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# OPTIMAL FLUID FLOW CHANNEL ARCHITECTURES IN BIPOLAR PLATES DEDICATED TO THE OPERATION OF FUEL CELLS IN MICROGRAVITY CONDITIONS

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**Abstract.** The development of energetic applications to be used in space implies the use of high efficiency systems with low or no maintenance needs and high reliability. Such systems are the fuel cells. The efficiency of FC devices is given mainly by the working fluids, the membrane electrode assembly (MEA) and by the architecture of the bipolar plates.

The bipolar plates have three main functions: the dispersion of fluids on the MEA, the extraction of electrical energy and the extraction of heat from the cell. One of the most important aspect is the even dispersion of working fluids on the MEA. In this respect there are a large number of approaches for optimizing the way the working fluids are dispersed in order to obtain maximum efficiency from the MEA. This means that the channel architecture on the bipolar plates need to offer optimal access for the fluids in order to realize a uniform diffusion on the MEA.

The present paper aims the development of channel architectures for optimized fluid flows within the fuel cell. The architectures shall be developed based on a constructal theory approach, by optimizing the surface dimensions and the channel geometry for the point to surface access. The result is a better access for working fluids to MEA, based on the constructal generated channel, in relation to the conventional serpentine or parallel designs.

***Key words***: Constructal theory, Fuel cell, Bipolar plate, Microgravity, Optimal flow.

## 1. BACKGROUND

Fuel cells are complex systems in the modern acceptance of system theory. The main features of a complex system consist in the fact that they have a complex architecture that is also formed by other sub-systems, emerging behaviour in the sense that the structures at higher hierarchical levels have their behaviour determined by the behaviour of the systems in the lower hierarchies. In some cases they can be adaptive in the sense that the system response function adjusts according to system outputs and generally the whole system response function cannot be estimated based on the component response functions.

Fuel cells correspond to all the characteristics of a complex system, being a synthesis that integrates electrochemical reactions, mass transfer processes, heat and electric power, irreversible physical and chemical processes of degradation as well as command and control systems.

The use of fuel cells in space programs has a long history starting from the first 1kW cell used in the Gemini program, and then the 1.5 kW alkaline cells in the Apollo program, where a power of 12 kW has been reached [1].

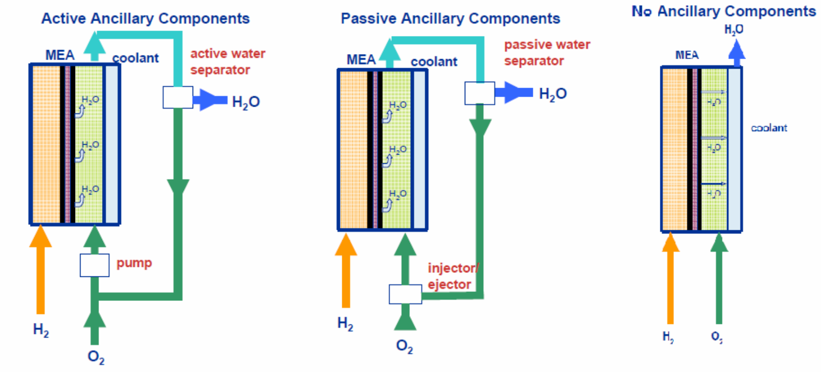

Fig. 1 – Microgravity fuel cell feeding schematics [2].

In recent years, researches have been concentrated in replacing mechanical components in fuel cell systems in order to reduce mass and power consumption and improve system reliability as a whole [3]. Concerns in the direction of thermofluid modelling of fuel cells have been related to overall problems with the administration of thermal fluxes and improvement of cell reliability [4, 5].

A synthesis of the present state of the art for fluid feeding schemes for fuel cells operating under microgravity conditions is shown in Fig. 1. Thus, it can be noticed that the hydraulic circuits are pressurized and impose a specific architecture to ensure fluid circulation both at the cell anode and cathode and through the cooling sections.

In order to optimize thermofluid flow structures there is a wide range of approaches reported in the literature. A multiscale analysis approach has been proposed in [6]. There were also developed models based on Thermoeconomics, placing a special focus on the conservation of energy resources, both in the design phase and in the operating phase of the systems through a multidisciplinary approach, combining engineering techniques with economic methods cost analysis to minimize energy consumption, emissions, and resulting waste/slurry.

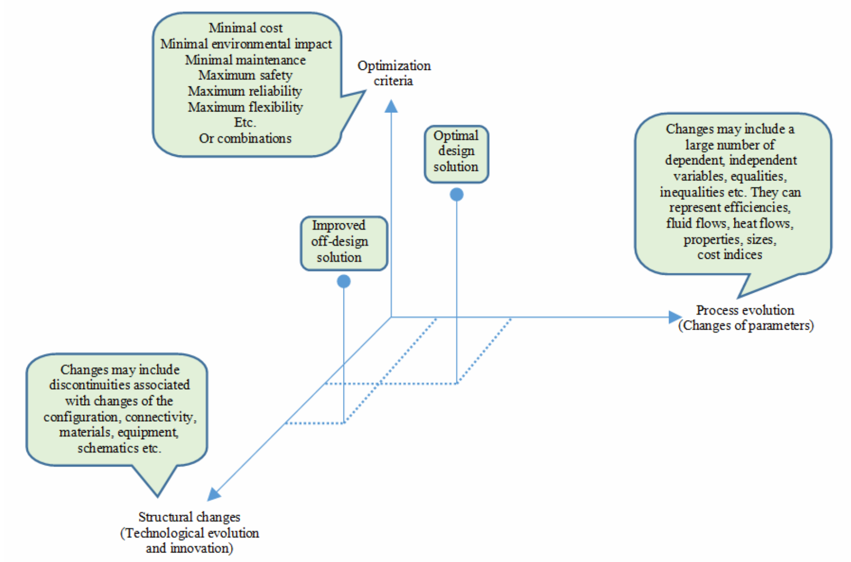

Fig. 2 – The complexity of the design space for stationary energy intensive systems.

In Fig. 2 it is proposed a graph based on the adaptation of thermoeconomic optimisation principles [7] and it presents a three-dimensional coordinate system to visualize the methodology. Thus, for a given objective function (minimum cost, minimum maintenance, etc.), an optimal design solution is characterized by an optimal structure (consisting of the components of the installation and the connections between them) and an optimal set of process parameters. From this perspective the result is that in such a complex space there can be no single optimal point. In this approach there may be several optimal solutions that can be identified at a preliminary stage and then analysed in detail.

Further developments in this direction focused more on expanding the exergy approach by introducing the concepts of cumulative exergy content and developing a common exergy reporting space for both the system (structure) and process components, respectively the exergy contained in various thermodynamic agents evolving in system components through various physical or chemical transformation processes with the constant destruction of the exergy contained. In this context, a chapter in thermodynamics called Exergoeconomy has emerged.

A development of optimization theories of thermofluid systems based on the principle of minimal entropy generated by a particular flow or heat transfer process has led to a new theory that allows a unitary approach to the relationship between process and structure called Constructal Theory [8].

Being a consecrated theory, a direction has also emerged in engineering design based on the constructional principle, called Constructal Design. One of these designs was developed also for a PEM fuel cell by Senn SM and Poulikakos D in 2004 [9].

## 2. THE DESIGN

The approach is based on the Constructal Law in general and on the applications for the optimization of fluid flows in particular. The full algorithm for the optimization is presented in the Shape and Structure, From *Engineering to Nature* [8], but for the development of the present case, there are necessary the optimization formulas for the elemental volume and for the first construct:

$$\frac{h_0}{l_0} = 2\left(\tilde{K}_0\,\phi_0\right)^{-1/2},\quad \tilde{l}_0 = 2^{-1/2}\left(\tilde{K}_0\,\phi_0\right)^{1/4},$$

$$\tilde{h}_0 = 2^{1/2}\left(\tilde{K}_0\,\phi_0\right)^{-1/4},\quad \Delta\tilde{P}_0 = \frac{1}{2}\left(\tilde{K}_0\,\phi_0\right)^{-1/2}. \tag{1}$$

For the first construct, the formulas are presented in Table 1:

*Table 1*

Formulas for the first construct

| $h_i/l_i$ | $\bar{h}_i$ | $\bar{l}_i$ | $n_i = A_i/A_{i-1}$ | $\Delta\bar{P}_i$ |
|---|---|---|---|---|
| $(2C_0/C_1)^{1/2}$ | $2^{1/2}C_0^{1/4}$ | $C_0^{-1/4}C_1^{1/2}$ | $(2C_1)^{1/2}$ | $(2C_0C_1)^{-1/2}$ |

For the development of the bipolar fuel cell design, it was considered a minimum width of the central pipe of one millimetre, which generated the shape having a length of 12.5 mm and height of 9 mm.

The first construct contained twelve elemental volumes, as it is presented in Fig. 4:

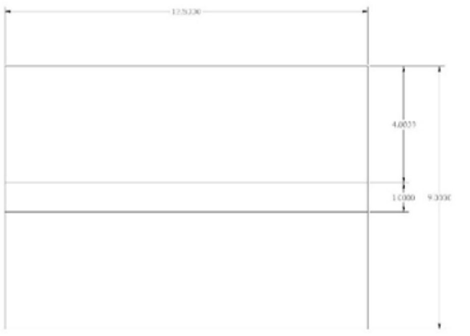

Fig. 3 – Elemental volume.

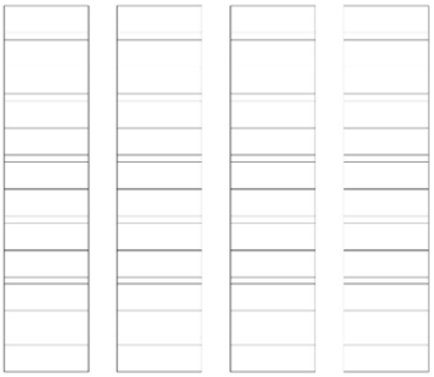

Fig. 4 – First order construct.

In Fig. 4 above, the first level construct is shaped as a rectangle. In order to cover the expected square shape of a fuel cell, there were used two identical constructs, placed next to each other.

## 3. THE ANALYSIS

The fluid flow analysis was developed by means of CFD. The obtained shape was enclosed buy a 2 mm wall, in order to contain the fluid (outer boundary).

As it can be noticed, the resulting shape has two inlets and two outlets, positioned in such a way as to allow the fluid to access the elemental volumes Fig. 5.

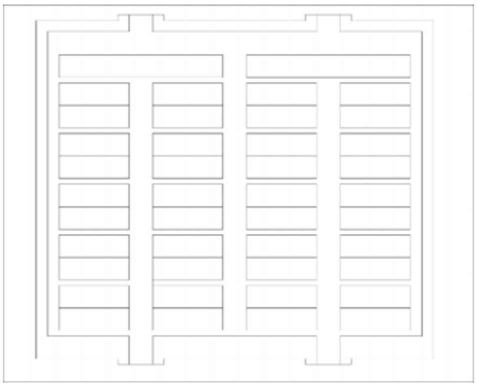

Fig. 5 – Enclosed constructs.

In order to simplify the analysis, it was extracted from the shape only the flowing channel and it was imported into the CFD analysis Fig. 6.

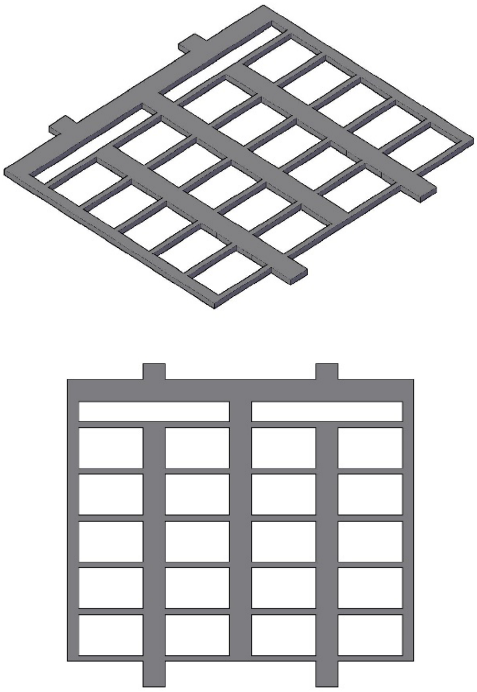

Fig. 6 – 3D flow channel.

For the analysis, it was considered a laminar flow, with two velocity inlets (bottom) and two outlets (top). The velocity flow inlet was set to 0.1 m/s and the working fluid was set to liquid urea. The exterior of the channel was set to a wall boundary condition. Gravity was set to zero.

## 4. THE RESULTS

In order to have a reference for the results of the constructal design, it was conducted a simulation of a single channel serpentine, with the same boundary and working conditions. The results are shown in Fig. 7:

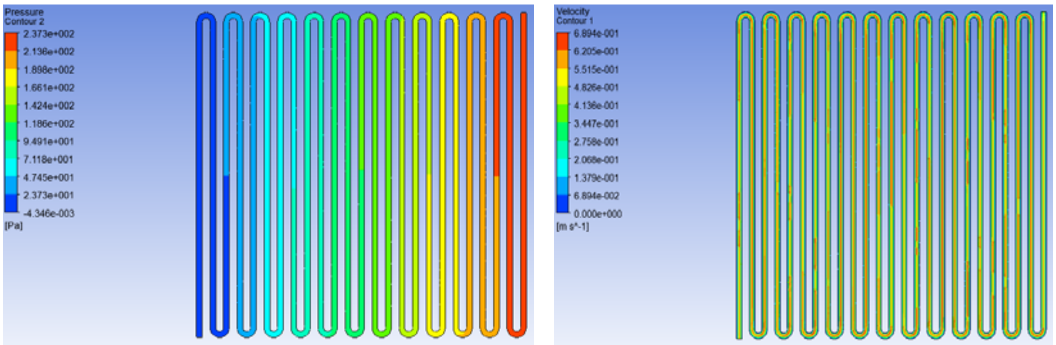

Fig. 7 – Single channel serpentine.

The results for the constructal design are shown in the figures below and are self-explanatory.

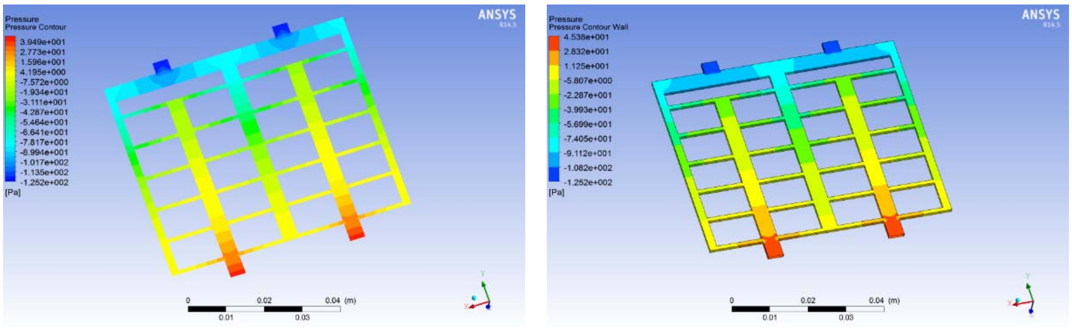

Fig. 8 – Pressure contours (left – sectioning plane, right – wall).

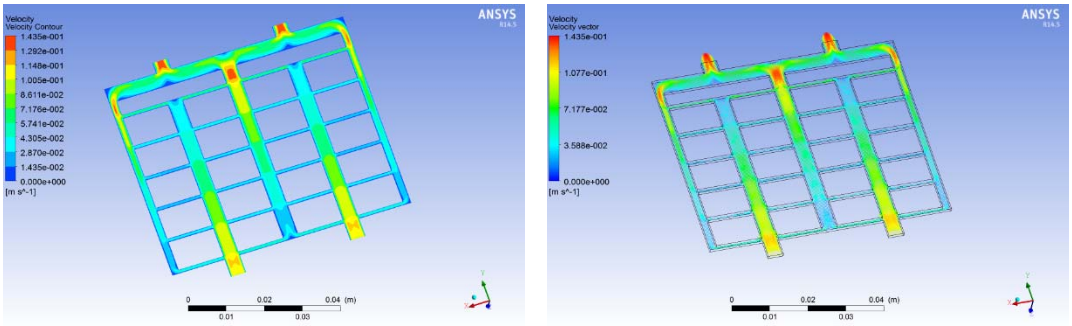

Fig. 9 – Velocity vectors (left – contours on the sectioning plane, right – 3D vectors).

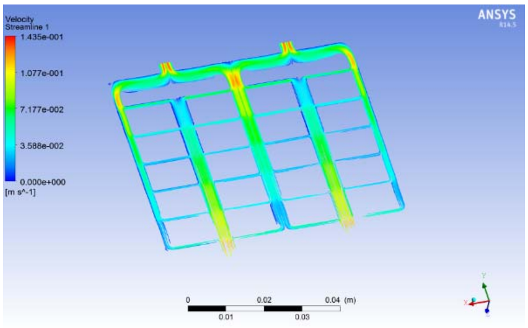

Fig. 10 – Streamlines through the analysed channel.

The most important aspect, which can be noticed from the analysis of the single channel serpentine and the constructal design, is the profile of the pressure inside the two volumes. In the single channel, the pressure builds up along the length of the channel, as in the constructal design, the pressure is distributed along the system. This leads to the possibility to increase the pressure of the system or the pressure drop, up to the maximum allowed working pressure.

## 5. CONCLUSIONS

By identifying the local and global constraints for the design, the constructal theory offers the opportunity to create a design for the flowing structures in a simple way, by considering only a basic set of parameters with the highest impact on the structure-process system.

The emerging structure in this case is rectangular, as the shape of the membrane-electrode assembly of the fuel cell is rectangular. At the moment, this form is easier and cheaper to produce, and at the same time it can be used to allow the fluid to exit the volume without major modifications. However, the next steps need to be in the development of non-rectangular shapes (e.g. the dendritic shape) for a reduction in the material raw used.

As it can be seen from the design and the analysis of the structure, in order to use the shape as an inlet and an outlet to the surface, there were considered two first constructs placed in parallel, in order to cover the envisaged area. At the same time, this conducted to a shape which presented for the outlet structure a similar optimal shape: the shape in the middle is the same first construct and the two shapes from the extremities are two halves of one construct. This translates in an optimal inlet for the fluid and an also an optimal outflow for the same fluid.

For the optimization of the flow, it can be noticed that there is a better access of fluids to the area, taking into consideration the conventional single channel serpentine. While the single channel builds up pressure as the length increases, the constructal shape distributes the pressure on the entire area or volume, producing a lower maximum pressure in the system.

The possibility to use the constructal design has a superior advantage over the classical approach of trial and error when developing new systems, as the constructal principles can be applied from the sketching phases of flow architectures, in a simple manner and with astonishing results for structure-process system optimization.

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