EFFECT OF INLET AIR TEMPERATURE AND RELATIVE HUMIDITY ON PERFORMANCE OF PEM FUEL CELL

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ABSTRACT

Present paper investigates the influence of inlet air temperature and relative humidity on performance of a PEM Fuel Cell stack with maximum power of 175 W. In order to control the inlet air temperature, a cooling system was designed and implemented. Changing the inlet air temperature in the range between 15°C and 25°C, it was experimentally proved that the lower temperature results in better fuel cell performance. This dependence was found to be non-linear.

Next step of the research was to take into account the air humidity and to analyze the cooling effect on membrane productivity. For this purpose, an air humidifier and a sensor were installed into the inlet channel. Experiments showed that the efficiency of the system is increasing with the growing relative humidity.

CFD simulation of the reactants flow inside the FC stack was conducted, helping to analyze thermal regime, velocity distribution and migration of hydrogen ions through the membrane on a cathode side. Using experimental data, it was detected that temperature on cathode side exceeds operational limits already at 120W power load.

NOMENCLATURE

Parameters

E_r	V	Reversible potential of FC
H	[%]	Theoretical efficiency of FC
ΔG	[MJ/kmol]	Gibbs free energy of the reaction
ΔH	[MJ/kmol]	Change of enthalpy of the reaction
P	[atm]	Pressure
T	[K]	Temperature
Φ	[%]	Relative humidity
$\tilde{v}$	[l/min]	Volumetric flow rate
$\tilde{V}$	[l]	Total consumption of gas within a period of experiment
Eel	[J]	Energy produced within a period of experiment
Pel	[W]	Electric power
Qtot	[W]	Heat released in one FC channel
A	[m^2]	Cross-section area of channel
x	[m]	Length of the channel

Subscripts

PEM	Proton Exchange Membrane
FC	Fuel Cell
LHV	Lower Heating Value
HHV	Higher Heating Value
RH	Relative Humidity
CFD	Computational Fluid Dynamics
HE	Heat Exchanger
MEA	Membrane-electrode assembly

INTRODUCTION

Fuel cell technology covers a broad range of applications, including backup power supply of isolated objects such as communication towers or small-sized settlements. It is essential to understand the dependence of performance of a fuel cell-based energy system on ambient conditions, such as air temperature and humidity, as it is often placed outdoors in special container. Despite the fact that theoretical efficiency of fuel cells is much higher than for combustion engine-based power generation systems, there are still many uncertainties regarding performance of chemical reactions on FC membrane which negatively affect overall FC performance. Heat generated inside the fuel cell causes degradation of a catalyst, membrane and diffusion layers. This heat has to be removed from the cell to keep the operation temperature within the range of 60-80 °C and hence achieve the maximum system efficiency [1].

Efficiency of the fuel cell system depends on many factors. In this paper, the influence of inlet air temperature and relative humidity on PEMFC efficiency will be discussed.

Temperature influence

Theoretical efficiency of any fuel cell can be found using the formula:

$$\eta = \frac{\Delta G}{\Delta H} \qquad (1)$$

ΔH is a fixed value, which can be equal to LHV of H_2 if the reaction product state is water, or HHV of H_2 if the reaction product state is vapor. However, Gibbs free energy depends on temperature and pressure of the process.

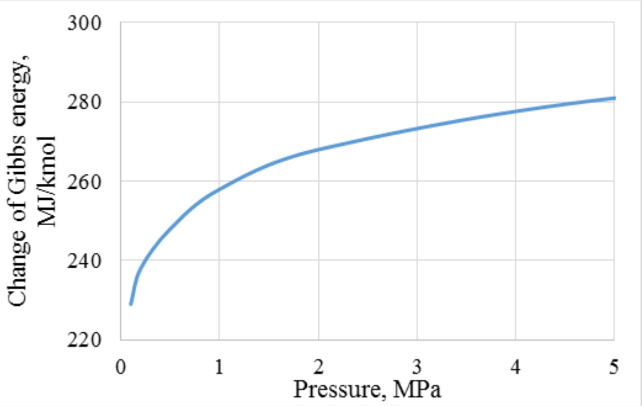

Figure 1: Relation between Change of Gibbs energy and pressure of reactants in the fuel cell under 298 K [2].

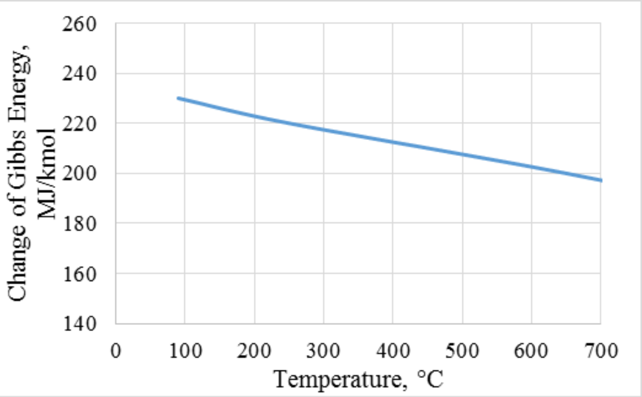

Figure 2: Relation between Change of Gibbs energy and operational temperature in the fuel cell under 0,1 MPa [2].

With a growing temperature Gibbs energy is decreasing, which means the efficiency of the process should go down. Gibbs energy is growing with an increased pressure, positively affecting the efficiency of the process. If the input parameters of reactants are the same, the effect of pressure P and temperature T on ΔG will look like on Figures 1 and 2.

The relationship between voltage and temperature is derived by taking the free energy, linearizing about the standard condition of 25°C, and assuming that the enthalpy change ΔH does not change with temperature [1]:

$$E_r = -\frac{\Delta G}{nF} = -\frac{\Delta H - T\Delta S}{nF} \tag{2a}$$

$$\Delta E_r = \frac{dE_r}{dT} \Big| \Delta T \tag{2b}$$

$$\Delta E_r = \frac{dE}{dT} \Big| (T - 25°C) = \frac{\Delta S}{nF}\ (T - 25°C) \tag{2c}$$

Because the change in entropy is negative, the open-circuit voltage output decreases with an increasing temperature; the fuel cell is theoretically more efficient at low temperatures [1]. The relation between reversible potential and temperature of the reaction is shown on a Figure 3.

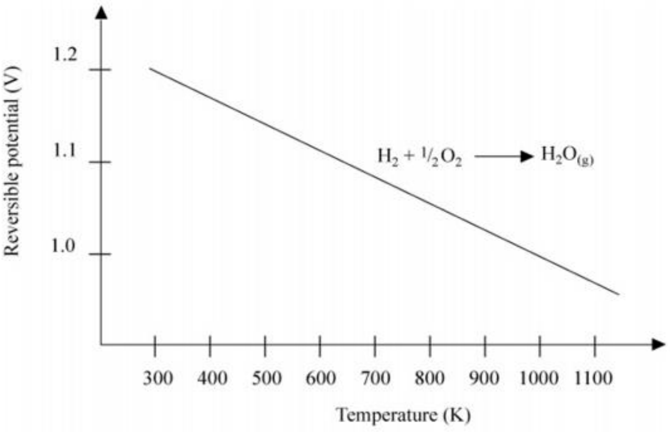

Figure 3: Relation between Reversible potential (V) and Temperature of the reactants in the fuel cell at 0,1 MPa [9].

However, the reaction kinetics grows with temperature [2], so mass transport, ionic conduction and other processes are faster at higher temperatures. To achieve maximum efficiency one should find a balance between two effects and choose the appropriate temperature range. For PEMFC fuel cells, the best operating temperature inside the FC stack is considered to be between 60 and 80 °C [1].

Influence of air relative humidity

There are two aspects of FC operation which humidity could have influence on, as FC membrane is very sensitive matter. Humidity is one of the parameters, which has an impact on membrane performance. If there is not enough humidity, the membrane can dry out and its permeability subsequently goes down. However, in case of over humidification water can flood the system and prevent interaction between reactants [1].

Very often ambient conditions differ from the ones that are required for normal operation of FC. Many publications in this field state that maximum power density of the PEM FC is achieved with 60% RH on cathode side and 100% on anode side [3].

Another aspect, which could be improved by RH increase, is the thermal regime inside FC system. Water from the air removes the heat inside the system by evaporation or with water mass removal.

It is critical not to let the working temperature of the FC to go above 90 °C, because this will accelerate water evaporation and result in membrane draught.

Fuel cell reaction is an exothermic process, which means electricity generation is coupled with the heat production. Considering that FC system efficiency experimentally varies around 50%, the rest 50% is dissipated in the form of heat. Heat generated in FC has to be removed from the stack in order to keep the operating temperature of the system in the appropriate range. That is why FC needs some technical devices to create proper surrounding conditions, especially the condition of inlet air. In our FC block, cooling fan is installed and automatically turned on when the operating temperature rises above the limit.

As precise control of the conditions is a technically difficult task, the permissible range of the conditions should be possibly widened within the frames of the desired range of FC efficiency.

Based on experimental set up described in more details in the next chapter the following objectives were stated:

1) During experiment:
    a) Determination of FC efficiency under fixed levels of RH (25-35% and 95-100%) and changing inlet air temperature;
    b) Determination of FC efficiency under fixed inlet air temperature and changing inlet air RH.
2) During CFD modeling:
    a) Display of a thermal regime inside the reactant channels and find optimal mass flow rate of the inlet air;
    b) Numerical investigation of the air and hydrogen flow behavior inside the FC channels.

EXPERIMENTAL SETUP

Description of the lab unit

The general view of the set-up is presented in Figure 4. Working procedure of the set-up is the following: Hydrogen comes from the intake source of middle pressure (15-30 bar) storage tank. 175 W PEM fuel cell is connected to the lead acid battery and the load. Load is provided by means of 10 electrical bulbs 20W each. Produced electricity can be stored in a 12V battery, which helps to stabilize power load consumption and generation. Battery meets the fuel cell start-up demand and meets the load demand whenever fuel cell is not working. When the fuel cell is operational, it provides power both for load and battery.

Figure 4: Experimental set up view

Hydrogen can be received from gas cylinder or extracted from metal-hydride. In our experiments, the first option was used. Schematic view of the lab unit can be seen in Figure 5.

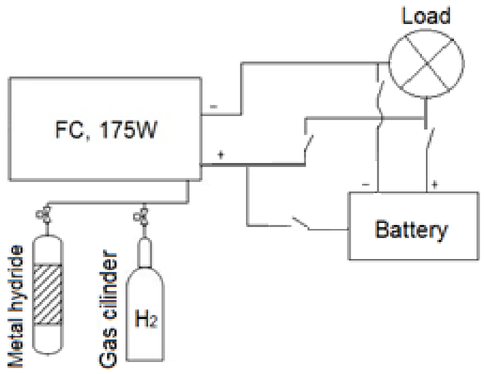

Figure 5: Schematic view of the lab unit

Description of the cell construction

PEMFC consists of several layers closely fixed to each other. Fuel cell has cathode and anode layers, membrane with thin layer of catalyst dispersed on its surface. Graphite plate represents cathode on one side and anode on the other side. Only two plates, first and the last ones, have one electrode on one side. Each graphite layer has gas channels for homogeneous distribution of reactants.

On anode side, hydrogen flows through the channels and after ionization, protons migrate through the membrane on a cathode side. Here oxidant flow catches hydrogen ions and results in water molecule formation, which should be flushed away with the coming air flow. Air flow through the channels should be provided with excess ratio approximately equal to 2. That is necessary to keep reaction rate on cathode side as fast as that on anode side and achieve the full conversion [2].

Water produced during the reaction has to be removed from the cathode area to let coming hydrogen ions react with oxygen. However, at the same time, membrane has to be sufficiently humidified with water to keep diffusion at the maximum level. To maintain membrane humidity high partial pressure of water vapor at both anode and cathode side should be preserved. Hydrogen ions migrating through the membrane take away water molecules with themselves, dissolved in membrane, so anode side of the membrane is usually less hydrated than cathode side [2]. Thus, humidity should be higher on the anode side. It correlates with results of [6].

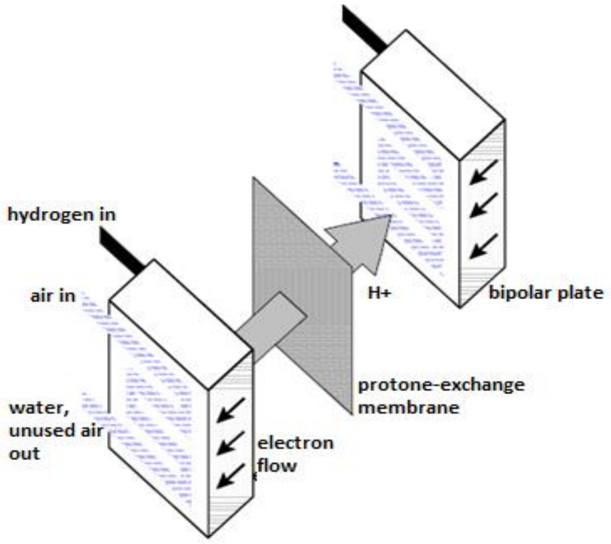

Figure 6: PEMFC geometry [1]

Description of the cooling system

To have a possibility to change the state of the inlet air, the following construction was created.

Air is blown by a fan (1) through the plate heat exchanger (HE) (4) to air reservoir (14) with an open outlet. The construction enables to have in the air reservoir the air flow with constant properties and very low overpressure and velocity. The second heat transfer medium in the heat exchanger is water from a thermostat. For analysis of heat exchange process, the following measuring equipment is used. Medium flows are measured by flow meters 6 and 3. For air side, additional measuring of flow is conducted by sensor 10, which is a pressure drop and velocity meter.

Temperature in each line is measured before and after temperature changing blocks: HE and FC (7 – 5, 2 – 9, 9 – 12). Absolute pressure in the second heat transfer line (water) is measured before the HE (16), and pressure difference is measured before and after the HE (18). In the air line, the absolute pressure is measured (15) in the air reservoir (14) and the pressure difference is measured before and after FC and HE (10, 17). The scheme enables to check the indication of sensors by calculations of heat and flowrate balances.

In order to humidify the ambient air, a room humidifier with piezo element was used.

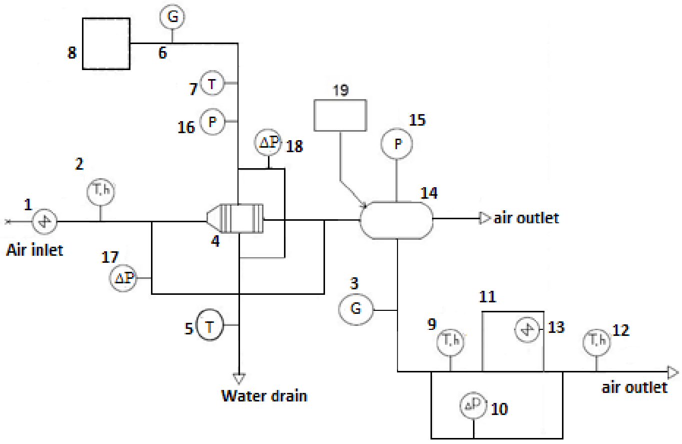

Figure 7: Cooling system scheme
1-Fan; 2, 9, 12-Temerature and humidity sensor (air); 3, 6-Flow rate sensor (air); 4-Heat exchanger; 5,7-Temperature sensor (water); 8 – Thermostat; 10, 17, 18 – pressure drop sensor (air); 11 – Fuel cell; 13 - FC fan; 14 - air reservoir; 15,16 - Pressure sensor (air).

EXPERIMENTAL RESULTS

Experimental set-up writes values once per 0.3 seconds into a log-file for further processing. Power output curve is shown on a Figure 8.

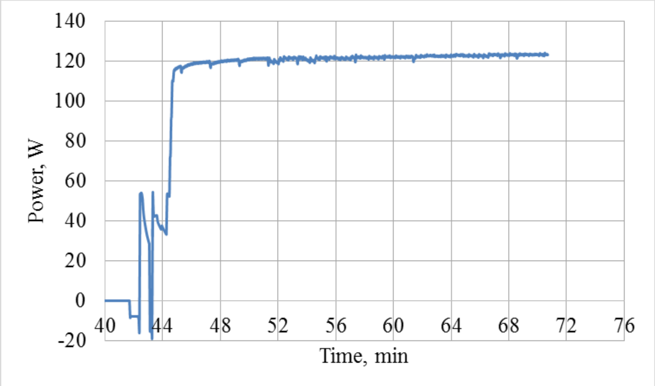

Figure 8: Typical behavior of the FC power curve

In the first experiment, only temperature effect on the FC performance was investigated. By means of installed heat exchanger, temperature range of 15-25 °C was achieved. Observation of influence of inlet air temperature was provided by efficiency of FC calculated using the following formula:

$$\eta = \frac{Qel}{\tilde{V} \times LHV} \qquad (3)$$

$$Qel = \int_1^2 Nel \times d\tau \qquad (4)$$

$$\tilde{V} = \int_1^2 \tilde{v} \times d\tau \qquad (5)$$

Integration method to define efficiency was chosen because of uneven behavior of experimental curves.

Relation between the inlet air temperature and efficiency of FC system is observed on a Figure 9. It is obvious from the graph that efficiency grows with decreased inlet air temperature.

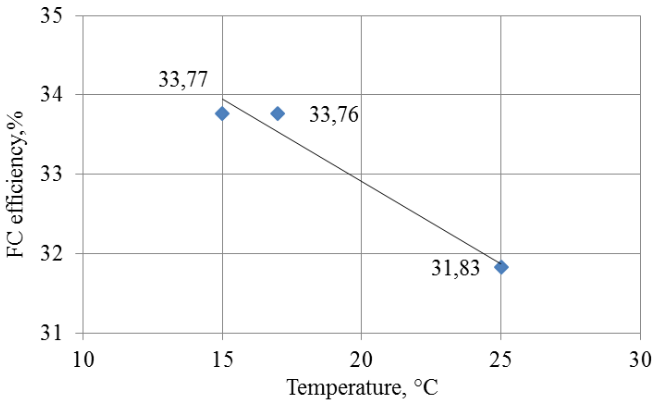

Figure 9: Effect of inlet air temperature of FC efficiency

As mentioned above, relative humidity has a considerable effect on FC performance. Therefore, to get investigate this effect, it was decided to add a humidity controller.

In the second experiment, cross effect of the inlet air temperature and humidity was investigated. Lab equipment allowed taking measurements of three humidity levels: 20-25%, 60-65% and 95-100%. Results were obtained for three temperatures: 19°C, 22°C and 24°C. As it can be observed from Figure 10, the efficiency of the system increases with inlet air RH. It was also experimentally proven, that temperature reduction positively affects the efficiency, regardless of the level of RH.

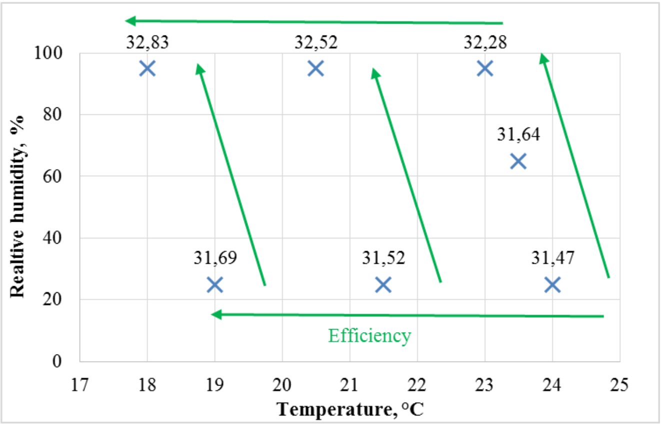

Figure 10: Effect of inlet air temperature and relative humidity on FC efficiency

However, mentioned dependence of the FC efficiency is relatively weak. In temperature range between 19ºC and 24ºC, the FC efficiency change around 0,6%. Variation of RH from 25 % to 100 % increases efficiency around 3,4% relative. The results of the first experiment are different in these values, but we suppose that it is connected with RH, which was not considered at that time.

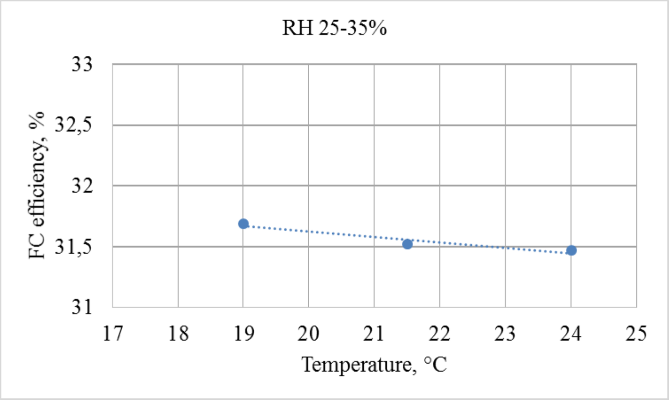

Figure 11: Temperature (˚C) effect on FC efficiency (%) at air relative humidity 25-30%

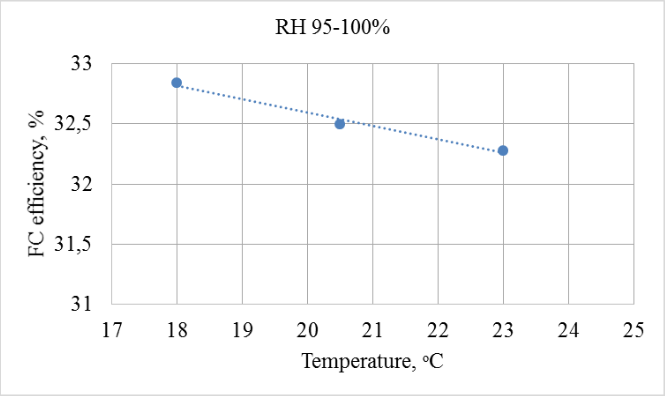

Figure 12: Temperature (˚C) effect on FC efficiency (%) at air relative humidity 95-100%

UNCERTAINTY ANALYSIS

All data from sensors was transferred to a PC by means of LabView software and ADCs (analog-digital converter).

Hydrogen flowrate and inlet air temperature were measured with 0,8% and 0,5% relative accuracy respectively. Electric power of the system is calculated using voltmeter and ampermeter results with overall system inaccuracy of 0,15%. Air humidifier used in experimental set up has relatively low accuracy of 3%, therefore one can observe RH range on Figures 11 and 12.

CFD MODELING RESULTS

The purpose of the modeling was to display thermal regime, the velocity distribution inside the channels and hydrogen protons migration through permeable border, corresponding to experimental conditions. Chemical reaction between hydrogen and air oxygen was not considered. As the modeling program, Star CCM+ 10.04.011 –R8 was used.

As a geometry part, two reactant flow channels inside the membrane-electrode assembly (MEA) were chosen (see Figure 13). The area of such channel is 1 mm^2 according to the real fuel cell dimensions. Upper channel is contiguous to cathode and bottom channel is contiguous to anode. Between channels there is a 0,3 mm layer which represents proton exchange membrane. The 3D geometry represents first 20 mm of electrochemical system. Such length was chosen to reduce the time of calculation.

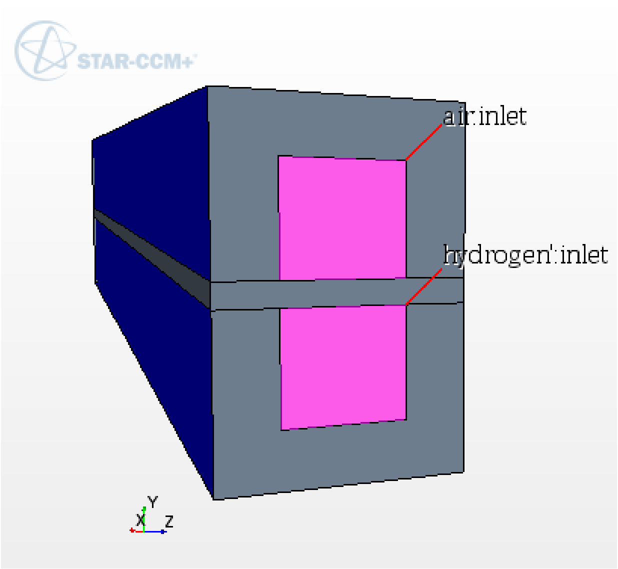

Figure 13: Geometry of FC channel

In the solution process, a mesh structure is very important for stability and precision of the results. Depending on which mesh type has been chosen the time and accuracy of simulation may change significantly. Considering simple geometry directed mesh tool was used with the following dimensions:

Mesh spacing in the channels: 3,3E-05 m;
Mesh spacing in the membrane: 2,5E-05 m;
Mesh spacing in the electrodes: 5E-05 m;
Number of layers along the length: 100

Air, hydrogen flow and membrane have gas physical model, while cathode and anode geometry parts are solid.

Models for solid regions are steady state, 3 dimensional with constant density. For gaseous regions, the same models have been chosen as well as segregated laminar flow and multicomponent non-reacting ideal gas.

For simplification of the calculation gas flows do not react with each other. Using tabulated data for kinematic viscosities [6] and experimental results for reactant's velocities it was found that both flows has Re number below 2300, which means inside both channels there is a laminar flow [6].

For boundary conditions, the following parameters were used:

- Inlet air temperature: 20 °C
- Inlet hydrogen temperature: 30 °C
- Inlet air flow rate: 9,79E-07 kg/s
- Inlet hydrogen flow rate: 1,28E-08 kg/s
- Pressure in the system: 2 atm

Boundary conditions are based on experimental data obtained from FC lab unit. For power load 120 W hydrogen flow rate is 1,6 l/min. Using this value, the stoichiometric air flow rate was calculated and doubled in order to provide the full conversion. Inlet air temperature is equal to ambient; hydrogen temperature is determined by storage system.

Hydrogen ions' penetration through the membrane can be seen in Figure 14. On the anode side there is only hydrogen gas delivered from a metal hydride. After passing through the proton exchange membrane, hydrogen ions mass fraction goes down. On the cathode side, oxygen from the air flow meets with hydrogen ions, and chemical reaction occurs. However, to simplify the simulation process, gases considered to be non-reacting.

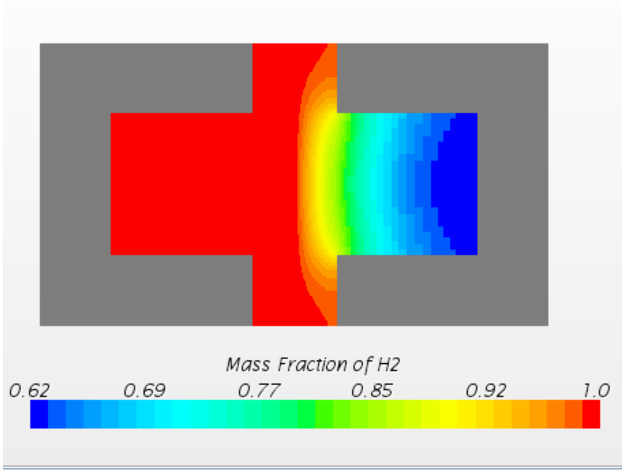

Figure 14: Penetration of hydrogen protons through the membrane

Some energy released due to chemical reaction converts into heat. According to experimental data 120 W of produced electric power will be accompanied with 93 W of waste heat. This heat is distributed inside the air channels where chemical reaction takes place. Distribution of heat depends on the channel length and can be written is the following way:

$$Q(x) = \frac{Q_{tot}}{A}(0{,}15 - x) \qquad (6)$$

Maximum fuel cell length is 0,15 m and cross-sectional area of FC channel is 1E-06 m^2.

Using mentioned above formula a filed function was introduced in the CFD modeling. As a result heat generated inside the FC channel at 120 W power load in some parts increases the system temperature until 84 °C. Heat distribution inside FC channels is represented on Figures 15 and 16.

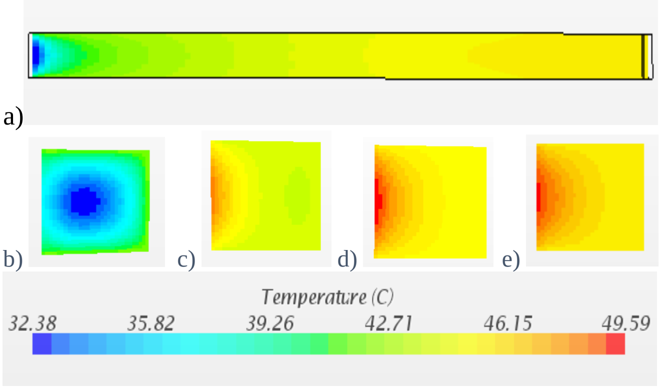

Figure 15: Thermal regime inside the hydrogen channel

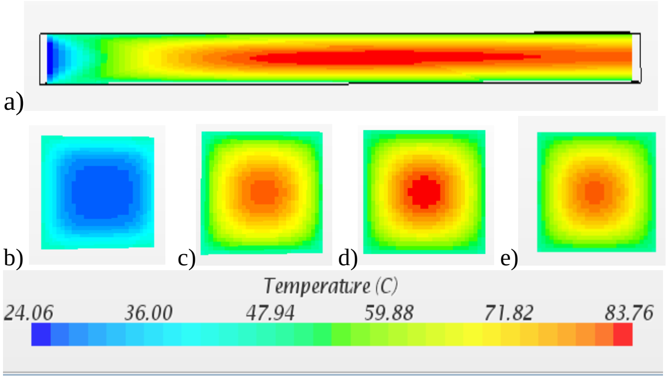

Figure 16: Thermal regime inside the air channel

The operation temperature of PEM fuel cell should be between 60 and 80 °C which means in our case inlet air temperature should be better controlled or air velocity should be increased. Breaking operation temperature limits may cause evaporation of water and membrane drought.

Figures 17 and 18 show hydrogen and air velocity profiles inside the FC channels. Velocity of hydrogen in the middle of the channel is almost the same on the whole length – 0,034-0,035 m/s.

Velocity profile of the air is more evident due to higher values. In the middle of the channel length velocity achieves stable value of 2,5-2,6 m/s. Considering characteristic dimension of the channel equal to 1 mm, calculated velocities and kinematic viscosities of gases show that both fluid flows have laminar behavior.

CFD simulations were performed with 5000 iterations and all residuals achieved relative inaccuracy of 10E-04.

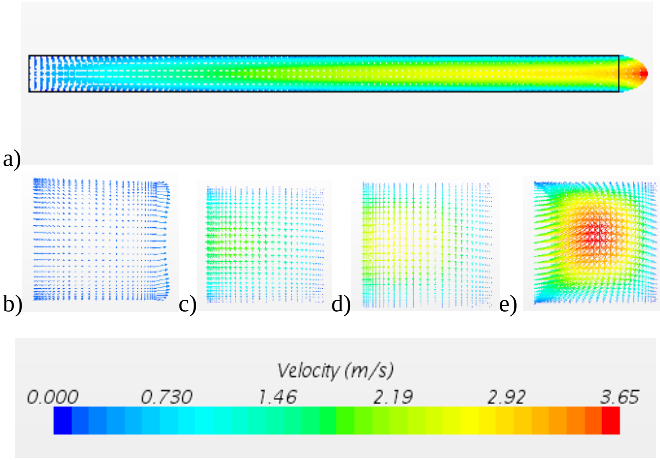

Figure 17: Air velocity inside the channel:
a)-longitudinal plane vector section, b), c), d), e)-cross-sections

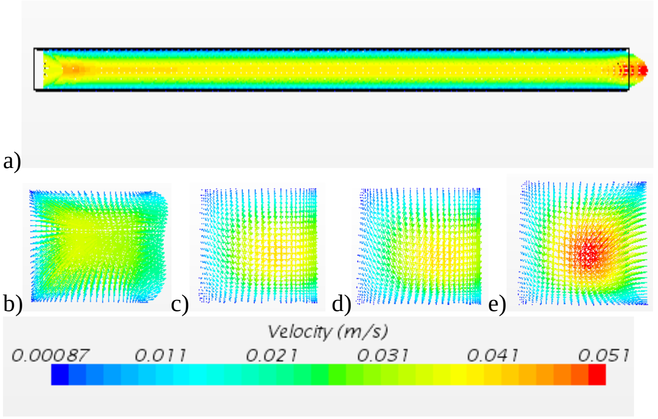

Figure 18: Hydrogen velocity inside the channel
a)-longitudinal plane vector section, b), c), d), e)-cross-sections

The following objectives were defined for a future research, based on the presented results above:

1. Increase temperature range of experiment by changing cooling media from water to ethylene glycol.
2. Increase period of observation at stable inlet conditions
3. Increase accuracy of mesh in CFD model
4. Change physics conditions from non-reacting mixture to reacting mixture of gases.

CONCLUSION

In order to reveal the effect of inlet air temperature and relative humidity on FC performance, an experimental facility was designed and constructed, having a conventional PEM Fuel Cell and an original metal hydride storage system. Experimental investigation conducted using the original equipment showed that the efficiency of a FC system is increasing with increased relative humidity and reduced temperature of inlet air in the range of experimental parameters (inlet air temperature 15°C - 25°C, inlet air relative humidity 25% to 100%).

However, the effect is relatively small – for the temperature range from 18 ºC to 24 ºC the FC efficiency rises on 0,6%. Relative humidity in observed range has a stronger influence, as its variation from 25% to 100% increases efficiency at around 3,4%. Furthermore, as our experiments had shown, low RH leads to FC degradation, decrease of the highest FC power output and FC efficiency in long term perspective.

CFD simulation of a single channel inside fuel cell allowed confirm existing problem of system overheating. Due to waste heat accumulation inside the system temperature can rise above operating limits and cause irreversible degradation processes. Thermal regime inside the FC can be controlled via T, RH and velocity of inlet air. CFD results helped to understand what is going on inside the system and prepared a platform for more complex simulations for scaled up geometries.

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