PhD thesis topic

Title: Modeling and simulation of the unsteady behavior of multi-stack fuel cell systems for transport applications

Laboratory : LHEEA UMR 6598 (team D2SE) Centrale Nantes
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Duration : 36 months
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Partners : LIFSE Laboratory (ENSAM Paris) and LAMIH Laboratoire (UPHF Valenciennes)
Keywords : fuel cell, modeling, simulation, optimization, thermal management, fluidic management, multi-stacks, control.

Context :

Hydrogen is a major candidate for the energy transition, enabling the storage of renewable energy and the decarbonization of mobility. Although current hydrogen production is mainly based on fossil fuels, the development of renewable and nuclear energy will allow low-carbon production. It will also be possible to use hydrogen production as a means of storing energy from fluctuating sources or during periods of low electricity demand.

Fuel cells are sensitive and expensive systems compared to conventional propulsion systems. One way to reduce the price of fuel cells is the mass production of standardized products that can then be combined to get the power required for different applications [1]. A single cell (e.g. 70 kW) can be used for passenger cars, while 3 or 4 cells will have to be combined for heavy-duty vehicles. This seems to be the industrial strategy targeted by vehicle and fuel cell manufacturers. The cost of Electrode-Membrane Assemblies could be reduced by a factor of 3 to 4, as highlighted by the analysis of Thompson et al. [2]. In this analysis, it is shown that the cost of auxiliary equipment (thermal, fluidic, electronic and control) accounts for about 50% of the total cost, with a contribution of 25% and 11% for the air loop system and cooling circuits, respectively.

In addition to the system cost, its performance also strongly depends on the efficiency of the thermal management systems and the air loop. The efficiency and durability of fuel cells can be improved through appropriate thermal and energy management, particularly with regard to temperature, humidity and pressure [3][4]. Precise control of the air supply and pressure is necessary to ensure efficient operation and avoid problems such as air shortage or cell blockage [5].

It is worth noting that the power absorbed by the air compressor can reach 10–25% of the net power produced by the fuel cell system [6], but with a well-designed balance of auxiliary equipment, an increase in air pressure can increase the power produced by up to 22% [7]. Cooling circuits must maintain the cell within a given temperature range for optimal performance [7] and under a specific temperature limit (typically 80 °C) to ensure its durability. This must be guaranteed under all circumstances and operating conditions, otherwise the cell membranes will deteriorate.

This is particularly complex due to the reduced maximum temperatures of the coolant compared to internal combustion engines, which requires the design of compact but efficient heat exchangers and fans [8]. These challenges become even more crucial for heavy-duty vehicles operating at reduced speeds. For on-road and off-road vehicles, significant variations in energy consumption result from various usage scenarios, leading to transient operations.

Large capacity batteries and large cooling water tanks can mitigate transient effects on the fuel cell, but this increases the cost and size of the system. Thus, the transient response capability of a fuel cell system represents a trade-off between equipment size and cost.

This thesis is part of a project involving several laboratories working on the experimental and numerical study of fuel cells in propulsion and their auxiliary systems.

Thesis progress:

The definition of the targeted power for multi-stack systems will be carefully studied at the beginning of the project in order to obtain the most representative results.

Simulations of the targeted multi-stack fuel cell system will be performed. They will provide the requirements and input parameters for the design of the air loop and cooling loop components (compressor, pump, fan, exchanger), including their interactions. This simulation will serve as a reference for comparison with improved models and optimized design of the air loop and cooling systems. Different duty cycles for transport applications will be defined and simulated to calculate efficiency, autonomy and consumption. The potential of replacing some component models or sub-models with neural networks or physics-guided neural networks will also be explored. This should significantly reduce the computation time while maintaining good accuracy. This approach has been successfully tested by Hubel et al [9]. Based on the experience gained with hybrid vehicles, a hierarchical control of the fuel cell system will be developed [10]. At the higher level, optimal control will be used to calculate low-level closed-loop setpoints (pressure, humidity, cooling, etc.) in order to maximize a criterion such as energy efficiency while taking into account the degradation of the fuel cell system. A low-level nonlinear control will then be used to ensure robust monitoring of these setpoints [11][12].

The work carried out during this thesis will provide a model of multi-stack fuel cell systems with its auxiliary systems, in steady-state and transient operation for transport and mobility applications. The work will start with a literature study to build a model from the existing and size the fluidic and thermal loops. This information will be used in the other works of the project, which will work on their side on the air supply systems and the thermal management systems. They will propose improved systems that will have to be integrated into the complete model and see their impact in stabilized operation and in transient operation. Energy efficiency will be an element to observe, but also the impact of the system and its operation on the life of the components. Real cycles will be tested in normal and extreme conditions.

The modeling will be done on an open source software of MODELICA language.

This thesis is part of a collaboration between the LHEEA (Centrale Nantes), LIFSE (ENSAM) and LAMIH (UPHF) laboratories as part of a generic ANR Call for Projects. The collaboration between the three laboratories is the ALTOS project: Air Loop and Thermal management Optimization for fuel cell Systems.

The thesis will be co-supervised by researchers from the LHEEA laboratory and the LIFSE laboratory. The workplace will be at the LHEEA laboratory in Nantes in the D2SE team with planned trips to the LIFSE in Paris. The LHEEA of Centrale Nantes is a joint research unit associated with the CNRS (UMR6598). Its research activities are organized around 4 scientific themes: Ocean engineering, Marine and urban atmospheric flows, Thermodynamics of energy systems and Hydrodynamics for health. The research objective of the D2SE team (Decarbonization and Decontamination of energy systems) is the modeling and experimental characterization of complex energy systems, with the societal aim of reducing the consumption of fossil fuels and pollutant emissions. The team has created strong links with the industrial sector, in fact, its field of research has strong societal and environmental impacts.

Laboratory LHEEA : https://lheea.ec-nantes.fr/
Laboratory LIFSE : https://lifse.artsetmetiers.fr/
Laboratory LAMIH : https://www.uphf.fr/lamih

Candidate profile:

- Engineering degree or Master's degree in Energy, Thermal and/or Fluid Mechanics
- Interest in experimental measurement techniques and modeling
- Rigorous, dynamic, enterprising
- Able to work in a team

To apply:
Send a CV, a cover letter, your academic results (transcripts of grades for the last three years) and a letter of recommendation to: georges.salameh@ec-nantes.fr

Références bibliographiques :

[1] M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, D. Hissel, "Hydrogen energy systems: A critical review of technologies, applications, trends and challenges," Renewable and Sustainable Energy Reviews, Vol. 146, 2021.

[2] S. T. Thompson et al. *Direct hydrogen fuel cell electric vehicle cost analysis: System and high-volume manufacturing description, validation, and outlook*. J. Power Sources, vol. 399, no. March, pp. 304–313, 2018

[3] L. Xing, et al. *Modeling and thermal management of proton exchange membrane fuel cell for fuel cell/battery hybrid automotive vehicle*. International Journal of Hydrogen Energy, 2022.

[4] Zhou, S., Xie, Z., Chen, C., Zhang, G., & Guo, J. (2022). Design and energy consumption research of an integrated air supply device for multi-stack fuel cell systems. Applied Energy, 324, 119704.

[5] Y. Qiu, T. Zeng, Caizhi Zhang, G. Wang, Y. Wang, Z. Hu, M. Yan, Z. Wei. Progress and challenges in multi-stack fuel cell system for high power applications: Architecture and energy management, Green Energy and Intelligent Transportation, Volume 2, Issue 2, 2023

[6] Y. Wan et al. *Improved empirical parameters design method for centrifugal compressor in PEM fuel cell vehicle application*. International Journal of Hydrogen Energy, 42, 2017.

[7] Vidović, Tino, Ivan Tolj, Gojmir Radica, et Natalia Bodrožić Ćoko. Proton-Exchange Membrane Fuel Cell Balance of Plant and Performance Simulation for Vehicle Applications. Energies 15, n° 21, 2022.

[8] H. S. Lee, et al. *Cooling performance characteristics of the stack thermal management system for fuel cell electric vehicles under actual driving conditions*. Energies, vol 9-5, 2016.

[9] M. Hübel, N. Nirmala, M. Deligant, L. Li. Hybrid physical-AI based system modeling and simulation approach demonstrated on an automotive fuel cell. 2022 Modelica Asian Conference, Tokyo, Japan.

[10] S. Delprat and M. Riad Boukhari. Reducing the Computation Effort of a Hybrid Vehicle Predictive Energy Management Strategy. IEEE Transactions on Vehicular Technology, vol. 70, no. 7, pp. 6500-6513, July 2021.

[11] C. Armenta Moreno, S.Delprat, R. R. Negenborn, A. Haseltalab, J. Lauber, M. Dambrine (2022). Computational reduction of optimal hybrid vehicle energy management. IEEE Control Systems Letters (L-CSS), vol. 6, pp. 25-30

[12] Nguyen C., Nguyen A.-T., Delprat S. (2023). Neural-Network-Based Fuzzy Observer with Data-Driven Uncertainty Identification for Vehicle Dynamics Estimation under Extreme Driving Conditions: Theory and Experimental Results. IEEE Transactions on Vehicular Technology