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Abstract: Nowadays underwater robotics aims at semi or whole autonomous underwater vehicles. Autonomy of underwater robots depends on their control systems usually based on artificial intelligence methods and capacity of supply sources mounted on their boards. The paper undertakes problem of using different power source than classical batteries to supply autonomous underwater vehicles. Fuel cell stack has been selected as an alternative power source. The mathematical model and designed simulator of fuel cell system have been presented. Moreover selected results of fuel cell system working have been inserted.

Key-Words: underwater vehicle power supply, fuel cell

1 Introduction

Design process of underwater vehicle demands resolving of problems from following fields: hull forms, hydrostatics & hydrodynamics, propulsion, thrusters, power system, control system, autonomy, computing & software, navigation, sensors. All itemized problems have considerable impact on underwater vehicle functionality. However basic exploitation parameters are mainly depended on supply system. Nowadays prevalent solution are accumulator batteries. In spite of their considerable development, using of alternative supply sources should be considered. One of these possibilities is using of fuel cell that is an electrochemical device, which change electrochemical energy into electrical energy in direct process. Analysis of accessible fuel cell technologies shows that the highest efficiency offers PEMFC (Polymer Electrolyte Membrane Fuel Cell or Proton Exchange Membrane Fuel Cell). This kind of fuel cell is particularly useful for underwater platform since it offer the highest gravimetric and volumetric power density (more than 700W/kg and 1100W/dm³) [1]. Owning this kind of power source can be stimulus for development of new underwater vehicle constructions.

After the preliminary analysis it could be stated that power system based on fuel cell supplied from metal hydrides storage has similar features (power, mass, volume) comparing with the newest lithium batteries. Moreover the hydrogen storage technology develops intensively, what gives good prognosis for future.

General diagram of alternative underwater vehicle power system has been presented in the fig. 1. The system is based on one fuel cell stack with nominal power 5 kW. The stack is supplied by pure oxygen and hydrogen subsystems in closed loop. While thermal management system is based on heat exchanger type liquid-liquid. Connected on the output power converter DC/DC is coupled in parallel with accumulators, what gives possibility of fast response on an electrical load change. Working of all subsystems is controlled and monitored by modern and reliable on underwater conditions programmable controllers Compact Rio.

Fig. 1. General diagram of an underwater vehicle power system based on PEMFC

The paper is organized as follows: section 2 presents used fuel cell mathematical model and designed simulator of fuel cell system; section 3 illustrates selected results of the numerical research; section 4 is the summary.
2 Fuel Cell System Simulator

In the paper an analytical control-oriented state space mathematical model of a PEM fuel cell has been used [3][5]. Principles of fuel cell operation can be found in many publications, for example in [2][4].

2.1 Fuel Cell Mathematical Model

In general fuel cell operation is described by presented in tab.1 operating parameters. Fuel cell operation can be subjected to environment influence (i.e. ambient pressure change), interaction with user (i.e. change of an electrical load current) or action of fuel cell subsystems (i.e. change of oxygen inlet mass flow rate).

Table 1 Operating parameters of fuel cell mathematical model

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I_d)</td>
<td>Fuel Cell current</td>
<td>[A]</td>
</tr>
<tr>
<td>(p_{O_2})</td>
<td>Oxygen inlet pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>(p_{H_2})</td>
<td>Hydrogen inlet pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>(p_{amb})</td>
<td>Ambient pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>(\dot{m}_{O_2})</td>
<td>Oxygen inlet mass flow rate</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>(\dot{m}_{H_2})</td>
<td>Hydrogen inlet mass flow rate</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>(\psi_{O_2})</td>
<td>Oxygen inlet humidity</td>
<td>[-]</td>
</tr>
<tr>
<td>(\psi_{H_2})</td>
<td>Hydrogen inlet humidity</td>
<td>[-]</td>
</tr>
<tr>
<td>(T_{stack})</td>
<td>Stack temperature</td>
<td>[K]</td>
</tr>
</tbody>
</table>

Overall stack voltage is equal to Nernst potential \(E_d\) minus following overpotentials:

\[
V_{FC} = E_d - \eta_{act} - \eta_{conc} - \eta_{ohm} - \eta_{ion} \tag{1}
\]

Here \(\eta_{act}\) is an activation overpotential, \(\eta_{conc}\) is a diffusion overpotential, \(\eta_{ohm}\) is an electronic ohmic overpotential and \(\eta_{ion}\) is an ionic conduction overpotential. Description of particular equation components can be found in [2][5].

Convective gas transport within the stack (its gas channels) is driven by a pressure gradient imposed by the fuel cell auxiliaries (i.e. hydrogen gas pump). Overall stack voltage and particular overpotentials are dependent on reactant gasses concentration in catalyst layer. Therefore their description is very important. Moreover flow rates and mole masses of reactant gasses should be known for set values of operating parameters especially for a load current. They can be determined on the base of the following equations (presented only for stack cathode):

\[
\frac{dm_{O_2}}{dt} = \dot{m}_{O_2,in} - \dot{m}_{O_2,act} - \dot{m}_{O_2,react} \tag{2}
\]

\[
\frac{dm_{H_2,O}}{dt} = \dot{m}_{H_2,O,in} - \dot{m}_{H_2,O,act} + \dot{m}_{H_2,O,gen} + \dot{m}_{H_2,O,MEM} \tag{3}
\]

Here \(m_x\) denotes a mass, while \(\dot{m}_x\) mass flow rate of species \(x\). Following indexes denote: \(in\) – inlet and \(out\) – outlet masses to and from cathode, \(react\) – participating in reaction and \(gen\) – generated masses and \(MEM\) – masses produced within membrane.

Equations (2) & (3) were written on the base of mass conservation law [3].

Water management is one of the critical aspects of successful FC operation. For best conductivity membrane should be fully humidified, what can be done in the case high water content in reactant gasses. On the other hand high humidity causes lower concentrations of reactant gasses and can cause condensation phenomena in gas channels. When condensation occurs, transport pathways of reaction gasses become blocked what result in cell potential decrease. Therefore description of membrane hydration is significant.

Water transport in the membrane can be related to three transport phenomena: water transport by electroosmotic drag, by diffusion and by convection [3]. Connection of equations describing three transport phenomena gives in result equation on water flow rate within membrane:

\[
\dot{m}_{H_2,O,MEM} = M_{H_2,O}A_{FC}\left(\frac{n_1}{F}D_e\frac{c_{H_2,O,a} - c_{H_2,O,x}}{\delta_m}\right) \tag{4}
\]

Here \(A_{FC}\) is a fuel cell active area, \(n_1\) is an electroosmotic drag coefficient and \(F\) is Faraday’s constant. While \(D_e\) is a membrane diffusion coefficient, \(c_x\) is concentration of species \(x\) and \(\delta_m\) is a membrane thickness.

More details about fuel cell mathematical model and mathematical models of subsystems components can be found in [2][3][4][5].

2.2 Fuel Cell System Implementation

Designed mathematical model of the fuel cell system in the form of differential equations and state space matrices representing equations of state was implemented in simulation environment Matlab/Simulink (fig. 2).

The main part of the system is 5 kW fuel cell stack from Nedstack Company. Parameters of the stack’s mathematical model were selected on the base of basic parameters from producer, calculated on the base of suitable equations [3][4] or tuned in the empirical way. The model was verified on the base of real 5 kW stack’s characteristics. Received results confirmed correctness of designed mathematical model [5].
Examined fuel cell stack has nominal power 5 kW during air supply. For the stack supplied by pure oxygen, increase of power stack was observed from nominal value 5 kW to almost 6 kW [6]. For the aim of operating parameters control and visualization presented in fig.3 GUI windows was designed.

Designed fuel cell system simulator enables plotting of many different characteristics (i.e. polarization curve, characteristics of stack power and efficiency dependent on generated stack current) for desired set of input parameters (i.e.: an electrical load, temperature, relative humidity and pressure of reactant gases). Selected results of simulator working has been presented in the next section.

3 Results of Numerical Research

In the fig. 4 polarization curves for increasing stack temperature have been presented. Increase of stack voltage has been observed for its temperature increase. The best operation conditions were received for temperature range 65-85°C.

The stack operation in presented temperature range influences mainly on minimization of ionic conduction overpotential, which reduces overall stack voltage. Moreover decrease of activation overpotential has been observed for temperature increase. On the other hand too high stack temperature causes process of membrane drying, what can cause decay of ionic conduction. Therefore the fuel cell producer recommended its operation in temperature 65°C.

In the next fig. 5 characteristic family of stack power dependent on stack current for different pressures of reactant gasses has been presented. Increase of reactant pressures influences on increase of stack power and voltage. It is connected with decrease of activation and diffusion overpotentials. Moreover Nernst voltage is bigger for bigger partial pressures of reactants [3]. However producer of modeled fuel cell recommended keeping of gas pressures with values close to 1 atm. It can testify about specific forms of gas channels, which provide their steady concentration within the stack for not very big values of pressure.
In the last selected fig. 6 characteristics of stack efficiency dependent on its current for different relative humidities of reactant gasses have been inserted.

![Graph](image)

**Fig. 6.** Characteristic family of stack efficiency dependent on stack current for different relative humidities of reactant gasses

Decrease of reactants relative humidity causes decrease of stack efficiency and also decrease of stack voltage and power. It is connected with the transport phenomena of hydrogen ion through membrane. In general hydrogen ion is transported together with water molecule [3]. On the other hand water overflow can plug gas diffusion layers and reactants access to catalyst. Moreover it has been observed with the aid of designed simulator that decrease of hydrogen relative humidity influence more intensively than decrease of oxygen relative humidity on decrease of the stack voltage. It can be caused by the fact that fuel cell cathode is humidified not only by oxygen but also by generated water.

### 4 Summary

On the base of carried out analysis and numerical research it can be stated that:
- analysis of PEM fuel cell features confirmed possibility of using PEMFC on the board of autonomous underwater vehicles,
- implemented simulator works correctly for steady state, what executed research confirmed [6],
- underwater vehicle operation will have to be preceded by starting fuel cell to achieve optimal parameters of reactant gasses and the stack (different producers estimate starting time from several to even more than ten minutes).

Received results of numerical research will be used in carrying out process of a prototype, what will give possibilities of practical verification PEMFC using for autonomous underwater vehicle power supply.

### References:


