INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 13195–13205

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Mechanical simulation of a Proton Exchange Membrane Fuel Cell stack using representative elementary volumes of stamped metallic bipolar plates

Willy Charon [a,*], Marie-Christine Iltchev [a], Jean-François Blachot [b,c]

[a] IRTES-M3M Research, UTBM, 90010 Belfort, France
[b] Univ. Grenoble Alpes, F-38000 Grenoble, France
[c] CEA, LITEN, 38000 Grenoble Cedex 9, France

ARTICLE INFO

Article history:
Received 14 April 2014
Received in revised form
30 May 2014
Accepted 23 June 2014
Available online 16 July 2014

Keywords:
Proton Exchange Membrane Fuel Cell
Stamped metallic bipolar plates
Finite element modelling
Mechanical analysis
Homogenisation method
Representative elementary volume

ABSTRACT

The control of the performance of a fuel cell needs the knowledge of mechanical stresses. A finite element model submitted to operational static loads is developed for pure mechanical analysis of a stack. Adapted to practical implementation in the frame of industrial projects, the tool runs on work stations. Modelling and simulations at the early stage of the stack architecture development are mandatory to lower the costs of the stack and to contribute in designing component dimensions and forms, particularly of stamped metallic bipolar plates or clamping systems. The model should also be useful for accurate local analyses and channel geometry of metallic bipolar plates must be modelled in detail. But the number of degrees of freedom is huge and some model simplification is required to compute a whole stack. The homogenisation technique was applied, replacing cell parts with composite finite elements or homogenised representative elementary volumes.

This method is explained considering a single cell. Then a fuel cell stack model is built and finally computed using homogenised properties. The distribution of stresses computed at stack level can be applied as boundary conditions on detailed models to analyse local phenomena.

Introduction: from a detailed single cell to a homogenized full stack

To control the lifetime of a fuel cell, it is essential to predict the mechanical stresses. The best method to reach this objective is to model the stack using finite elements (FE) and to submit the model to the environmental and operational loads. Response simulation allows predicting the mechanical stresses that can be analysed and reworked to compute the electrical performances, or the lifetime after implementing the concepts of reliability. Of course the

* *Corresponding author*. Tel.: +33 384 58 3061; fax: +33 384 58 3146.
E-mail addresses: Willy.Charon@utbm.fr (W. Charon), Marie-Christine.Iltchev@utbm.fr (M.-C. Iltchev), jean-francois.blachot@cea.fr (J.-F. Blachot).
http://dx.doi.org/10.1016/j.ijhydene.2014.06.125

model has to be sufficiently accurate to be used in the design process.

The type of FE model depends on the purpose. In the case of PEMFC subjected to dynamic loads in transportation environments, the design of a stack connection to the chassis of a car needs a 3D dynamics model to define the eigenfrequencies of the stack [1], but a detailed description of the stack geometry is not mandatory since the data can be updated using tests. Other purposes really linked to the stack design need to estimate dynamic displacements and stresses, and require simulations taking into account the stiffness, inertial and damping forces, requiring a detailed description of the stack. The work of Ahmed [2] addresses an intermediate state (free vibration analysis). It provides insight into how the natural frequencies of the PEMFC should be tuned to avoid high amplitude oscillations by modifying the material and geometric properties of individual components. Since it was not really a design step of an actual stack, a detailed description of the bipolar plate was not necessary. Such a description is a real challenge, when applied to a multi-cell stack, as we will see later on.

Recent in-house dynamic tests showed that the mechanical dynamic response at high dynamic loads is particularly non-linear. This is due to non-linear stiffnesses as contacts between components of the cells but also to particularly complex friction phenomena. A good modelling of the stiffness into the stack is mandatory before considering the internal dynamic forces. Of course, it is not obvious that such models are appropriate in the context of transportation. But if the first eigenfrequency of the stack is high and when the connections of the stack to the vehicle provide good filtering, the external solicitations can be considered as quasi static. Then a static model, i.e. with only the internal stiffness forces, can be considered as good enough to estimate the behaviour of the stack.

A lot of local investigation studies are reported in the literature. They generally implement local 2D FE models (in opposite to full stack models). Full stack models were implemented particularly for investigation of the effect of clamping pressure on the stress distribution in the stack.

A single cell was designed for numerical simulation and experiments by Lee and all [3]. No detail is given on the meshing and the number of degrees of freedom (DoF). Good results on interfacial stresses (pressure films) are reported. Liu [4] has developed a two-cell stack model with graphite bipolar plates. The high stiffness of the graphite bipolar plates did not require particularly attention on a fine meshing. The interfacial nodes between either the bipolar plate and the membrane/electrodes assembly (MEA), or the end plate and the bipolar plate were coupled in the normal direction to model the contact behaviour. Although only two cells were considered, the number of degrees of freedom (not mentioned) should have been relatively high since the material behaviour was assumed to be linear elastic and isotropic (instead of anisotropic) in order to reduce the relatively high computation time. Another study [5] implemented an original approach appropriate for designing the stack assembly but it is not suitable for the local stresses. The stack system is considered as a mechanical equivalent stiffness model consisting of numerous elastic elements (springs) in either series or parallel connections. Basic components were defined and equivalent stiffnesses and thermal expansion coefficients were computed. Good results are reported on a single PEMFC between the spring model and a 3D FE model in the axial direction of the fuel cell. Bates [6] addressed a single-cell PEMFC and a 16-cell. Unfortunately, no detail is given on the FE meshing and model. Therefore the limits of the model are not predictable.

The number of papers dealing with the mechanical simulation of the mechanical stresses in fuel cells is increasing. The results are more and more accurate and the obtained values are used to deal, for example, with the inhomogeneous compression of the MEA or with the associated electrical contact and thermal resistances [7,8]. But none of them integrates stamped metallic bipolar plates due to the difficulty of their simulation.

We consequently decided to develop a tool for pure mechanical analysis of a stack. Adapted to a daily implementation in the frame of industrial projects, the tool runs on common work stations. To lower the cost of the stack, modelling and simulations are supposed to be carried on at the early stage of the stack architecture development. The resulting tool can contribute in the design of component dimensions and forms, particularly of bipolar plates or clamping systems.

Since the model is also used for accurate local analyses, a detailed modelling of the channel geometry of metallic bipolar plates is mandatory. The meshing is necessarily fine with consequently a dramatically high number of degrees of freedom. This is the reason why the models developed in the first phase are limited to one quarter of a single fuel cell assembly.

To determine the behaviour of a real stack with several cells under mechanical loads, some model simplification is necessary, such as the replacement of cell parts with composite finite elements. Also representative elementary volumes (REV) of bipolar plates, showing heterogeneous medium properties are replaced with homogeneous solids leading to an equivalent mechanical behaviour.

The results computed at stack level have to be applied as boundary conditions on detailed models to analyse local phenomena.

Considering the objective of the modelling work, the paper is organized as follows:

- the description of the main features of the local models considering a single cell
- the development of the homogenization method as applied to bipolar plates
- the properties of the entire fuel cell stack,
- from the results of the fuel cell stack analysis to prediction of the local behaviour

The mechanical modelling of a single fuel cell

A very good correlation was observed between FEM detailed calculations and experimental stress field obtained, for example, during assembly of a single cell stack, confirming the choice of the FEM calculation method. For comparison