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Operational characteristics of proton exchange membrane (PEM) fuel cells

Abstract. *The article presents a study conducted on a fuel cell stack PEM type (Proton Exchange Membrane) with a capacity of 300W. The dynamics of the work of the stack has been shown, electrical efficiency of a stack has been stated. There have also been stated an external characteristics and the power curve of the stack. The impact of the coefficient of excess air on the work of the stack has been examined..*

Streszczenie. *W artykule przedstawiono badania przeprowadzone na stosie ogniw paliwowych typu PEM (ang Proton Exchange Membrane) o mocy znamionowej 300W. Pokazano dynamikę pracy stosu, wyznaczono sprawność elektryczną stosu. Wyznaczono charakterystykę zewnętrzną oraz krzywa mocy stosu. Zbadano wpływ współczynnika nadmiaru powietrza na prace stosu. (**Charakterystyka zewnętrzna ogniwa paliwowego typu PEM**)*

Keywords: fuel cell, the external characteristics of the stack, electrical efficiency, hydrogen
Słowa kluczowe: Ogniwo paliwowe, charakterystyka zewnętrzna stosu, sprawność elektryczna, wodór.

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Introduction

Fuel cells are electric – chemical devices where direct transformation of chemical energy into electric one takes place. This way of transforming one kind of energy into the other is an essential advantage of fuel cells because it gives an opportunity of reaching high efficiency of energy conversion process which is not limited by Carnot's cycle efficiency. The following advantages of fuel cells can be listed: high efficiency, very low greenhouse gas emission, low level of noise, modular structure, ability to work with low loads, ability of reverse working, very good regulation abilities. The major disadvantage is a very high cost of single fuel cells whose electrodes must be covered with platinum in order to fulfil their function of producing electric energy. Big financial expenditures are spent all over the world on research and development of cells. It let us think that in the future these sources will be widely used in distributed generation units or generative objects, joined directly to distributive nets or located in electro – energetic net of a receiver).

The rule of working on the example of PEM fuel cell

In Fig. 1 the rule of working of PEM (Proton Exchange Membrane) fuel cell has been presented.

Fuel is supplied in a constant way to anode whereas oxidant is supplied to cathode. The electrolyte in PEM fuel cell is a polymer membrane which conducts protons. An anode is a catalyst for hydrogen dissociation into protons (ions H+) and electrons. Ions H+ go through polymer membrane which conducts protons and is an insulator for electrons. Electrons go through external circuit, creating external current of a cell. On a cathode, protons and electrons go into the reaction with oxygen, producing water which is the only side effect of PEM fuel cell.

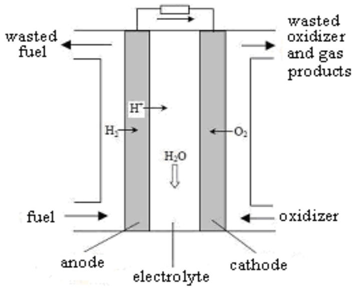

Fig.1. The rule of working of PEM fuel cell [2]

Below there are presented chemical reactions which occur on cathode and electrode and also a total reaction:

- the reaction on an anode: $2H_2 \rightarrow 4H^+ + 4e^-$,
- the reaction on a cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$,
- total reaction: $2H_2 + O_2 \rightarrow 2H_2O$.

A single cell has voltage below 1 V, that is why a lot of single cells join creating so called piles. A pile consists of single elements where each element includes an anode, cathode and ion exchange membrane.

The external characteristics of a fuel cell

The diagram presented in Fig. 2 has been divided into three areas. Three kinds of losses can be distinguished: loss of activation, losses connected with the decrease of pressure due to inner resistance of a cell and weight losses. The decrease of pressure in area I is the result of so called activation losses. These are the losses of the energy which is needed to allow the load to overcome the electrical layer which came into existence on the line of electrode and electrolyte.

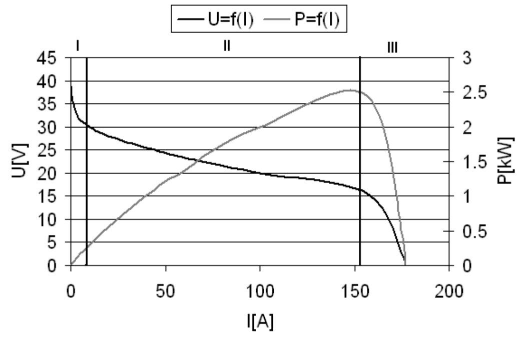

Fig.2. The external characteristics and power curve of a fuel cell

In the area II the voltage decreases linearly with the increase of current intensity. This is the area of ohm losses caused by the inner resistance of a cell i.e. resistance of electrodes and electrolyte. In order not to allow big losses of power, the resistance of electrolyte should be possibly small.

The area III with the highest values of power intensity is called the area of mass transport losses. These losses occur when gases in the contact with catalyst and electrode are used up faster than they can reach them. The consequence of this phenomenon is a sudden decrease of voltage.

PEM fuel cells – operation optimization and load change response

For the application of PEM fuel cells a virtual power plant of several fuel cells (and other types of power plants) is favorable for the operation due to two main reasons. PEM fuel cells are capable of bearing quick load shifts. However, a change in the supply of the reactant gases is slow. Load shifts may result in short time spans with over- or undersupply of the reactants and therefore reducing the lifetime of a fuel cell [3].

Generally, a fuel cell with modest load changes and constant operation parameters will have a higher lifetime, so one reason for virtual power plants is the possibility of splitting the load over several fuel cells so that each fuel cell can run at optimal operation parameters. The second reason is the distribution of the fuel cell plants will help to generate the energy locally where it is needed, which will reduce transfer losses. Moreover, the generated heat of the fuel cell systems can be used for district heating.

A virtual power plant has various other advantages [4, 5], nonetheless it requires a smart grid for communication between the subsystems and possibly a central power plant control (fig. 3). The communication is important to synchronize the decentralized subsystems not only to deal with load change response, but also to transfer status and security information. The market price can also have an influence on the production of a virtual power plant. Additionally it is possible to include the information of weather forecasts or other grid operators to predict the generation of wind and solar so load changes can be prepared in advance. As fuel cells need time to start up this advantage is crucial for the operation management.

For the start process, fuel cell systems based on reformat gas require up to two hours to heat up the reformer. Systems based on pure hydrogen only require a view minutes to start up, but should not run on full load until the system temperature is stabilized at the nominal operation temperature (50-70°C for PEM fuel cells).

The heat production of the stacks is enough to heat up the system and excess heat needs to be dissipated to keep the stack temperature stable.

Besides the reactant and thermal operation of a fuel cell system, the electrical operation is rather simple. A fuel cell behaves like a direct current source while the voltage is dependent on the load current and the quality of the fuel cell including aging. The cell voltage will depend on the operation conditions as well as temperature, humidity and pressure of the reactants has a direct influence on the cell voltage. The load current can be changed until the power output is at the required level. However, the virtual power plant approach allows dealing with small power differences of the decentralized systems without this requirement. Therefore, a single system can run at optimal load and stable current.

The results of the tests on PEM fuel cells stack

In this chapter there will be presented the results of a study on the stack fuel cells of PEM type with the following parameters:

- rated power 300W,
- open circuit voltage of a single cell 0.9 V,
- nominal operating temperature 60 ° C,
- number of cells-5.

The load of the stack at the time of the measurements was an electronic device DC-LOAD allowing to adjust the load current in the range from 0 to 60 amps.

The following tests have been conducted:

- the work dynamics of the stack,
- determination of external characteristics,
- the examination of the impact of the coefficient of excess air lambda on the power generated by a stack.

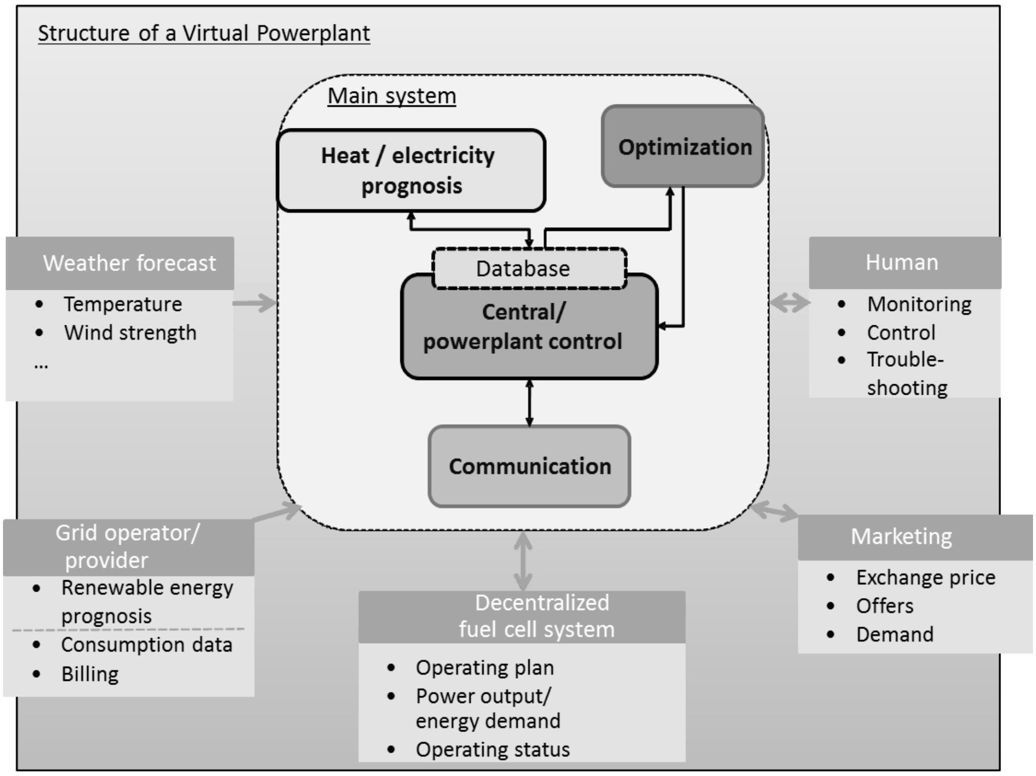

Fig.3. Structure of a virtual power plant showing connections to external systems

The measurements were carried out at various points of the straight line characteristics of U = (f) (I) i.e in the area of "loss of ohm" fuel cells. The Figure 4 and 5 shows the waveforms of a measured voltage and current as well as produced power and used fuel (hydrogen).

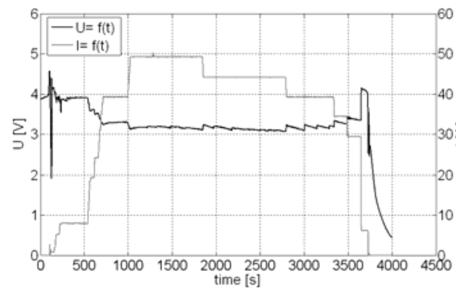

Fig.4. Waveforms of the measured voltage and intensity of current

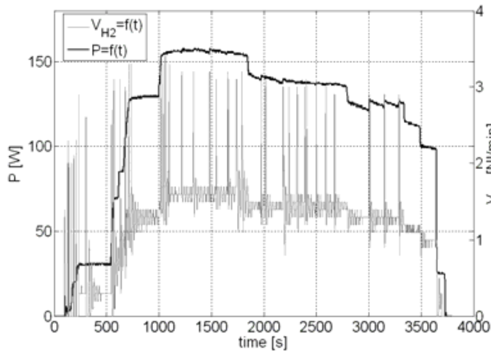

Fig.5. Waveforms of generated power and consumed fuel

Recorded voltage is the algebraic sum of voltage of all five single cells. Fuel cell stack quickly adapts to a change of load, i.e. with the increase in workload, the generated power increases in a very short period of time (black signal). In proportion to the increase of load, the use of fuel-hydrogen increases. Visible "peaks" on a recorded course of the used hydrogen are the result of automatics of PEM cells system, which periodically performs so called "flush out" of the anode. From time to time for a short while, opens the electrovalve at the outlet of hydrogen from the cell. "Purging" is aimed at cleansing the anode from any impurities which cause the deterioration of the cell work.

Hydrogen consumption by a stack of cells can be determined from dependence.

$$V_{H_2} = 22{,}42\frac{I \cdot n}{z \cdot F}\left[\frac{Ndm^3}{s}\right] \tag{1}$$

where: V_{H2} – the flow of hydrogen delivered to the anode [Ndm^3/s], I – current intensity [A], n – the number of individual cells in the stack, z – ion load, F – the Faraday constant [C/mol].

The efficiency of the electrical power generation of the examined stack can be calculated from the dependence

$$\eta_{el} = \frac{P}{V_{H2} \cdot Q_{wH2}} 100[\%] \tag{2}$$

where: η_{el} – electric efficiency of the stack [%], P – electric power [W], V_{H2} – flow of consumed hydrogen [Ndm^3/s], Qw_{H2} – hydrogen calorific value [MJ/Ndm^3].

Electric efficiency of an examined stack within the certain work condition is 50% (fig. 6)

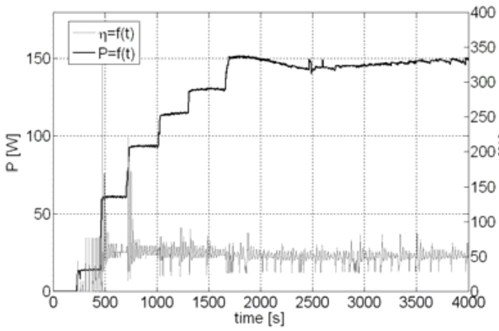

Fig.6. Waveforms of generated power and electrical efficiency of the stack

Determination of the external characteristics of the fuel cell stack

Operating temperature of a stack influences its voltage current characteristics (Fig.7) When the working temperature is lowered, the activation losses increase. A current-voltage characteristic is moved down in terms of characteristic with face value of a nominal temperature. Increased working temperature of a cell has an influence on the reduction of activation energy, so the activation losses are lower. A current-voltage characteristic is moved up in terms of characteristic with face value of a nominal temperature. It should be remembered that too high temperature will cause the desiccation of a membrane which will result in the loss of ion conductivity. The loss of ion conductivity will cause the decrease of the value of current generated by the stack.. Besides, with the higher working temperature, the steam pressure in electrolyte material will increase. This can cause mechanical damage of a cell.

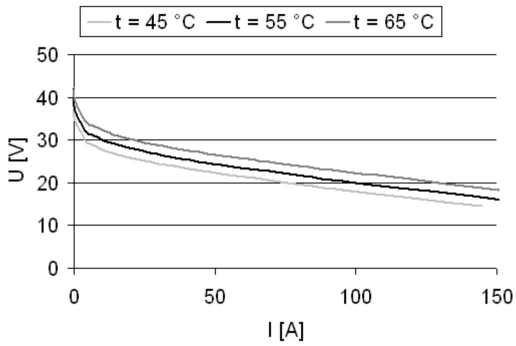

Fig.7. The effect of temperature on external characteristics

To correctly determine the external characteristics of a fuel cell, measurements should be carried out in a state of steady heat and apply "purging" in order not to lose the ion conductivity. The Figure 8 shows a course of value of temperature work of a cell . Measurements were taken at a temperature rating equal 60 ° C. Characteristics has been presented in a chart. The Figure 9 shows the external characteristics and curve of power designated for the nominal operating temperature of a stack. Two areas have been marked -activation start I and area of ohmic losses II.

In the third area, the measurements were not taken because overloading the stack with the biggest currents is not recommended because it will shorten the life of the stack.

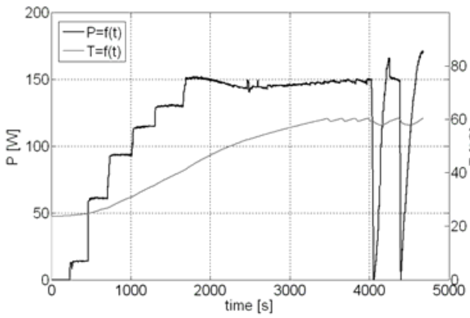

Fig.8. Waveforms of generated power and operating temperatures of the stack

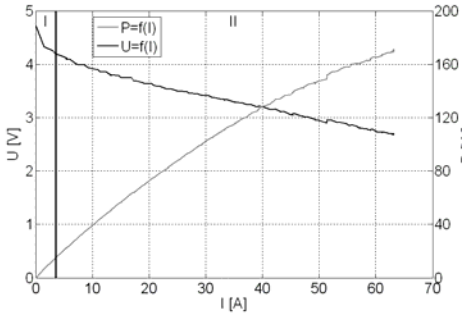

Fig.9 Designed external characteristics and the power curve of the stack

The examination of the impact of the coefficient of excess air lambda on the power generated by a stack

Air to a cathode channel is supplied by a compressor which allows the regulation of coefficient excess air lambda. The amount of air supplied can be calculated from the formula

$$V_{pow} = \frac{22{,}42}{0{,}21} \lambda \frac{I \cdot n}{z \cdot F} [\frac{Ndm^3}{s}] \quad (3)$$

where: Vpow – flow of air supplied to the cathode [Ndm^3/s], I – current intensity [A], n - the number of individual cells in the stack, z – ion load, F – Faraday constant [C/mol], λ – the coefficient of excess air flow entering the stack

Table 1. The results of the measurments

Temperature t [°C]	Lambda coefficient λ	Power P [W]
60	3,2	162,95
60	3,7	166,38
60	4,2	169,65
60	4,7	171,26

The influence of coefficient of excess air lambda on the power generated by the stack was tested. The results of the measurements are shown in the table 1. The effect of lambda coefficient on generated power by a stack shown in the chart number 10.

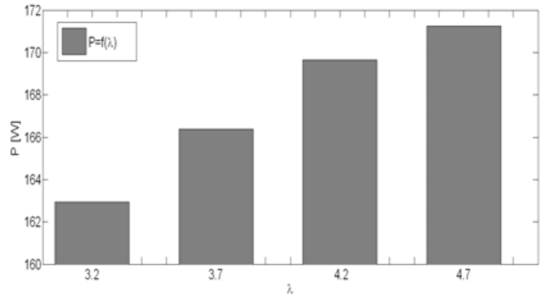

Fig.10. The effect of lambda coefficient on generated power

Conclusions

The tests performed let us draw the following conclusions:

- with lower temperature of cell working temperature, activation losses increase, current-voltage characteristic of a cell is going down in terms of characteristic for rated temperature,
- increased cell working temperature has an influence on decreasing activation energy, external characteristic of a cell is going up in terms of characteristic for rated temperature. However, too high temperature will cause desiccation of a membrane which will result in disappearance of ion conductivity,
- with the increase of the coefficient of excess air lambda, the generated power of a cell increases.

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