larger DC currents require more oxidant airflow. A downstream sensor measures the air mass flow rate and fine-tunes the compressor speed for the required DC current output. The oxidant air is humidified before reaching the fuel cell stack to maintain water saturation of the PEM and prolong the lifetime of the fuel cell system. Any drying of the PEM will greatly reduce the life of the fuel cell system. A humidity exchanger transfers both fuel cell product water and heat from the wet cathode outlet to the dry incoming air. (Note that the cathode is the positive terminal.) The excess product water is discharged from the system, as both liquid and vapor in the exhaust.

At high DC current levels, more heat is generated. It is important to keep the fuel cell stack temperature at a constant operating temperature; therefore, the fuel cell stack temperature has to be controlled. Fuel cell systems are either liquid-cooled or air-cooled. Hot liquid or hot air from the cooling system may be used, via a heat exchange system, for thermal integration purposes. The Nexa fuel cell stack is air-cooled. A cooling fan located at the base of the Nexa power module blows air through vertical cooling channels in the fuel cell stack. The fuel cell stack operating temperature is maintained at 65^{o}C by controlling the speed of the cooling fan. The fuel cell stack-temperature is measured at the wet cathode air-exhaust. The cooling system is also used to dilute hydrogen that is purposely purged from the Nexa Power Module during normal operation.

The Nexa Power Module provides automatic provisions to ensure operator safety and prevent equipment damage. A warning or alarm occurs when an unusual or unsafe operating condition occurs, depending on severity. During a warning period, the Nexa Power Module continues to operate and the Fuel Cell Controller attempts to remedy the condition if possible. During an alarm, the Fuel Cell Controller initiates a controlled shutdown sequence. Details on the fuel cell system and its operation are available elsewhere [1].

3 Performance Analysis and Results

Fig. 4 shows the schematic diagram of the fuel cell system for performance analysis. It consists of hydrogen gas supplying canisters, fuel cell module, relay, diode, DC/AC inverter and resistive loads.

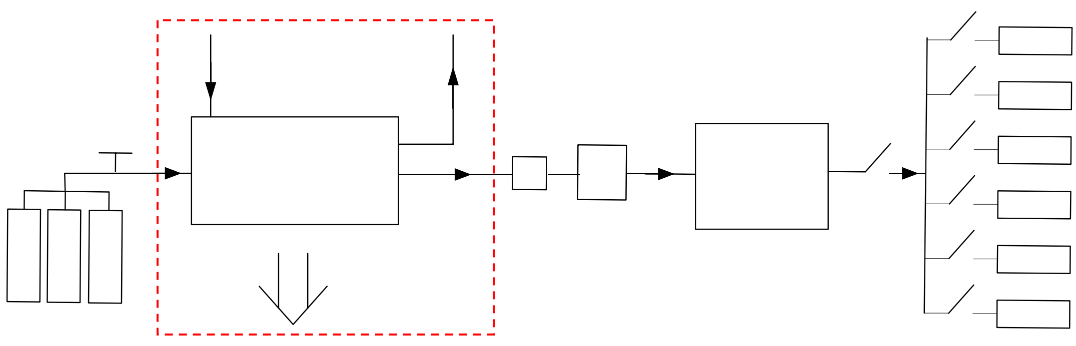

Fig. 4. *Schematic of the Experimental Setup of Fuel Cell Module for Performance Analysis.*

There are three metal hydride canisters in which hydrogen is stored in solid form. Each canister has 80 g, 900 standard liters of H_2 capacity. Hydrogen gas pressure varies 0 to 17 bars (g) in the storage canister. Diode prevents applying reverse potential to the fuel cell stack by a battery or some other DC power module integration. The relay is open when the Nexa module is off or in standby, and it is close when the unit is running. In a basic PEM fuel cell, a chemical reaction occurs between hydrogen and air (or oxygen) as below. Inverter is also used for AC electricity applications and six resistive loads, each 100 W. Load characteristic of the fuel cell module depending on time for an experiment can be seen in Fig. 5. In the experimental setup, the resistive loads are connected to the inverter in order to obtain the performance of the fuel cell module. The distributions of polarization, net power production and gross power for the fuel cell module are represented in Fig. 6, based on the experimental data. In addition to parasitic power inside the fuel cell system, inverter's fan consumes about 175 W for cooling. In Fig. 6, it can be seen that the parasitic power increases depending on current density increase.

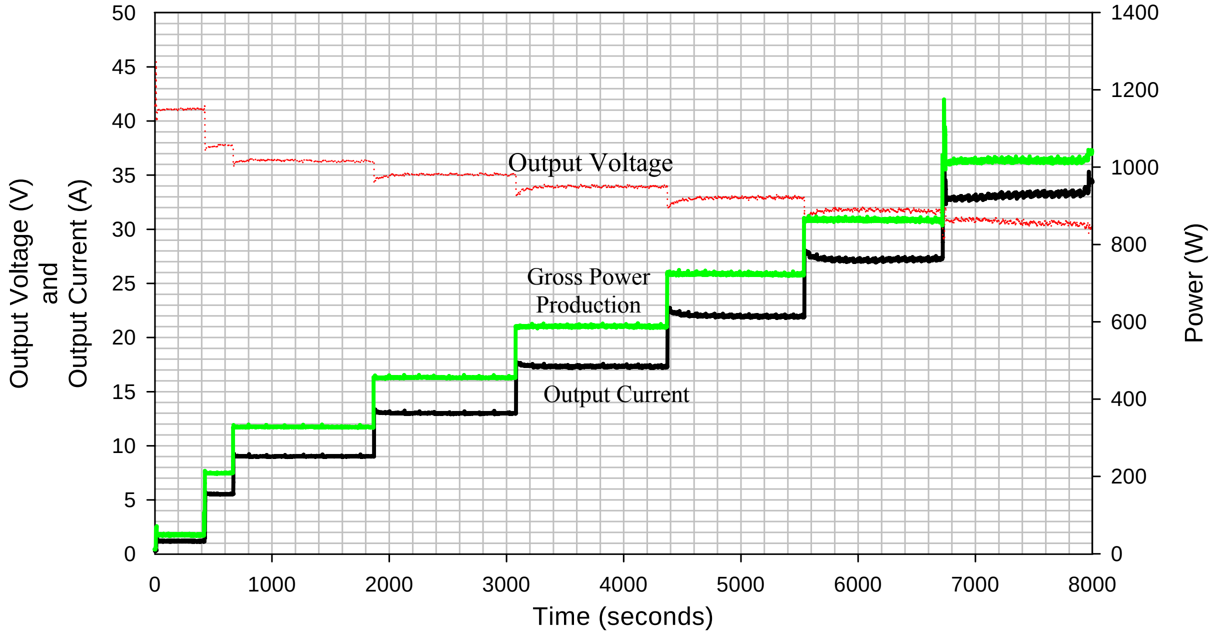

Fig. 5. *Load Characteristics of the Nexa Fuel Cell Module.*

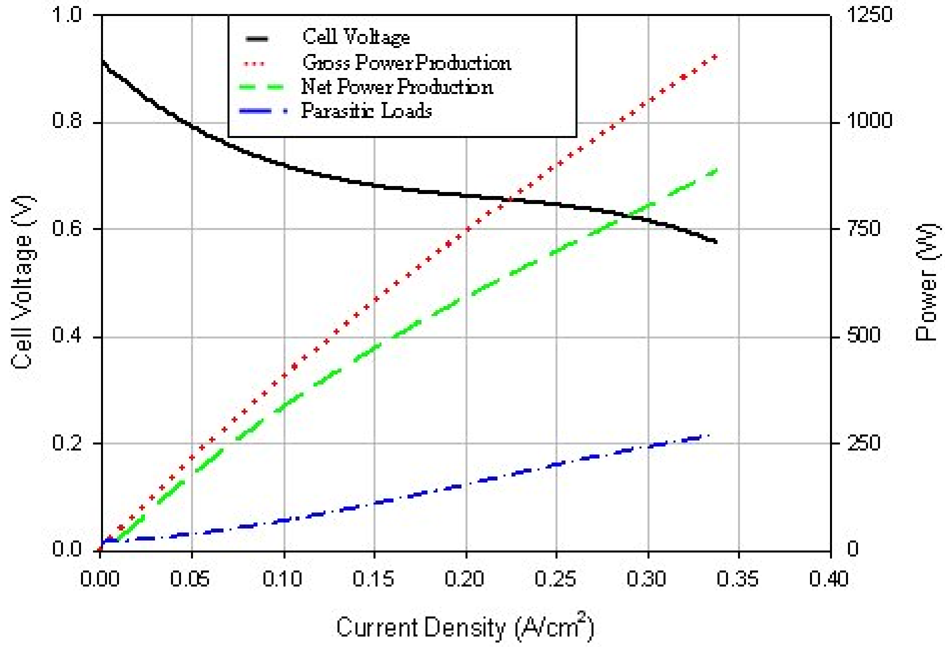

Fig. 6. *Polarization and Power Curves of Fuel Cell Module.*

Hydrogen from metal hydride tanks is pressured at 12.7 bars in initial condition. When hydrogen is consumed by fuel cell system, its pressure decreases as shown in Fig. 7. Hydrogen flow rate increases depending on current density increase. Air is used for oxidant to react hydrogen gas. Fig. 7 also shows the inlet air flow rate. Reactant air flow rate is measured by fuel cell module via its logging feature. The product air flow rates can be calculated through [3]:

$$\dot{m}_{air,out} = 3.57\times10^{-7}\times\lambda\times\frac{\dot{W}_{net}}{V_{cell}} - 8.29\times10^{-8}\times\frac{\dot{W}_{net}}{V_{cell}} \text{ (kg/s)} \tag{1}$$

where λ is stoichiometric air ratio, and its variation is shown in Fig. 8, depending on the experimental current values for the Nexa Fuel Cell Module. At 5.6 A (0.047 A/cm^2), the curve of stoichiometric air ratio decreases slightly because inverter's fan is starting to run. V_{cell}, output voltage per cell, was calculated from experimental output voltage data and number of stack's cells as 47.

The products, water and unused (oxygen depleted air), flow rates vary with current density as Fig. 9. Hydrogen leakage or unused hydrogen gas flow rate was neglected due to its insignificant, small amount. Water production flow rate was obtained from real time data. Unused air flow rate was calculated from Equation 1 above.

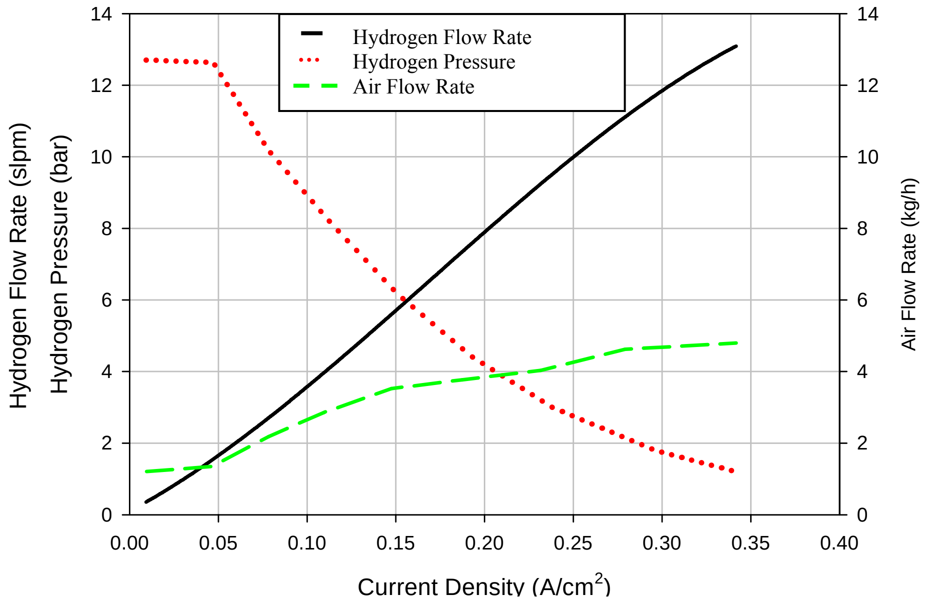

***Fig. 7.** Hydrogen Air Inlet Flow Rates and Pressure Variations of Fuel Cell Module.*

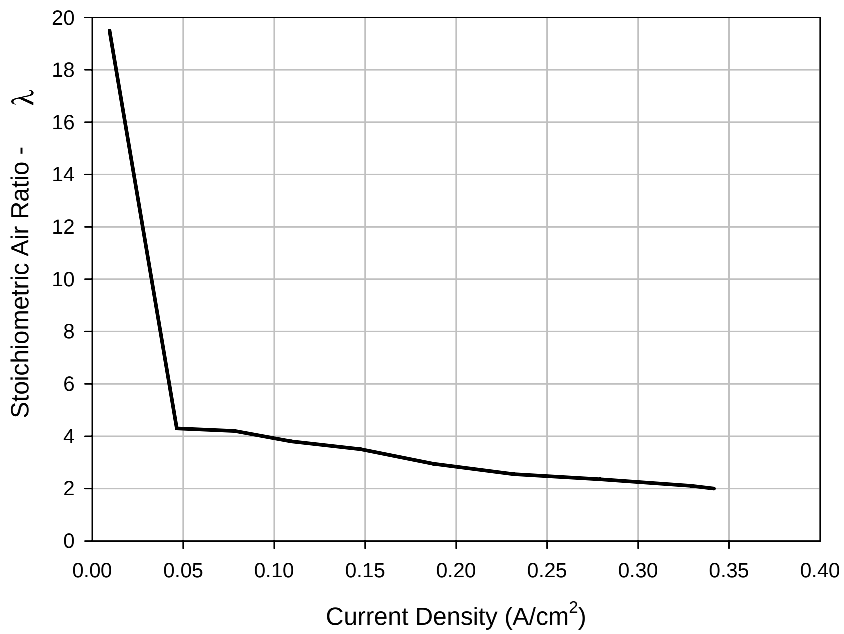

***Fig. 8.** Stoichiometric Air Ratio Curve for Different Loads.*

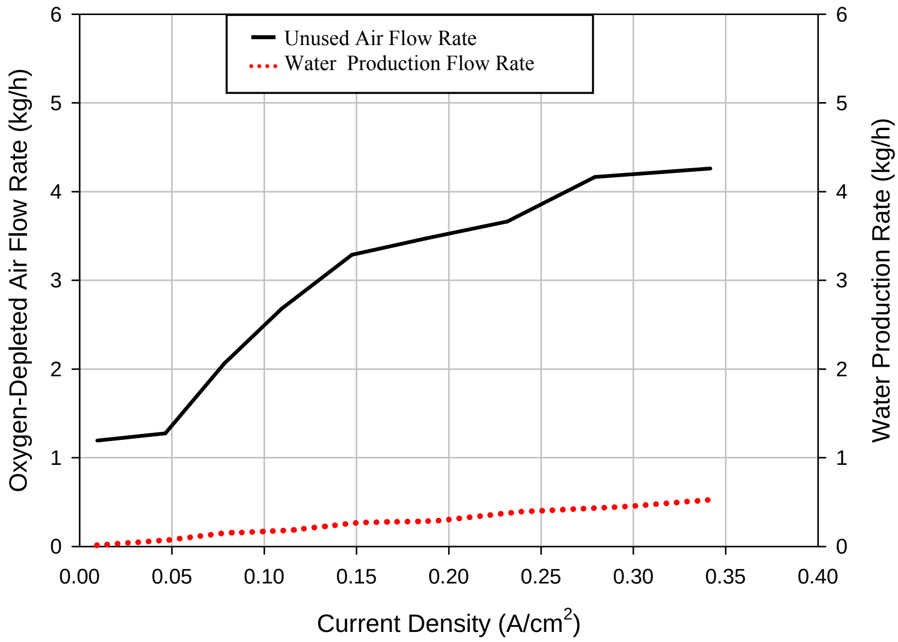

Fig. 9. *Products Flow Rates of the Fuel Cell Module.*

The energy efficiency of the system can be calculated from Equation 2 using the experimental $\dot{W}_{net}$ and $\dot{m}_{H_{2,in}}$ data:

$$\eta_{energy,system} = \frac{\dot{W}_{net}}{(HHV_{H_2} \cdot \dot{m}_{H_2})_{in}} \tag{2}$$

Fig. 10 shows the net power productions and calculated energy efficiencies at different current density values. It can be seen that energy efficiency decreases while net power production increases. At about 5.6 A (0.047 A/cm^2), the inverter starts to give AC electricity. The inverter's fan consumes approximately 175 W same at the whole operating condition. It is assumed to be a load.

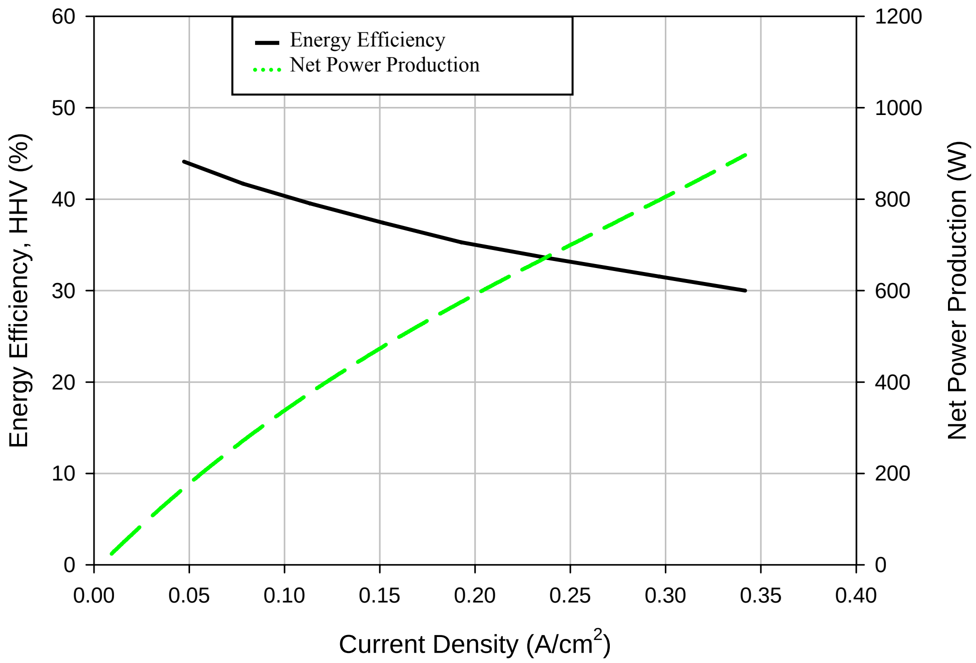

Fig. 10. *Net Power Production and Calculated Energy Efficiency Curves of Fuel Cell Module.*

Here in this section we briefly present an exergy analysis of the PEM fuel cell system. Note that determination of an effective utilization of a PEM fuel cell and measuring its true performance based on thermodynamic laws are considered to be extremely essential. Theoretically, the efficiency of a PEM fuel cell based on the first law of thermodynamics makes no reference to the best possible performance of the fuel cell, and thus, it could be misleading. On the other hand, the second law efficiency or exergetic efficiency of a PEM fuel cell, which is the ratio of the electrical output over the maximum possible work output, could give a true measure of the PEM fuel cell's performance. Energy analysis performed on a system based on the second law of thermodynamics is known as exergy analysis [4]. In the fuel cell module, a basic reaction occurs as below.

H_2 + Air $\longrightarrow$ H_2O + Unused Air (Oxygen-depleted Air) + Electrical Power + Heat

The exergy efficiency of a fuel cell system is the ratio of the power output, over the exergy of the reactants (air + hydrogen), which can be determined by following formula [5, 6]:

$$\eta_{exergy,system} = \frac{\dot{W}_{net}}{\left(\dot{E}_{air} + \dot{E}_{H_2}\right)_{\text{reactant}}} \tag{3}$$

Here, if the potential and kinetic exergies are neglected, the total specific exergy transfer consists of the combination of both physical and chemical exergies as

$$ex = ex_{ph} + ex_{ch} \tag{4}$$

The physical exergy is calculated from:

$$ex_{ph} = \left(h - h_o\right) - T_o\left(s - s_o\right) \tag{5}$$

If reactant gases are assumed as ideal gases, it results in

$$ex_{ph} = c_p\left(T - T_o\right) - T_o\left[c_p \ln\left(\frac{T}{T_o}\right) - R\ln\left(\frac{P}{P_o}\right)\right] \tag{6}$$

The chemical exergy is associated with the departure of the chemical composition of a system from that of the environment. The chemical exergy can be calculated from [e.g., 4, 6, 7]:

$$ex_{ch} = \sum x_n ex_{ch}^n + RT_o \sum x_n \ln x_n \tag{7}$$

For the sake of simplicity, the chemical exergy considered in the analysis is rather a standard chemical exergy that is based on the standard values of the environmental temperature of 298 K and pressure of 1 atm. Generally, these values are in good agreement with the calculated chemical exergy relative to alternative specifications of the environment. The values of the chemical exergies for the reactants are taken from published literature [e.g., 4] as listed Table 2. Hydrogen and air are assumed to supply to the fuel cell module at room temperature, 300 K. Air enters to the module dry and it is heated at the cell operating temperature.

Table 2. *Chemical exergy values of reactants for a fuel cell.*

Reactant	ex_{ch}^n ***(kJ/kg)***
Hydrogen	159138
Air	0

The PEM fuel cell is one of the most promising types of fuel cells. It is considered an excellent device for future power plants, expected to produce clean electricity at high conversion rates, low emissions and low noise levels from the hydrogen. Exergy analysis could be considered as a basis for future works dealing with the thermoeconomic optimization of a fuel cell plant under investigation, with the aim of finding the optimum set of design parameters.

In this study, exergy analysis of the fuel cell system was carried out to evaluate the fuel cell efficiency and following assumptions and values are used for an exergy analysis:

- Flow of reactants is steady, incompressible and laminar.
- All gases are ideal gases.
- Kinetic and potential exergies are neglected.
- Dead state pressure is 1 bar and dead state temperature is 298 K.

Finally, calculated exergy and energy efficiencies are presented in Fig. 11. Energy efficiencies of the module for this experimental setup are between 44% and 30% when exergy efficiencies vary from 38% to 24.5% at the current density of 0.047 to 0.348 respectively. It can be said that energy and exergy efficiency decreases because of reactants' flow rates and hydrogen pressure. Reactants' flow rates increases depending on load increasing. However, hydrogen pressure decreases when output current increases.

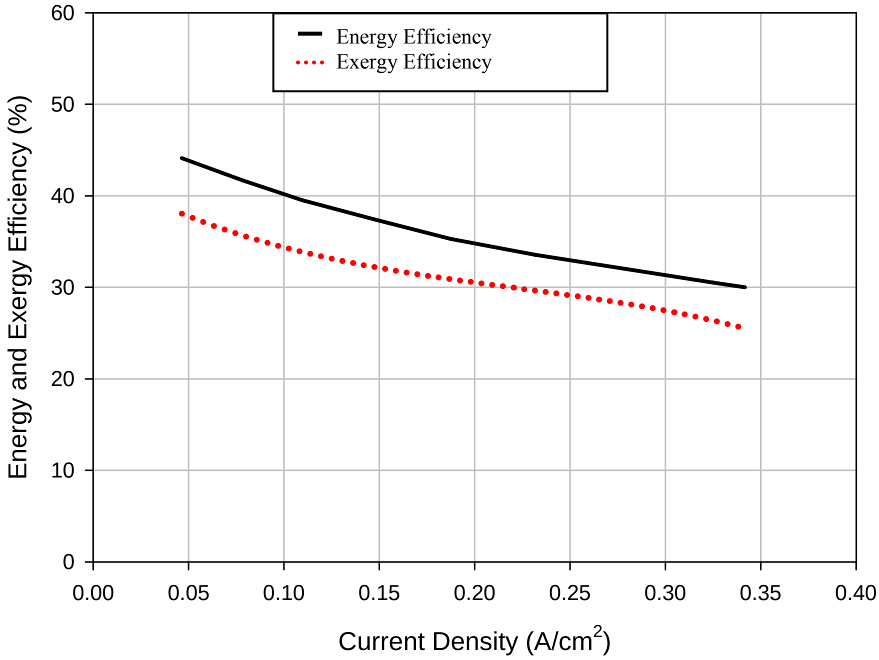

Fig. 11. *Variation of Energy and Exergy Efficiencies of the Fuel Cell Module.*

4 Conclusions

In this paper, we have conducted a brief thermodynamic analysis, in terms of energy and exergy, of a 1.2 kWp Nexa PEM fuel cell system in order to investigate its performance in terms of energy and exergy efficiencies at different operating conditions. The results show that the PEM fuel cell system has some high irreversibilities, exergy destructions, resulting in lesser exergy efficiencies compared to the corresponding energy efficiencies. The future work will concentrate of full-scale exergoeconomic analysis of the system independently and as a part of the solar-hydrogen energy system.

Acknowledgements

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Nomenclature

c_p : Specific Heat Value (kJ/kgK)

$\dot{E}$: Total Exergy Rate (W)

ex_{ch}^{n} : Chemical Exergy at dead state

ex : Total Exergy per mass (W/kg)

h : Enthalpy (kJ/kg)

h_o : Enthalpy at dead state (kJ/kg)

$\dot{m}$: Mass Flow Rate (kg/s)

P : Pressure (bar)
P_o : Dead State Pressure
R : Gas Constant (kJ/kgK)
T : Temperature (K)
T_o : Dead State Temperature (K)
V_{cell} : Cell Voltage (potential) (V)
$\dot{W}_{net}$: Net Power Output (W)
x_n : Mole Fraction (%)
η : Efficiency (%)
λ : Stoichiometric Air Ratio

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