IOP Conference Series: Materials Science and Engineering

Development of a PEMFC dynamic model and the application to the analysis of fuel cell vehicle performance

IOP Conf. Series: Materials Science and Engineering **628** (2019) 012006 doi:10.1088/1757-899X/628/1/012006

Development of a PEMFC dynamic model and the application to the analysis of fuel cell vehicle performance

Wei Liu[1], Zhijun Peng[2], Bill Kim[3], Bo Gao[3], Yiqiang Pei[1]

[1]State Key Lab of Engines, Tianjin University, China
[2]Faculty of Creative Arts, Technologies and Science, University of Bedfordshire, UK
[3]AVL Powertrain, UK

Corresponding author's e-mail: Jun.Peng@beds.ac.uk

Abstract. In order to investigate basic output performances of PEMFC (Proton Exchange Membrane Fuel Cell) stack, a dynamic model of PEMFC stack has been developed by combining electrochemical sub-model and thermodynamic sub-model. With necessary validation, it demonstrates that modelling results and experimental data are in very good agreement in terms the U-I curve and power output. By applying the dynamic model to analyse performance outputs of PEMFC stack and applying the model for FC-Hybrid vehicle powertrain configuration, it demonstrates that improved PEMFC quality with increased maximum current density could increase the peak power output and also increase the working efficiency, although the increase of peak power is not linear relation with the increase of maximum current density. Higher working temperature of PEMFC would benefit the increases of both peak power output and efficiency. Compared to working temperature, ambient temperature's increase could also make positive influence on power output and efficiency, though the influence is weak. Coupling the dynamic model with a powertrain model of FC-Electric hybrid vehicle, the analysis suggests that both PEMFC stack and battery stack should have similar size for general driving condition. Too big either PEMFC stack or battery stack would increase the total weight then contaminate the fuel/energy economy.

1. Introduction

Along with the commercialisation of ground electric vehicles including hybrid vehicles and battery vehicles, the development of FCVs (Fuel Cell Vehicles) has been rapidly accelerated in recent years. Toyota Mirai, Honda Clarity, Hyundai ix35 PEMFC have been sold for several years. Compared to plug-in battery (hybrid or pure battery) electric vehicles, it is boosted that FCVs have obvious advantages for using more clean energy [1, 2].

Researches around fundamentals of fuel cells have been carried out widely and deeply in both academic and industrial fields, with both advanced experimental methods and numerical simulations. For meeting the product development of FCVs, more and more works for the FC powertrain configuration and the integration with other relating systems are urgently required, in terms of improved power density, cell durability, more effective catalyst loading, manufacturing cost reduction, and so on [3, 4]. While a comparable driving range as compared to HEVs (Hybrid Electric Vehicles, normally with combustion engines) and BEVs (Battery Electric Vehicles) is currently very important from the customer's viewpoint, fuel consumption or energy consumption is always the firstly critical factors for vehicle developers.

As there exist highly coupled, non-linear transport phenomena and electrochemistry in fuel cell, modelling therefore plays an important role in giving an understanding of what is happening inside a cell where the typical length scale of a few microns to millimetres poses some difficulties on experimental work. In addition to wide CFD (Computational Fluid Dynamic) investigations to internal flows and external cooling systems [5, 6], various control models [7, 8] and dynamic models [9, 10] have been developed and applied for studying some fuel cell components' performances or entire stack systems' operating performances.
It is therefore the objective of this study to build a dynamic model of PEMFC stack which can be easy to couple with FCV powertrain model for exploring the powertrain's working performances under various design and operating conditions.

2. Model description

2.1 Model structure and sus-models
The dynamic model of PEMFC stack mainly consists of two main sub-models, electrochemistry and thermodynamic models. As shown in Figure 1, the electrochemistry includes Nernst potential model, ohmic losses, concentration losses and activation losses. The thermodynamic model combines mass and energy conservation, heat transfer, water management, etc.

2.2 Model validation
To validate the dynamic model of PEMFC stack, experimental data based on a 2 kW Horizon PEMFC stack have been used. The test system is shown in Figure 2.

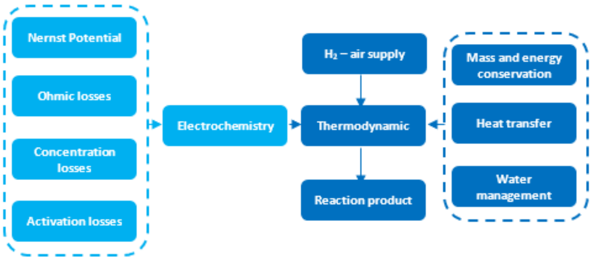

Figure 1 PEMFC dynamic model structure

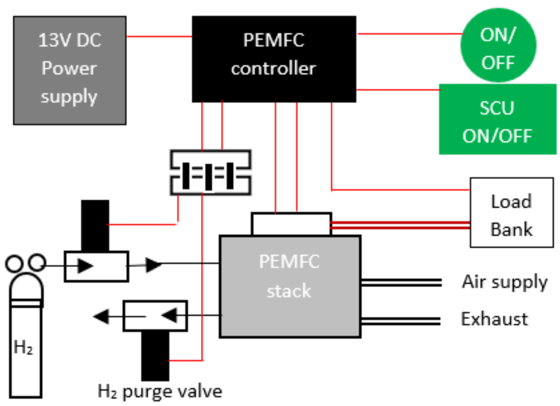

Figure 2 Fuel cell stack and test system

From the results shown in Figure 3, it demonstrates the modelling output for the U-I curve and power output as function of current. When the model can produce a very reliable results which are in very good agreement with the experimental data, as reflected on U-I curve and power output, it suggests the model can be used to simulate PEMFC output with adequate confidence.

3. Results and discussion

Based on successful validation to the dynamic model, PEMFC output performances and effects of some design parameters and operating parameters were studied with the model. In the final section of 'Results and Discussion', the PEMFC dynamic model is used for coupling with a FC-Electric hybrid vehicle model to examining the optimal integration between PEMFC stack and battery stack.

3.1 FC Stack performances

Applying PEMFC (Proton Exchange Membrane Fuel Cell) stack to vehicle powertrain, it is more concerned of the fuel consumption rate and powertrain energy efficiency. As shown in Figure 4, modelling results of SHC (Specific Hydrogen Consumption) and efficiency as function of power output of fuel cell stack are presented and compared with experimental results. Basically, the fuel cell stack's efficiency is following the variation of the voltage and with some similar trend. At the peak power point, the efficiency is about 40%, which is very similar as diesel engines' efficiency of peak power.

But the efficiency at part-load is much higher than full load, and it reaches the max value while the power output is going down to the point close the idle condition. Based on this, the specific hydrogen consumption is lower under low load condition than high load condition.

In terms of the comparison between experimental results and modelling results, it shows the model has produced very successful prediction for the efficiency. Although for the hydrogen consumption rate, there is some small gap between experimental data and modelling results at some power value, it has very good agreement for the trend.

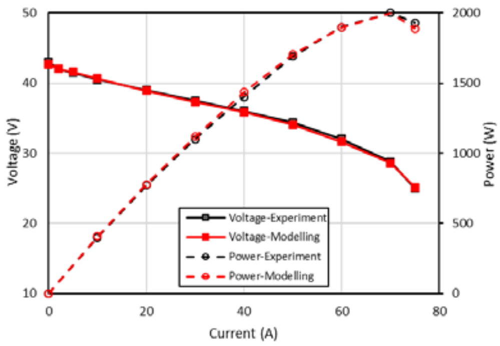

Figure 3 Model validation result

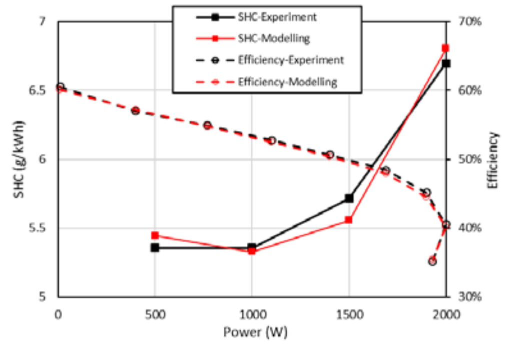

Figure 4 SHC (Specific Hydrogen Consumption) and efficiency as function of power

3.2 Effects of design parameters

For this case, three kinds of PEMFC with different maximum current densities 0.5 A/cm2, 1.0 A/cm2 and 1.5 A/cm2, respectively, are compared. As different current density reflects different design and manufacture quality, the higher the current density is, the higher the power output produces for the same fuel cell size.

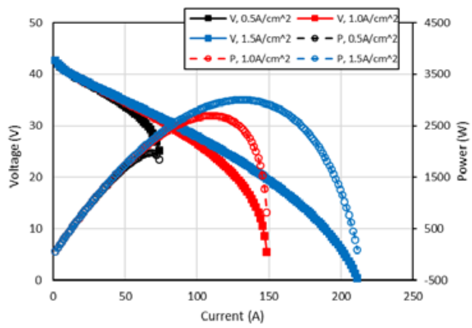

Figure 5 Effects of fuel cell quality on outputs of voltage and power

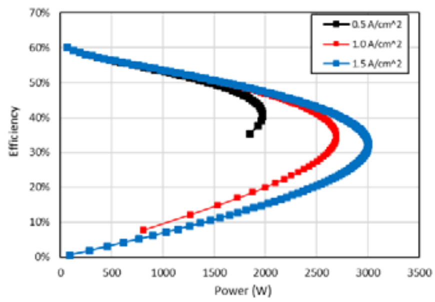

Figure 6 Variation of efficiency as function of power with different fuel cell quality

The voltage and power outputs as function of the current density are demonstrated in Figure 5. From U-I and Power-I curves, it can be found, although higher maximum current density can result in voltage output at higher current and make the maximum power output higher, the increase of power output is not linear as the increase of maximum current density. From 0.5 to 1.0 to 1.5 A/cm2 of maximum current density, the peak power outputs are 1.97 kW to 2.69 kW to 3.00 kW. The efficiencies for three different current density are presented in Figure 6. From the results, it suggests that efficiencies at the peak power point get apparent reduction with the increase of maximum current density. With 0.5 A/cm2 of maximum current density, the efficiency at the peak power of 1.97 kW is about 41.16%. But it decreases to 34.64% at 2.69 kW for 1.0 A/cm2, and to 32.02% at 3.00 kW for 1.5 A/cm2.

If keeping all of those three maximum current densities working at 41% of efficiency, the power output can increase from 1.97 kW to 2.50 kW and 2.67 kW, respectively.

3.3 Effects of operating parameters

To find how the working temperature influences the output performances, the simulation has been carried out with the dynamic model and results are presented in this section. As shown in Figure 7 and Figure 8, the results are produced by just changing the working temperature but keeping other parameters constant. From the U-I curve, it shows that under low current condition, the voltage output keeps decrease with the increase of working temperature. This is mainly due to increased working temperature making the activation losses increased. Under high current condition, higher working temperature makes the concentration losses reduced, resulting in higher voltage output. Then this is beneficial for some obvious increase of peak power output. For 30, 65 and 100 °C of working temperature, the peak power output can increase from 1.79 to 1.97 to 2.14 kW, respectively.

In addition to the increase of maximum power output by increased working temperature, the working efficiency has also apparent increased under high load condition. As presented in Figure 8, the efficiency at maximum power output point (1.79, 1.97 and 2.14 kW) are 38.31%, 41.16% and43.79%, respectively. If keeping the fuel cell stack working under 45% of efficiency, the power outputs are 1.64 kW, 1.87kW and 2.12 kW, respectively, for three working temperatures.

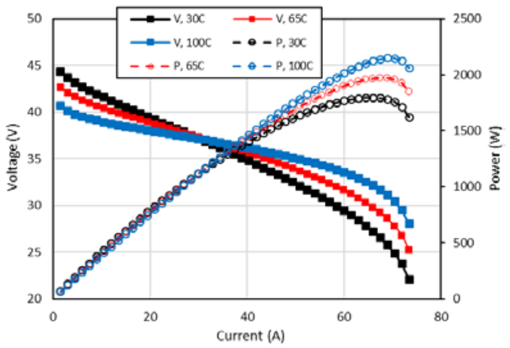

Figure 7 Effects of working temperature on outputs of voltage and power

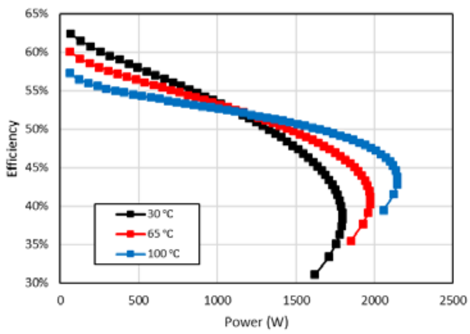

Figure 8 Effects of working temperature on efficiency

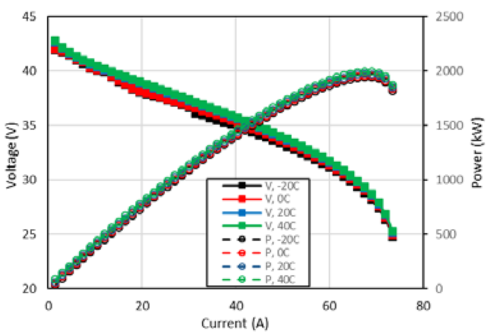

Figure 9 Effects of ambient temperature on outputs of voltage and power

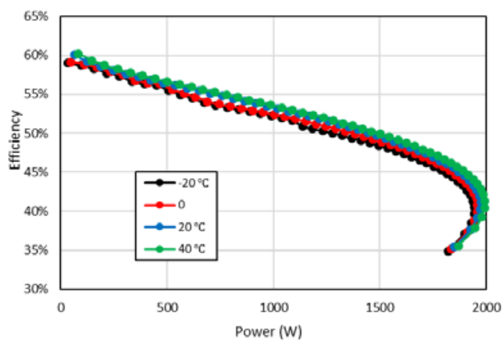

Figure 10 Effects of ambient temperature on efficiency

The next case is for changing ambient temperature but keeping other parameters constant. As shown in Figure 9, the voltage output will have slight increase with increased ambient temperature, this should be due to reduced ambient temperature reducing heat losses from the PEMFC stack to cooling air. Then from -20 to 40 °C, the maximum power output can increase from 1.94 kW to 1.99 kW, about 2.58% increase rate. As shown in Figure 10, effects of ambient temperature on PEMFC efficiency can't be also ignored, in particular under part-load conditions where are the general working area of road vehicles. For instance, if the ambient temperature increases from -20 °C to 40 °C at 1 kW, the efficiency can increase from 52.23% to 53.61%, with an increased rate of about 2.64%. At the peak power point, the efficiencies are 40.53% and 41.30% for -20 °C and 40 °C, respectively.

3.4 Application on vehicle performance analysis

By applying the dynamic model of PEMFC stack into vehicle powertrain model, different hybrid configurations (FC-Electric), as shown in Figure 11, were explored. The top configuration is more like current passenger FCV as developed in Toyota Mirai. The vehicle model can also consider other cases, such as plug-in hybrid (FC-Electric) as shown as the middle one in Figure 11, and much bigger battery stack as shown as the bottom one in Figure 11. By analysing the hybrid configuration detail with the vehicle powertrain model, coupled with the PEMFC dynamic model, the optimal integration between PEMFC stack and battery stack has been produced, as shown in Figure 12.

As shown in Figure 12, in order to achieve the lowest fuel/energy consumption, the optimal integration between PEMFC stack and battery stack is about 50 kW battery size and 60 kW PEMFC stack, for the analysed vehicle case. To increase either PEMFC stack size or battery stack size would make the powertrain too heavy, then increase fuel/energy consumption. If the battery pack is too small, the fuel/energy consumption would also increase because of the lack of adequate energy regeneration.

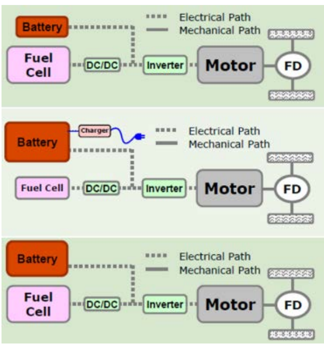

Figure 11 FCV powertrain configuration

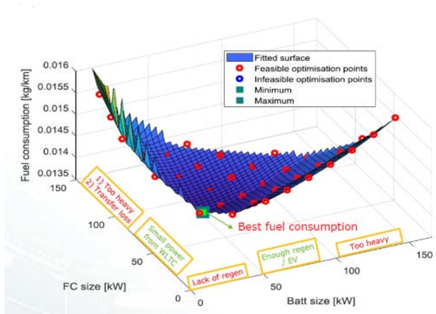

Figure 12 Optimised FC stack size and battery size for FCV

4. Conclusions

In this reported research, a dynamic model of PEMFC stack has been developed by combining electrochemical sub-model and thermodynamic sub-model. The validation demonstrates that modelling results and experimental data are in very good agreement in terms the U-I curve and power output. By applying the dynamic model to analyse performance outputs of PEMFC stack and applying the model for FC-Hybrid vehicle powertrain configuration, the following conclusions have been derived.

- Improved PEMFC quality with increased maximum current density could increase the peak power output and also increase the working efficiency, although the increase of peak power is not linear relation with the increase of maximum current density.
- Higher working temperature of PEMFC would benefit the increases of both peak power output and efficiency.
- Compared to working temperature, ambient temperature's increase could also make positive influence on power output and efficiency, though the influence is weak.

- Coupling the dynamic model with a powertrain model of FC-Electric hybrid vehicle, the analysis suggests that both PEMFC stack and battery stack should have similar size for general driving condition. Too big either PEMFC stack or battery stack would increase the total weight then contaminate the fuel/energy economy.

5. Recommendations for the future research – a). the model can be optimised to include different cooling conditions, such as air cooling and water cooling. b). the model can be improved to consider possible leaking of hydrogen, because it has been found hydrogen leaking is an important factor for influencing hydrogen consumption rate in practical PEMFC vehicles.

6. Reference

[1] Pouria Ahmadi, Seyed_Hosein Torabi, Hadi Afsaneh, Yousef Sadegheih, Hadi Ganjehsarabi, Mehdi Ashjaee, The effects of driving patterns and PEM fuel cell degradation on the lifecycle assessment of hydrogen fuel cell vehicles, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2019.01.165, 2019.
[2] Farah Ramadhani, M. A. Hussain, Hazlie Mokhlis, Muhamad Fazly, Jarinah Mohd Ali, Evaluation of solid oxide fuel cell based polygeneration system in residential areas integrating with electric charging and hydrogen fueling stations for vehicles, Applied Energy, Volume 238, Pages 1373-1388, 2019.
[3] Zhifeng Xia, Bowen Wang, Zirong Yang, Kangcheng Wu, Qing Du, Kui Jiao, Effect of operating conditions on performance of proton exchange membrane fuel cell with anode recirculation, Energy Procedia, Volume 158, Pages 1829-1834, 2019.
[4] Tao Chen, Shihua Liu, Jiwei Zhang, Mengnan Tang, Study on the characteristics of GDL with different PTFE content and its effect on the performance of PEMFC, International Journal of Heat and Mass Transfer, Volume 128, Pages 1168-1174, 2019.
[5] Guobin Zhang, Kui Jiao, Multi-phase models for water and thermal management of proton exchange membrane fuel cell: A review, Journal of Power Sources, Volume 391, Pages 120-133, 2018.
[6] Z. Peng, P. Choopanya, CFD Investigation into Internal Flows of PEM Fuel Cell for Optimal Performances, Advanced Materials Research, Vol.724-725, PP757-761, 2013.
[7] Zhixiang Liu, Lun Li, Yi Ding, Huiwen Deng, Weirong Chen, Modeling and control of an air supply system for a heavy duty PEMFC engine, International Journal of Hydrogen Energy, Volume 41, Issue 36, Pages 16230-16239, 2016.
[8] Lianghui Huang, Jian Chen, Zhiyang Liu, Mohamed Becherif, Adaptive thermal control for PEMFC systems with guaranteed performance, International Journal of Hydrogen Energy, Volume 43, Issue 25, Pages 11550-11558, 2018.
[9] A. Saadi, M. Becherif, D. Hissel, H. S. Ramadan, Dynamic modeling and experimental analysis of PEMFCs: A comparative study, International Journal of Hydrogen Energy, Volume 42, Issue 2, Pages 1544-1557, 2017.
[10] Zhen Wu, Peng Tan, Bin Chen, Weizi Cai, Meina Chen, Xiaoming Xu, Zaoxiao Zhang, Meng Ni, Dynamic modeling and operation strategy of an NG-fueled SOFC-WGS-TSA-PEMFC hybrid energy conversion system for fuel cell vehicle by using MATLAB/SIMULINK, Energy, Volume 175, Pages 567-579, 2019.

Acknowledgement
The authors would like to acknowledge the financial support to the work reported here by Innovate UK through the project of FCHCV (113618), and the contribution from research assistants Xinyu Wang, Zhisheng Gu and Keni Huang for result processing.