PERFORMANCE ANALYSIS OF A 5 kW PEM TYPE FUEL CELL WITH A NATURAL GAS REFORMER

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Abstract. *This paper analyzes the experimental performance of a 5 kW PEM (Proton Exchange Membrane) type fuel cell. It uses a natural gas reformer for producing hydrogen, which reacts with the feed air oxygen. The electric power generated by the fuel cell is used to feed a 1,3 kW critical load (computer and air conditioning) and a grid connected load in the laboratory. This paper analyzes its performance, comparing to the manufacturer specifications. The cell output power was set to two values, respectively, 2,5 kW and 4 kW. Output power, natural gas flow rate, efficiency and temperature were measured as a function of time, so that performance parameters could be calculated. Its performance is then critically examined.*

Keywords. *Fuel cell, Proton Exchange Membrane (PEM) cell, Natural gas reformer, Catalytic partial oxidation, Steam reformer*

1. Introduction

Mankind has been using petroleum for some time as an energy source in power engines for transportation and for producing electric energy. Presently, in the USA, 80% of the produced electric energy comes from fossil fuel burning, through Rankine cycle engines (steam turbine) and Brayton cycle engines (gas turbine). Due to several factors, like natural resource shortage and environment pollution, there has been recently a search for new energy sources, mainly the renewable ones.

Fuel cells have been investigated for potentially producing electric energy at high efficiencies and low environment pullution, using hydrogen and oxygen in a catalytic partial oxidation chemical reaction. One of the first cells to be developed was the solid oxide one in 1937. Alkaline and Molten carbonate cells followed in 1946. Then , solid polymer in 1960 and direct methanol cells were the next ones. The only commercially available cell today is the phosphoric acid one , sold for roughly US$ 5000/kW for the 200 kW size, and was developed in 1967. However, the more recently developed Proton Exchange Membrane (PEM) is simpler and more compact than other types (Hogens, 2003), having a good potential of being used in vehicles.

Low power fuel cells, about 5 kW to 10 kW, are being developed for residential type applications, and are not economically feasible today. Most of them do not have a reformer and produce electric energy directly from hydrogen, which is expensive. Thus, a great effort has been put on developing a natural gas reformer in order to increase its efficiency and the hydrogen production capacity, and to reduce the operating cost.

This paper presents the performance analysis of a 5 kW PEM type fuel cell prototype, manufactured by Plug Power in USA. Natural gas is fed to the unit, so that hydrogen can be produced in the reformer. The potential of using cogeneration is analyzed. It is in the semi-commercial stage, being presently tested by three more countries in the world, that is, Germany, Japan and Brazil.

2. Operating principle of a fuel cell

In a fuel cell, an inverse electrolysis process occurs. Hydrogen is fed to the anode, and oxygen, to the cathode. Fig. (1) presents the basic components of a fuel cell. It is frequently described as a continuous operation battery or an electrochemical device (Angelle & Simon, 2002, Dietrich, 2001; Cook, 2001).

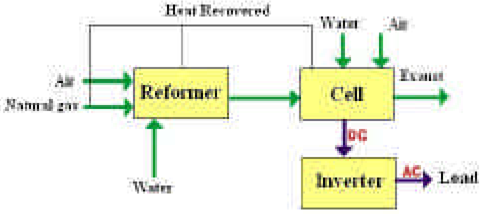

Figure 1 : Fuel cell basic components

The fuel cell is composed of (a) a reformer, where hydrogen is produced from natural gas, (b) a fuel cell, known as battery, where electricity is generated, and, (c) an inverter, where the DC current is converted into AC current. The reformer uses water for reforming the natural gas. The battery produces and uses water for humidifying the electrolyte.

In the fuel cell, hydrogen is combined with the feed air oxygen in a catalytic chemical reaction, to produce continuously water and electric energy, as long as there is a continuous supply of hydrogen and oxygen (Dietrich, 2001; Cook, 2001; Hirschenhofer et all, 1998). In conventional batteries, the fuel and the oxidizer must be periodically supplied to it, by inverting the chemical reaction in a process known as charging the battery.

The fuel processor includes a desulfurizer bed, a catalitic partial oxidizer, two high temperature shift converters, one low temperature shift converter and one preferential oxidizer (to burn remaining CO to CO_2).

Although there are several types of fuel cells, all of them work under the same principle. A basic unit is composed of one anode and one cathode, which are separated by an electrolyte, which, for the PEM cell, is a solid membrane. Hydrogen is fed to the anode , where it is ionized, releasing electrons, Eq. (1). These ions are directed through the electrolyte to the cathode, where oxygen from air is fed to. The electrons move towards an external circuit, thus forming a DC current, returning to the cathode, where they are combined with the oxygen, which is ionized, Eq. (2). Hydrogen and oxygen ions are then combined, forming water, Fig. (2), and releasing heat to the atmosphere, which can be small, depending on the operating conditions (Cook, 2001; Hirschenhofer et all, 1998; Onsite, 2000; Resource Dynamics Corporation, 1999; Holcomb, 1999). Fuel cells use catalysts to promote the chemical reaction.

Thus, due to practical construction considerations of the fuel cell, heat will be always released, and the cogeneration can increase the usage of the fuel available energy. Research has been conducted to reduce the amount of released heat, and thus increasing the amount of produced electric energy. In internal combustion engines, the second law of thermodynamics limits the amount of heat that can be converted into work. Thus, potencially, fuel cells can be much more efficient than heat engines.

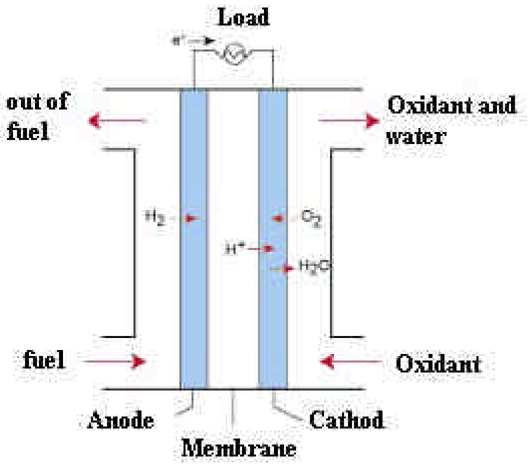

Figure 2. Operating principle of a fuel cell

3. Theoretical considerations of the PEM type fuel cell

Following (Angelle & Simon, 2002), Eq. (1) describes the anode reaction; Eq. (2) describes the cathode reaction; and, Eq. (3) describes the formation of water. Considering one kmol of hydrogen, the following equations can be written, together with all parameter calculation.

$$H_{2(g)} \rightarrow 2H^+ + 2e^- \tag{1}$$

$$2e^- + \frac{1}{2}O_{2(g)} \rightarrow O^{2-} \tag{2}$$

$$2H^+ + O^{2-} \rightarrow H_2O_{(liquid)} \tag{3}$$

Following (Angelle & Simon, 2002; Khartchenko, 1998), the overall chemical reaction can be written as :

$$H_{2(g)} + \frac{1}{2}O_{2(g)} \rightarrow H_2O_{(liquid)} \tag{4}$$

In Eq. (4), considering, as a reference state, that hydrogen, oxygen and water are each one at 0,1 MPa and 25 °C, (Angelle e Simon, 2002; Van Wylen et allii, 1995; Khartchenko, 1998), calculate the Gibbs Free Energy variation of the reaction (? G = -237141 kJ) and the enthalpy variation of the reaction (? H= -285830 kJ).

According to the second law of thermodynamics, the reversible work between the two states in Eq. (4), neglecting kinetic and potential energy variation, can be written as :

$$W^{rev} = \Delta G = \Delta H - T\Delta S \tag{5}$$

The theoretical efficiency of the PEM type fuel cell can be defined (Angelle & Simon, 2002; Khartchenko, 1998) as the ratio between the reversible work and the enthalpy variation :

$$h_{TFC} = \frac{\Delta G}{\Delta H} \tag{6}$$

Considering liquid water in Eq. (4), (Angelle & Simon, 2002; Khartchenko, 1998) calculate the maximum thermal efficiency of the fuel cell at reference conditions as 83%.

The Gibbs Free Energy variation can also be used to calculate the reversible voltage,E_{rev} , (Angelle & Simon, 2002; Van Wylen et allii, 1995; Khartchenko, 1998) :

$$E_{rev} = -\frac{\Delta G}{jF} \tag{7}$$

where j=2 is the number of electrons in Eq. (1), the Faraday constant F=96485 C/mol of electrons.

The reversible voltage, considering liquid water in Eq. (4), is 1,229 V(Angelle & Simon, 2002; Van Wylen et all, 1995; Khartchenko, 1998).

Considering that hydrogen, oxygen and water are not at the reference state, the reversible voltage E_{Trev} of an electrochemical reaction can be expressed by the Nenrst equation , (Van Wylen et allii, 1995; Virginia Tech , 2002).

$$E_{Trev} = E_{rev} - \frac{\overline{R}T}{jF}\ln Q \tag{8}$$

where $\overline{R}$ is the universal gas constant, 8,3145 kJ/kmol-K

T is temperature (K),

Q is the activity coefficient.

E_{rev} is a function of temperature and pressure, as in Eq. (7). Therefore, Eq. (8) can be written as :

$$E_{Trev} = E_{rev} - \frac{\overline{R}T}{jF}\ln\left[\frac{a_{H_2O}^{\upsilon_{H_2O}}}{a_{H_2}^{\upsilon_{H_2}}\, a_{O_2}^{\upsilon_{O_2}}}\right] \tag{9}$$

where a_{H2O}, a_{H2} e a_{O2} are water, hydrogen and oxygen activities, respectively, v_{H2O}, v_{H2} e v_{O2} are stoichiometric coefficient in Eq. (4).

Assuming the ideal gas model, and that the liquid water activity is equal to one, the following equation can be written for the activity a_i of an ideal gas i :

$$a_i = \frac{x_i p}{p_0} \tag{10}$$

where p is the mixture total pressure,

p_0 is the reference pressure,

x_i is the component i molar fraction.

When both hydrogen and dry air are at 0,1 MPa and 25 ^{o}C, the following theoretical reversible voltage can be calculated from Eq. (9) and (10) :

$$E_{Trev} = 1{,}229 - \frac{8{,}3145 \times 298{,}15}{2 \times 96485}\ln\left[\frac{1}{1 \times \sqrt{0{,}210}}\right] = 1{,}219\text{V} \tag{11}$$

The cell voltage is also limited by the reaction kinetics. The cell delivers electric energy only when it is demanded; however, the operating voltage is lower than the zero load voltage due to several loss mechanisms. They are frequently called *overpotential* , being defined as the deviation from the theoretical potential (Khartchenko, 1998). The potential drop can be better understood from the performance curve or Tafel graph (Angelle & Simon, 2002). It represents the cell voltage as a function of the current density, which is the number of electrons that flows per second through the circuit, or current per unit area. It also shows the way the reaction proceeds towards its final state, and is shown in Fig. (3).

According to (Angelle & Simon, 2002; Karl, Khartchenko, 1998), three sources of losses are responsible for the cell voltage drop, which are known as (a) *Ohmic polarization* or *Ohmic loss,* (b) *Activation polarization,* and (c) *Concentration polarization.*

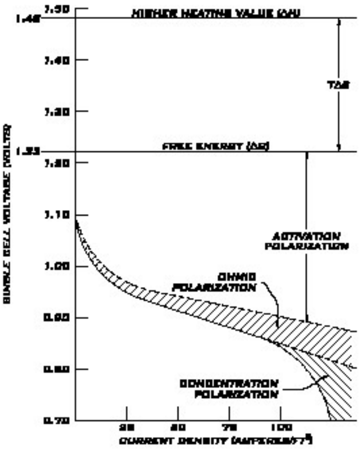

Figure 3. A fuel cell typical performance curve (Angelle & Simon, 2002).

- *Ohmic polarization* (E_R) – Its due to the resistance of the conductor material to the electron flow, and thus current. The manufacturers have been able to reduce its effect by using higher conductivity materials for the electrolyte, electrodes and cell electric circuit conections.
- *Activation polarization* (E_{act}) – When the load is applied to the cell, a reaction lag results in a resistance to flow in the electrode-electrolyte interface.
- *Concentration polarization* (E_{conc}) – In high current densities, the inability of the rectants to diffuse rapidily through the electrodes causes a voltage drop.

The actual fuel cell voltage E_{real} is therefore lower than the theoretical reversible value E_{Trev} , being expressed by the following equation :

$$\mathrm{E_{real} = E_{Trev} - (E_{act,a} + E_{act,c} + E_{conc,a} + E_{conc,c} + E_R) = E_{Trev} - \sum \Delta E} \tag{12}$$

where subscripts *a* and *c* refer, respectively, to anode and cathode, $E_R = i\mathrm{R}$, the *ohmic polarization,* is the product between the current and the ohmic resistance, $\sum ?E$ is the summation of all overpotentials.

The actual fuel cell thermal efficiency ($?_T$) , (Angelle & Simon, 2002; Khartchenko, 1998; Energy Nexus Group, 2002; Pulgar, 2002), can be calculated by the ratio between the output electric energy and the input fuel energy. Considering Eq. (1), the following expression can be written :

$$\eta_{\mathrm{T}} = \frac{(2\mathrm{FV_{exit}})}{\mathrm{HHV_{H_2}}} \tag{13}$$

where F is the Faraday constant,

$\mathrm{HHV_{H2}}$= 285830 kJ/kmol of H_2 is the high heating value of hydrogen,

$\mathrm{V_{exit}}$ is the output cell voltage. Substituting the values,

$$\eta_{\mathrm{T}} = \frac{\mathrm{V_{exit}}}{1{,}481} \tag{14}$$

Equation (14) takes into account all the losses due to overpotentials and the operating conditions, when operates with pure hydrogen. Another way of defining thermal efficiency is by multiplying the ratio between output cell voltage ($\mathrm{V_{exit}}$) and the theoretical reversible voltage (E_{Trev}), and the theoretical thermal efficiency ($?_{\mathrm{TFC}}$), Eq. (6).

$$\eta_T = \left(\frac{V_{exit}}{E_{Trev}} \right) \eta_{TFC} \tag{15}$$

Since the actual fuel cell thermal efficiency has been calculated, the heat rejected to the atmosphere (Q_{rej}) can be calculated, (Angelle & Simon, 2002; Khartchenko, 1998; Energy Nexus Group, 2002), as :

$$Q_{rej} = m_{H_2,u} HHV_{H_2} (1 - \eta_T) \tag{16}$$

where $m_{H_2,u}$ is the amount of hydrogen consumed by the fuel cell.

The heat rejected to the atmosphere (Q_{rej}) is also the maximum energy that can be used for cogeneration.

In distributed electric energy generation applications, one of the most feasible ways to feed the fuel cell is by means of natural gas (Angelle & Simon, 2002; ONSITE, 2000; Resource Dynamics Corporation, 1999; Energy Nexus Group, 2002). Its requires the use of fuel processor or a reformer, which converts catalytically natural gas or other fossil fuels into a hydrogen rich gaseous fuel (Energy Nexus Group, 2002). Considering, as a reference, water at the vapor state, typical reformer efficiency ranges from 75 % to 90 %, (Energy Nexus Group, 2002). The reformer efficiency ($?_R$) is defined by the ratio between the produced hydrogen chemical energy and the available natural gas chemical energy, as consumed in the reformer.

Three types of reformer are available, according to (Energy Nexus Group, 2002; Pulgar et allii, 2002).

- *Steam reformer (SR)* – uses steam. Requires a large amount of input heat to the process, because of the highly endothermal reforming reaction.
- *Partial oxidation reformer (PO)* – uses gaseous oxygen or air. Burns part of the fuel, releasing heat to the reforming process.
- *Autothermal reformer* – uses both steam and oxygen (or air). Operates about the *thermal neutral point*,not requiring or releasing heat to the reforming process.

Finally, the thermal efficiency (LHV) of a fuel cell ($?_T$), including the reformer efficiency ($?_R$), can be expressed as :

$$h_T = \left[h_R \times \left(\frac{m_{H_2,u}}{m_{H_2,R}} \right) \times \left(\frac{V_{exit}}{E_{Trev}} \right) \times h_{CE} \right] \tag{17}$$

where, $m_{H_2,R}$ is amount of hydrogen generated in the reforming process.

$?_{CE}$ is the conversion efficiency between DC power and AC power including auxiliary loads.

4. Results

A 5 kW PEM type fuel cell, manufactured by Plug Power, serial number 167, was tested in this research and shown in Fig. (8). The model is totally instrumented. It has temperature, pressure, voltage and current sensors, so that data are acquired every second, and stored in a computer, and available in a graph form over a 24 h period.

When starting its operation, the fuel cell does several operations, before generating electric energy. First of all, a gas cleaning procedure inside the reformer unit is done, through blowers. Due to the fact that the cell is grid connected, the utility company supplies energy to the start up process. In this research, the output power was set to 2,5 kW and 4,0 kW. The reformer then operates for about 1:30 h, before reaching the steady state condition. Then the fuel starts generating electric energy at 2,5 kW, as in Fig. (4), as long as the CO concentration in the reformer gas gets lower, which is the principal reason for delaying electric energy production.

The power was set to 2,5 kW for about 100 min. Then it was set to 4,0 kW. According to Fig. (5), the natural gas flow rate (standard liter per minute – slm) increases until the selected power is reached.

Figure (6) shows the maximum, minimum and average voltage generated by each of the 86 cell units, which provides DC current. For the 2,5 kW generation, the average voltage was 0,7 V per unit. For 4,0 kW, 0,65 V per unit, approximately.

The fuel cell efficiency (LHV) as a function of time is shown in Fig. (7). It increases from 23,2% to 27,6% until reaching 2,5 kW. When the power is set to 4,0 kW, the average efficiency decreases to 25,3%, which matches the manufacturer's value.

The fuel cell waste heat availability can be estimated from the measured data, at 4 kW cell output AC power, for evaluating its cogeneration potential. The fuel cell thermal efficiency (HHV) can be calculated from Eq. (14), using the measured output cell voltage V_{exit} = 0,65 V, resulting in h_T = 0,44, for pure hydrogen. From Fig.(10), the overall DC output stack power (composed of 86 elements) is approximately 5,4 kW. Thus, the input hydrogen high heating value per unit time is 5,4/0,44 = 12,3 kW. Subtracting from this value the fuel cell output power, it can be found that 12,3 – 5,4 = 6,9 kW is the waste heat availability (liquid water in the exhaust) to be used in the cogeneration process.

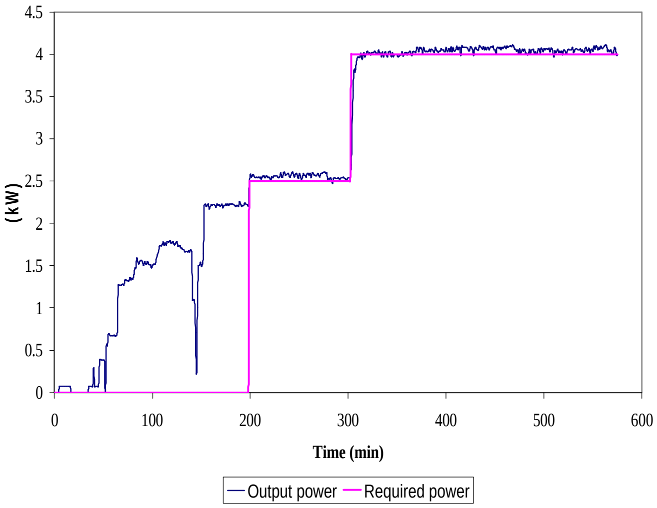

Figure 4 . Fuel cell power supply

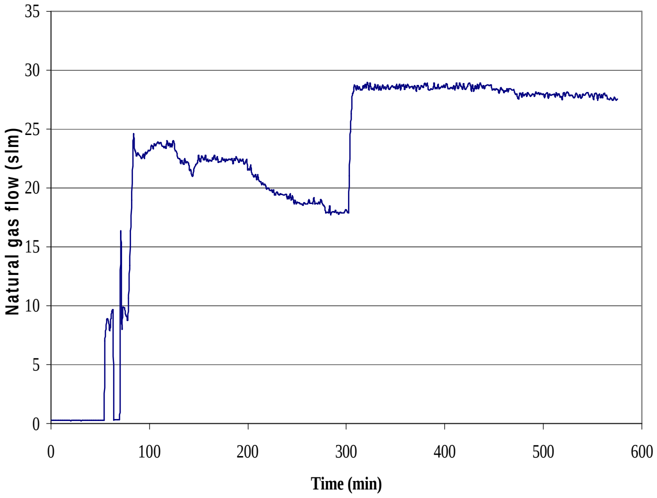

Figure 5. Fuel cell natural gas consumption

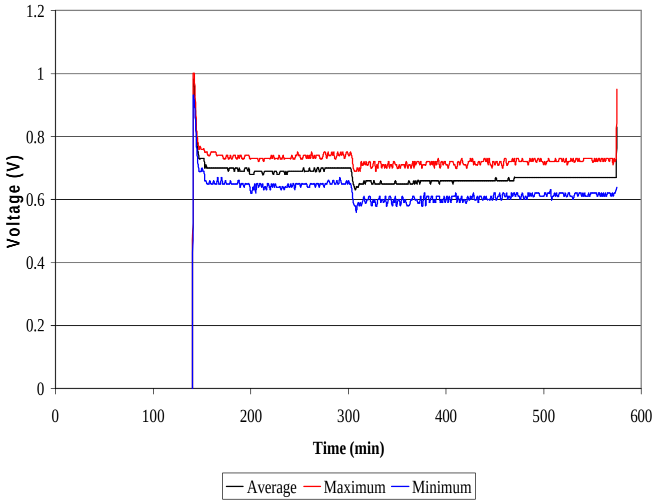

Figure 6. Maximum, minimum and average fuel cell voltage

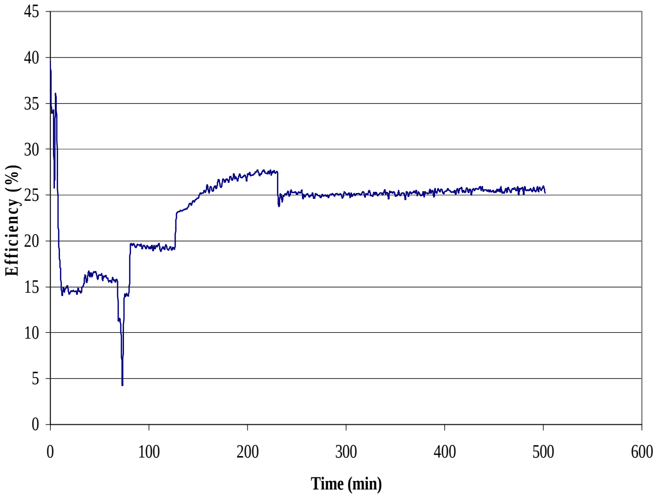

Figure 7. Fuel cell efficiency (LHV)

Figure 8. The 5 kW PEM type fuel cell at PUC-Rio

The natural gas composition during the fuel cell test, on March 12, 2003, was measured by CEG, the Gas Utility Company, as indicated in Table 1. Fig. (9) shows the cell specific fuel consumption as a function of time. It can be seen that it reaches a value of 0,42 Nm^3/kWh at 4 kW, under steady state condition. Fig. (10), also at 4 kW, shows the DC output stack power, the AC output cell power and the inverter efficiency as a function of time, showing that, under steady state conditions, a 75% inverter efficiency value can be reached. The auxiliary load, like pumps, batteries and fan, is DC energy supplied, before being inverted into AC.

Table 1. Natural gas composition on March 12,2003

CO_2	C_2H_6	N_2	CH_4	C_3H_8	IC_4	NC_4	IC_5	NC_5	$+C_6$
0,3720	7,3310	0,6150	90,4230	1,2380	0,0060	0,0100	0,0020	0,0020	0,0030
HHV = 39515 kJ/Nm^3 LHV = 35688 kJ/Nm^3 Specific gravity = 0,6082 Density = 0,7336 kg/Nm^3 Values at 20 °C and 1 atm									

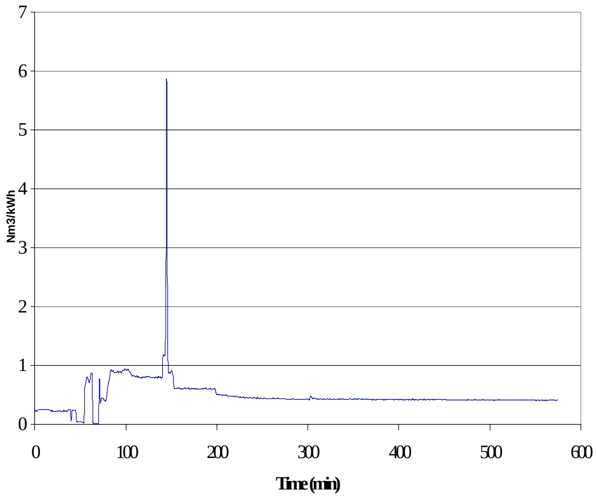

Figure 9. Cell specific fuel consumption (Nm^3/kWh)

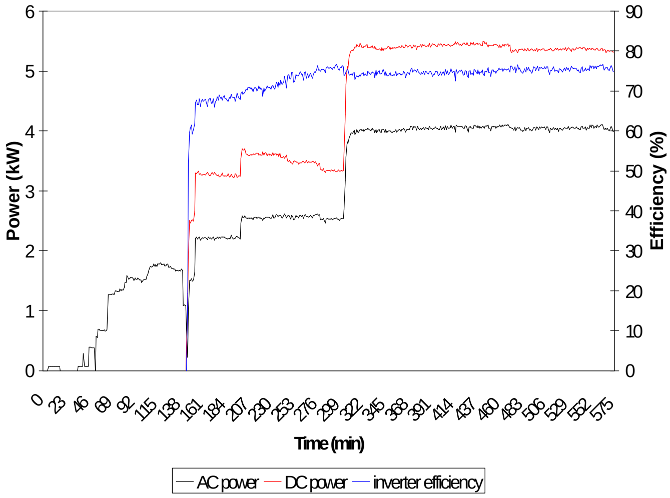

Figure 10. DC and AC power and efficiency of inverter.

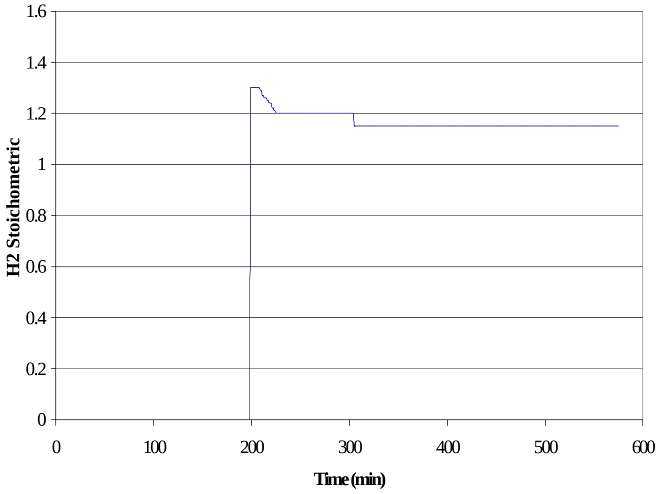

Figure 11. Ratio between hydrogen mass produced by the reformer and consumed by the fuel cell.

A Fig.(11) shows that the ratio between hydrogen mass produced by the reformer and consumed by the fuel cell can reach 1,2 for 2,5 kW and 1,15 for 4 kW. The reformer efficiency h_R =0,73 at 4 kW, can be calculated from Eq. (17), and measured values of $m_{H_2,R} / m_{H_2,u}$ =1,15, V_{exit} = 0,65 V, E_{Trev} = 1,219 V, h_{CE} =0,75, and h_T = 0,253 (from Fig.(7), natural gas). It can be seen that it is slightly outside the 75% to 90% range, as mentioned by (Energy Nexus Group, 2002).

5. Conclusions

The fuel cell which was tested in this research with natural gas has a low efficiency, matching the manufacturer data and it is hoped that in the near future it increases substantially. Fuel cell efficiency with hydrogen, reformer efficiency and output voltage, were measured and calculated, matching the ranges as indicated by the literature. The fuel cell waste heat availability was estimated for cogeneration purposes, aiming to increase fuel chemical energy usage, and thus the overall efficiency of the process.

Considering a natural gas cost of R$ 0,36 per Nm^3, a power output of 4,0 kW, and a specific fuel consumption of 0,42 Nm^3/kWh, the cost of the produced energy is R$ 0,15 per kWh.

6. Aknowledgements

The authors are indebted to LIGHT/ANEEL for having financially supported this research. Also, The authors would like to thank Evêmero Callegari for his assistance in assembling the fuel cell and taking the data.

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