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DESIGN, MANUFACTURING AND TESTING OF A LOW-PRESSURE POLYMER ELECTROLYTE FUEL CELL

S. GALLI, M. GRANATI, I. LAGANA', G. MONTELEONE and A. POZIO
ENEA - Hydrogen and Fuel Cell Project Via Anguillarese 301, 00060 - Rome, Italy
galli_s@casaccia.enea.it

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Abstract : Solid Polymer Electrolyte Fuel Cell (SPEFC) looks as a promising technology for portable energy production. R&D activities in ENEA are devoted to design and test a portable SPEFC operating at low-pressure, just above atmospheric one, in order to simplify system and decrease energy consumption for air supply. Design criteria are established with the aim to realize bipolar plate flowfield schemes for a stable and reliable fuel cell operation.
The bipolar plates are designed and directly manufactured in our labs by means of a compact computer numerical control milling machine, useful at the early stage of research to evaluate alternative designs and changes in novel and complex flowfield layout.
To reduce system volume and parasitic energy consumptions passive cooling and self-humidification are studied and tested.

1. Introduction

Although the outstanding international efforts and funding in RD&D, fuel cell technology has been remaining at the prototypal product level, due to their high costs and actual questionable overall efficiency and reliability. Even if firstly proposed for medium power applications (e.g. from few to some tenths of kW for automotive, domestic cogeneration systems, backup power or remote power supply) fuel cell technology, and SPEFC mainly, is finding more attention for small (below 1 kW) and micro (few watts) portable energy production. Due to their high energy density and using hydrogen as fuel, stored in small replaceable cartridges as pressurized gas, under liquid state (e.g. as methanol) or in hydride (metallic or as chemical hydride), small fuel cells could represent an alternative to the current battery technology.
At this scale, as simplicity and reliability have a greater importance than energy efficiency, the system should consist of less typical auxiliaries (e.g. fan, compressor, heat exchanger, humidifier, pump, control system and sensors), reducing overall system power consumptions, weight, volume and costs.
From the technical point of view it will be critical to have a deep insight in chemical and physical fuel cell processes and phenomena (mass and heat transport and fluid dynamics, mainly) in order to design properly the main fuel cell components.
The objective of the effort in ENEA is then to develop and demonstrate a simple fuel cell stack operating at low-pressure (less then 50 mbar), for the moment of limited power output (about 100 W), with limited auxiliaries (for cooling and humidification) and parasitic power consumptions.

2. Water management issues in solid polymer fuel cell

Mass transport represents a critical point in SPEFC operation, and it has been treated in a large number of theoretical and experimental studies at different levels of details and complexity [1-4]. In order to simplify models and solution of related mathematical equation system, approaches are limited to mono- and bi-dimensional geometries, or to isothermal system, or to single-phase flow and almost always to steady-state conditions.

Unfortunately normal operation inside fuel cell seems to have some intrinsically unstable processes, especially evident at higher current density. Some experimental observations in literature have revealed that the growth of water droplets on the cathodic gas diffusion layer (GDL) side surface is a periodic intermittent process, with liquid water accumulated inside GDL and then expelled from it under capillary force to form surface droplets. Droplets attached to the carbon paper under the influence of surface tension are then removed mechanically from cathodic air only when they reach a certain size, forming a film [5].

Afterwards, in the channel and under the shear stress of the core air flow, the liquid film is gradually removed toward the channel exit according to the two-phase flow pattern and a steady-state model could be applied with sufficient reliability [6].

Flow discontinuous behaviors, with possible channel clogging, could supervene if flowfield channels and manifolds don't allow a smooth and continuous flow to the stack outlet: then GDL and last part of channels could flood, limiting gas diffusion to the electrode with a continuous decrease of performance. The overall behaviour of fuel cell, at least at high current density and reaction water production, looks then intrinsically unstable [7].

If not promptly removed water fills the cathodic compartment, causing fuel to starve and the cell to operate as an electrolysis cell, with an inverted polarity powered by adjacent cells [8,9].

In order not to flood fuel cell compartments and to have more stable or less critical operation, reaction water removal should be eased by an appropriate design of bipolar plate channels and manifold and by an as much as possible high air flow rate.

In the case of a low-pressure fuel cell, where reaction water evaporation is promoted, the air draft should be controlled to entrain the only produced liquid water.

Besides these observations about water production and removal we have to consider gas input humidification and their capability to evaporate reaction water. Operating fuel cell at a low-pressure condition, power density is limited and the maximum stack temperature as well. In these conditions it should be possible to operate the stack without any external cathodic air humidification system [10].

3. Thermal management

Fuel cell thermal management, requested to maintain its temperature below a maximum acceptable value, is an other challenging issue for designers of SPEFC systems. For high-density power generation, the thermal management strategies and actual approaches must be built upon liquid phase forced convection cooling.

The literature concerning modelling and analysis [11] shows that the maximum temperature zone of a parallel-cooling channels stack can be located in the central area of the cell. A slight decrease of temperature is generally noticed in external cells (near end-plates) and then more critical temperatures can be envisaged in the central zone of the membrane plane of the inner electrochemical cells.

The lower power density of a low-pressure fuel cell stack has, as obvious and positive results, that the heat cooling duty is reduced. As the cooling due to the cathodic air flow looks moderate and incompatible with water management [10], a passive cooling system has to be conceived to cool firstly the more critical heating point represented by the central portion of inner cells. Heat pipe technology has the prerequisite for an effective passive heat management: installing a heat pipe cooling plates inside stack, with evaporator tip placed at the centre of cooling plate, heat can be transferred at high flux to an external air cooling heat–exchanger. Such a cooling set up is simpler, cheaper and more reliable than a liquid cooling system as:

1. no ancillaries (pump, control, filter, deionizing bed, valve) are needed;
2. no active controls are required to transfer heat (ensured by the nature of heat pipe operation);
3. stack temperatures are insensitive to minor irregularities in cooling plate manufacturing;
4. cooling plate is slimmer;
5. there are no risks of medium leakages and operation is near atmospheric pressure.

Due to intrinsic heat pipe operation, where heat flux increases according to the temperature difference between heat source and sink, stack heat transfer (and cooling) can improve as power produced is increased.

4. Manufacturing

In order to study and test experimentally various flowfield schemes and their effects on fuel cell performance, it was requested a rapid prototyping method and hardware to realize main stack elements (bipolar plate, end plate, seal, seal mould and cooling plate), sometimes with complex patterns, in limited quantities, short time and at affordable costs.
For limited bipolar plate production, standard graphite and resin-graphite composite rough plates were chosen for their availability, economy and easily workability.
Working with graphite as primary material, various manufacturing methods have been investigated, as machining of solid graphite, or injection and compression moulding of graphite-polymer resin mixture. Even if the machining method has little chance for eventual mass production, it results to be the easiest method to realize bipolar plates with innovative design for rapid prototyping at the early research stage as in our case.
The answer was found in the desktop milling rapid-prototyping technology that offers compact machines able to combine simplicity of use to an accurate 3-D milling. By means of a compact computer 3-D numerical control mini-milling machine novel flowfield schemes for bipolar plate can be easily designed and the machine directly programmed by powerful advanced CAM-CAD software.
Milling machine is used both in preliminary operation for refining surface plate as well as for produce accurate molds for MEGA assembly production [12].

5. Test bench description

To evaluate fuel cell performance and to investigate fuel cell phenomena, attention was focused on the gas humidity control and measurement and on the overall stack pressure drops. Starting from a commercial fuel cell station a test bench was set up in the laboratory to operate and measure the stack performance up to 1 kW.
On focusing our attention for testing small stack (6-20 cells), some adjustments were introduced to allow accurate control and measurement of humidity content of small anodic and cathodic flow rates and to simulate actual fuel cell operation.
Both the reactant gases are controlled by mass flow controllers (Porter), and then humidified (Bronkhorst, CEM) before entering the stack. The humidity content is accurately measured by cooled mirror dewpoint meters (Michell Instruments) at the stack inlet and outlet. The overall anodic and cathodic pressure drops are measured by differential pressure transmitters (Yokogawa). The overall pressure drop measurement can be a useful data to monitor and

evaluate, coupled with single cell potential monitoring, the condition inside stack during testing.
Gas pressure control was substantially modified in the original testing station installing forward pressure regulators, before stack, to simulate the air and hydrogen supplies as in an actual low-pressure fuel cell operation.
Tested stacks have cells of two different size area (50 and 106 cm^2) with Nafion membrane electrode assembly inserted into a gasket and forming the MEGA element.
The cathodic air can be fed into the open cathodic channels from ambient by natural or forced convection (by auxiliary fans) or by a conduit using measured and controlled air.
The hydrogen can be configured in the open mode, with a continuous gas discharge, or in the dead-end mode with no flow and some periodic controlled blows by a solenoid valve.
An electronic load allows the delivered current to be fixed at the desired value.

6. Preliminary tests, stack design criteria and future works

The above considerations about fuel cell phenomena and some preliminary tests with a small commercial demonstrative SPEFC gave us useful hints about design criteria of the low-pressure stack. The demo convection fuel cell (Fuel Cell Store) has a maximum power of 100 W (@12V), vertical-parallel open cathodic channels and fans for cooling.
As first critical criterion for our stack design, the cathode side was chosen open so that air can flow directly from the environment entrained by a small blower, and reaction water droplets can drip by gravity. With open parallel vertical cathode channels, the size of the channel apertures are expected to affect both fluid flow and water removal and, consequently, the performance and stability of the fuel cell.
The air-breathing operation option, with air moved only by natural convection, was rejected due to the poor efficiency and control at low temperature during the start-up. In preliminary tests with the commercial fuel cell it was observed that a slight minimum draft, provided by an aside air flow of small fans, is needed to maintain air circulation inside cathodic channels. Strangely it was observed, always in the same set-up, that a direct upwards forced flow to cathode side produces an abnormal reduction in the fuel cell voltage.
In our stack design downwards cathodic air flow will be tested so to ease water droplets removal under the gravitational attraction, even if this can counteract the natural thermal convection at higher temperature operation.
In order to avoid reaction water to pool on GDL and channel surface, due to both surface tension and capillarity force, care is required in designing both the cathodic flowfield and anodic one as well. In fact flooding was experimentally noticed, at low-current operation, in anodic compartment of demonstrative fuel cell, even with the cathodic side apparently free of static liquid water and anode in open mode operation Early flowfield patterns are aimed to ease water removal in the last part of the channels.
As our eventual stack will run on pure hydrogen and the anode will be operated in dead-end mode, it is envisaged that water (and traces of inert gases) can build-up inside anodic compartment. The simpler method to free anodic compartment, avoiding more complex solution (e.g. hydrogen recycle and water separation), will be then to vent frequently and periodically [13].
Even if a passive and innovative thermal technology is under study to control stack heat management and reuse thermal energy to improve overall efficiency, present low-pressure fuel cell design will be directly cooled by external fans, whose power should be few percent of maximum fuel cell one. After determining maximum no-cooling performance, heat pipe cooling plates will be inserted to evaluate improvements and its limits.

At the same time, accurate measurements and evaluation of humidity conditions of fuel cell and the exiting gases will be performed for a balanced water management.

In this project the fuel cell power system is designed to operate on the only direct power supplied by the fuel cell, even if a hybrid system (with a small battery as dump load) could provide more operational duration before hydrogen refill, more steady-state behavior and a quicker response at start-up.

According to the previous design criteria, various designs of cathodic flowfields and system configurations are under study, to be realized and tested in future. By using the desktop milling rapid-prototyping technology, it is possible to produce directly the fuel cell elements with complex and original patterns in our lab, in order to rapidly test new concepts and verify hypotheses.

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