Journal of Power Sources 303 (2016) 126–136

Contents lists available at ScienceDirect

Journal of Power Sources

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

Application of current steps and design of experiments methodology to the detection of water management faults in a proton exchange membrane fuel cell stack

Philippe Moçotéguy*, Bastian Ludwig, Nadia Yousfi Steiner [1]

European Institute for Energy Research (EIFER), Emmy-Noether-Str 11, 76131 Karlsruhe, Germany

HIGHLIGHTS

- DoE identifies and puts in order factors impacting water management in PEMFC.
- Two methods are developed to compensate for degradation before DoE analysis.
- Degradation changes factors impacting water management in PEMFC.
- DoE can be used for developing a diagnostic tool for faulty water management.

ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form
21 October 2015
Accepted 23 October 2015
Available online 11 November 2015

Keywords:
PEMFC
Current steps
Dynamic behaviour
Water management
Design of experiments
Fault detection

ABSTRACT

We apply a 2^{5-1} fractional factorial Design of Experiments (DoE) test plan in order to discriminate the direct effects and interactions of five factors on the water management of a 500 We PEMFC stack. The stack is submitted to current steps between different operating levels and several responses are extracted for the DoE analysis. A strong ageing effect on stack and cell performances is observed. Therefore, in order to perform the DoE analysis, responses which values are too strongly affected by ageing are “corrected” prior to the analysis. A “virtual” stack, considered as “healthy”, is also “reconstructed” by “putting in series” the cells exhibiting very low performance drop.

The results show that stacks and cells' resistivities are mostly impacted by direct effects of both temperature and cathodic inlet relative humidity and by compensating interaction between temperature and anodic overstoichiometric ratio. It also appears that two responses are able to distinguish a “healthy” stack from a degraded stack: heterogeneities in cell voltages and cell resistivities distributions. They are differently impacted by considered effects and interactions. Thus, a customised water management strategy could be developed, depending on the stack's state of health to maintain it in the best possible operating conditions.

1. Introduction

As the levels of available fossil fuel decrease and as pollutant emissions need to be reduced, alternative energy resources gain more and more attention. Among them, the proton exchange membrane fuel cells (PEMFCs) are one of the most promising candidates for both stationary and automotive applications, as a substitute to traditional systems such as internal combustion engines. They indeed possess several highly advantageous features such as: high efficiency, high power density, low environmental impact, low operating temperature (under 80 °C), simplicity in construction and operation. It can also sustain operation at high current or in discontinuous mode and fast power response at normal temperature [1]. However, their large deployment into the market is still hindered by some issues like low lifetime, reliability and robustness. And, amongst all the related causes, water management is one of the most critical [2,3].

Besides this, due to the rapidly increasing cost of experiments at stack or system levels, efficient experimental approaches are

---

* Corresponding author.
E-mail addresses: mocoteguy@eifer.org (P. Moçotéguy), ludwig@eifer.org (B. Ludwig), nadia.steiner@univ-fcomte.fr (N. Yousfi Steiner).

[1] Current affiliation: LABEX ACTION CNRS, FEMTO-ST UMR CNRS 6174, FCLAB Research Federation FR CNRS 3539, University of Franche-Comté, rue Thierry Mieg, 90010 Belfort, France.

http://dx.doi.org/10.1016/j.jpowsour.2015.10.078

Nomenclature

a	DoE coefficient
A	Vector of DoE coefficients
C	Coefficient of dispersion matrix
e	Error
h	Relative humidity [%].
k	Number of factors
N	Total number of experiments
p	Number of DoE model coefficients
r	Number of replicates
s	Overstoichiometric ratio.
t	Time [s]
T	Temperature [K]
U	Voltage [V]
x	DoE equivalent model parameter
X	Design matrix
y	Response value at a given operating condition
Y	Vector of responses

Greek letters

α	Confidence level
β	DoE equivalent model coefficient
ϕ	Heterogeneity in cell resistivity distribution
ρ	Resistivity [$\Omega.m^2$]
σ	Standard deviation
χ	Reduced centred factor
ψ	Heterogeneity in cell voltage distribution

Subscript, superscript

a	Anode
LOF	Lack of fit
PE	Pure error
c	Cathode
corr	corrected
dc	Domain centre
dew	Dew point
exp	experimental
i, j	Identifier number
int	interpolated
η	Double layer capacitance charging
$\bar{}$	Average
$\hat{}$	Estimated

required to minimize the number of runs without sacrificing quality. With this aim, Design of Experiments (DoE) methodology already proved its strong added value in both research and industrial applications. Moreover, this methodology provides an empirical model with studied factors and interactions as parameters that bring additional added value to the experiments. Finally, the underlying statistical and modelling approaches of Design of Experiments facilitate the interpretation of the results, especially for the understanding and the optimization of complex systems [4–8].

As shown in 2009 by Wadhame et al. [9], DoE have already widely been used in the development of materials, components, stacks and even systems performance evaluation. Since then, some other studies used the design of experiments approach for experimental studies of the effect of components manufacturing process [10,11] or nature [12,13] together with cell design [14–16] or operating conditions [13–15,17] on the performances of a PEMFC. Some other studies were also related to the characteristics of the humidifier [18] or reformer [19] on their performance. Finally, some studies aimed, through the approaches underlying the design of experiments methodology, at modelling the performance and behaviour of PEMFC.

Amongst all these studies, only few of them are related to the impact of operational parameters on water management:

- Torchio et al. [20] studied the influence on the electric and thermal powers of a 800 W_e PEMFC stack of some cathodic variables involved in water management: cathodic flow inlet temperature, humidity level and overstoichiometric ratio. They showed that the inlet flow temperature has a significant positive effect on the electric power whatever the current density and that overstoichiometric ratio has a significant positive effect, especially at high-current density on electric power and negative effects on the thermal power. However, humidity level does not have any significant effect on either electric or thermal power, whatever current density level. These results were explained by water flooding in the cathode flow channels.
- Flick et al. [13] discerned and quantified the effect of a microporous layer (MPL) on the impact of water management on the voltage and the cathodic pressure drop in a single cell PEMFC.
- Kahveci et al. [17] optimized the output power density of a 25 cm^2 single cell by studying the effect of reactant flow rates and both operating temperature and humidity level. They found that the humidification and cell temperature are the main factors affecting the power density.

However, none of these works deal with the influence of operational parameters on the effect of water management in the distribution of cell performance and dynamic behaviour of a full stack, as characterized by a high enough data acquisition frequency. Also, none of them applied this methodology to the development of a diagnostic tool.

2. Design of experiments approach

DoE methodology relies on [4–8]:

- Randomization of the experiments order. Both the allocation of the experimental material and the order in which the individual runs are performed are randomly determined. This merges all the sources of variability (uncontrolled or nuisance factors, sensor drift, general background noise in the process, …) within the experimental error.
- Replication of the experiments. This aims at identifying the sources of variability both between runs and potentially within runs and at determining whether the observed differences are statistically significant. Usually, replicates (at very least 3, better 5) are performed at a single standard reference point, which is commonly the domain centre. In such case, the replicates must be regularly spread all along the experimental sequence in order to detect potential “unusual” behaviour: ageing, drift of the response, impact of uncontrolled or nuisance factors during the experimental sequence, …
- The postulate of an a priori empirical Multi Linear Regression (MLR) mathematical model of the response with considered reduced centred factors and interactions as parameters. Its