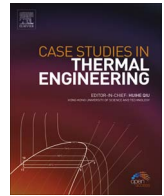


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Heat management methodology for enhanced global efficiency in hybrid electric vehicles

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ABSTRACT

The transportation impact on pollution and global climate change, has forced the automotive sector to search for more ecological solutions. Owing to the different properties of Fuel Cell (FC), real potential for reducing vehicles' emissions has been witnessed. The optimization of FC integration within Electric Vehicles (EVs) is one of the original solutions. This paper presents an innovating solution of multi-stack Fuel Cell Electrical Vehicle (FCEV) in terms of efficiency, durability and ecological impact on environment. The main objective is to illustrate the interest of using the multi-stack FC system on the global autonomy, cycling, and efficiency enhancement, besides optimizing its operation performance.

1. Introduction

Global warming and energy crisis are among the serious issues that threaten both developed and developing countries because of their ill-effects on the planet. However, no concrete solution is introduced to curb the expected undesired impacts. According to the International Energy Agency (IEA), the global CO₂ emissions from fuel combustion increase annually starting at 15.5Gt in 1975 to 32.1 Gt in 2015 [1]. In emerging countries, the witnessed CO₂ and NO_x emission rise rates are considerably accounted for through relevant scientific researches, political plans and roadmaps, besides both economic and environmental strategies. China is the highest CO₂ emitter since 2006 reaching 8.3 Gt in 2012 (55.46 Mt CO₂ in 1950). Thus, the total CO₂ emissions increased more than 100 times during about 62 years [2].

Regarding the Green House Gases (GHG) emissions rate, the contribution of road transport to the total European Union (EU) emissions has increased from 13% share in 1990 to almost 20% in 2013 [3]. About 23% and 30% of the total EU emissions are due to CO₂ and NO_x respectively [3]. Although the EU legislation that tends to reduce these emissions, the proposed propositions in reality are still not that ecological [4].

The use of primary energies annually increases but not their availability [4,5]. Real solutions should be proposed to limit their consumption in all sectors and particularly in the transportation that represents 78.9% of the fossil energy use. In France, sincere efforts have been performed to decrease the energy consumption by 23.5 Mtep (−5.7%) from 2015 to 2016. Therefore, the energy independence of the county has increased to 51.9%. However, the majority of the French energy independence comes from Nuclear energy use. Accordingly, Renewable Energy (RE) technology improvement and deployment should be considered as a worldwide perspective [6,7]. In Germany, RE is 50% more than in France. However, their energy independence is around 41% [7]. In 2013, the

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Nomenclature		P_{Thermo}	External Power provided by Thermocouples
$P_{cleared_out}$	Cooling power evacuated by the radiator	SOC	Battery State Of Charge
$P_{cooling}$	Cooling power needed to maintain the cell around its optimal temperature	T_{cell}	Cell temperature
P_{excess}	Heating power in excess produced by one cell and transmitted to the next one	T_{f1}	Fluid entry temperature in the cell
$P_{internal_heating}$	Internal power produced by the cell	T_{f2}	Fluid exit temperature out of the cell
		T_{max}	Maximum Cell temperature ($\approx 80^{\circ}C$)
		T_{min}	Minimum Cell temperature ($\approx 23^{\circ}C$)

energy self-sufficient was over 61% in USA, mostly due to oil stocks [8]. Different countries are still suffering from energy-dependency on other countries such as both Morocco and Jordan (about 10% of energy independence) [9].

Fig. 1 shows the GHG emissions by sector for EU-28 and France according to the European Environment Agency (EEA) and the Interprofessional Technical Centre for Studies on Air Pollution (CITEPA) respectively. Road transportation is the first GHG emissions mode with more than 72% and 94.6% of total share for EU-28 and France respectively [10,11]. The private cars represent considerable percentage (44.4% and 53.1% respectively). This value is more than the double percentage of heavy duty vehicle emissions.

In addition to the pollution, road transportation is an important part of the countries' outcomes. In France, 77% of the annual transportation is due to road transportation according to the Ministry of Ecology, Sustainable Development and Energy [10]. In 2016, the road transportation cost 360 MC that represents about 17% of the annual French Gross Domestic Product (GDP).

In this context, Fuel Cell (FC) transport systems are considered as one of the convenient solutions for clean transportation. Thanks to its physical and chemical properties, Hydrogen becomes among the main players in the future energy systems for a sincere step-wise transition from today's fossil system to a CO₂ emission-free energy supply for both, stationary and mobile applications. Hydrogen has a relatively high gravimetric energy density (120 MJ/kg), which is 3 times higher than oil and 200 times higher than a lithium battery [12]. Indeed, the use of the hydrogen produced by the water electrolysis using RE sources, combined with a FC, provides a feasible option for green energy cycle. The hybridization of FC and battery can be assumed among the best combined system in terms of power and energy owing to the high gravimetric energy of hydrogen. This advantage increases the autonomy of the vehicle and confers a high interest in this hybridization. Proton Exchange Membrane Fuel Cells (PEMFCs) has the particularity of an average starting time constraining to combine FCs with a power source as battery. The battery assures the start-up when FCs regenerate the vehicle energy during braking. The FCs can be easily integrated into the Electric Vehicle (EV) compared to other technologies that results more desired hybrid systems.

Towards the development of hydrogen economy and the fossil fuels independency, different quantitative and qualitative research efforts have been performed to develop EVs powered by the PEMFC [13]. However, this technology is still expensive mainly because of the rarity and cost of Platinum. According to the French Atomic Energy Commission (CEA), half price of PEMFCs is due to Platinum

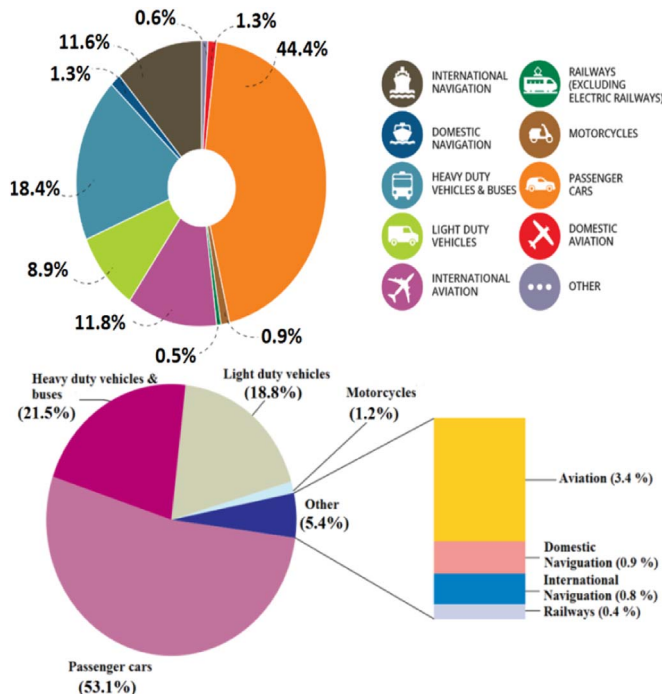


Fig. 1. Comparison of EU28 and US GHG emissions [10,11].

[14]. Researches are in progress to limit the platinum use in order to reduce the FC price [13]. Therefore the combination of less expensive metals (cobalt, nickel or palladium) with platinum in FCs or the development of active layers reducing the quantity of platinum can be considered [14].

The recent studies of the Ministry of Economy, Trade and Industry (METI) in France highlight that 40kT of Platinum is available [15]. Nowadays, the annual global production is around 150 T (0.11% of the total every year). The estimation of the increase of FCEV would lead to an annual production increase to 450 T (0.33% of the total).

The originality of the paper is in favor of the innovating Thermal Management (TM) research on the multi-stack FC and the effect on FCs efficiency and lifetime. An original thermal regulation is proposed. The numerical simulations lead to characterize the FC heating. The proper TM of a multi-stack FC system allows a better use of the FCs increasing their lifetime. In addition, knowing the relationship between FC temperature and efficiency will help enhancing the system global efficiency.

The present paper is organized as follows: in Section 2, a comprehensive literature review that shows the importance of controlling the FC parameters and the relevant TM is illustrated. Section 3 focuses on the interest of the multi-stack system and provides an overview of the overall battery/FC system's configuration and modeling. The feedback controller methodology between the two sources is presented in Section 4. The thermal transfer management architecture is introduced in the Section 5. The numerical simulation results shows the heating and cooling needs for the multi-stack FC global efficiency enhancement are discussed in Section 6. Finally, the conclusions and the perspectives of the research are drawn in Section 7.

2. Literature review

Numerous studies have illustrated the particular FC power effect on stationary applications. Ellamla et al. (2015) have studied the cogeneration of FC and Power Combined Heat Power (FCCHP) systems in the residential sector to help solve energy shortages, climate change and energy conservation issues [16]. In addition, Bigdeli (2015) has proposed different optimal hybrid techniques for the management of a hybrid power generation system including photovoltaic (PV), FC and battery [17]. The PEMFC technology is very promising and brings several studies about the effect of internal and external PEMFC parameters to improve FC efficiency, sizing and cost as highlighted by Noguer et al. (2015) [18]. Eren and Gorgun (2015) have studied the optimal sizing of FCEV [18,19].

As FC lifetime is one of the restrictive parameters, numerous studies have focused on enhancing the efficiency and lifetime of the FC by modeling methodology (parametric effect, flow rate regulation, and current compensation technique ...etc) as presented by Sharma et al. (2015) and Mayur et al. (2015) [20,21].

To improve FC reliability, investigations have been performed on degradation factors. Ahmad et al. (2015) have analyzed the compression effect on PEMFC while Hou et al. (2016) have highlighted the effect of road vibration on their performance and degradation [22,23].

As the PEMFC cost is one of the limiting factors, various studies, mostly on electrolyte membrane, have been achieved to enhance efficiency and reduce the platinum. Torkavannejad et al. (2015) have introduced three novel architectures of PEMFCs, called circular, square and octagonal duct-shaped in order to reduce cost and improve the efficiency [24].

The hybridized system control issue is important and numerous researches have proposed the energy management of FCEVs to increase power delivery and to enhance the system performance combining the battery with Supercapacitors (SC) as supposed by García et al. (2013) [25]. Then, Sikkabut et al. (2015) have proposed a control strategy algorithm based on nonlinear flatness-based controllers [26]. Furthermore, different studies on electrical powertrain configurations have focused on reducing hydrogen consumption as introduced by Sari et al. (2016) [27].

Finally, the FCs TM challenges becomes one of the most complicated and interested issue. To solve the cold, start two TM strategies (keep warm and Thaw at start) have been introduced by Amamou et al. (2015) [28]. FC optimal temperature issues was explored through TM strategies and the temperature model by Fagundes et al. (2015) [29]. Jaeyong et al. (2015) have presented TM strategies for a PEMFC system to evaluate the parasitic power of the cooling system with changes in the operating temperature [30]. Diverse researches are proposed to increase the stack efficiency by air cooling control as proposed by Hwang and Kim [31]. To treat water management and humidification methods, Moçotéguy et al. (2016) have proposed a Design of Experiments (DoE) test plan in order to discriminate the direct effects of several factors on the water management [32].

Answers of these questions are essential for figuring out the real and actual development of FC technology because of their direct impact on the FC durability, efficiency, consumption and behavior.

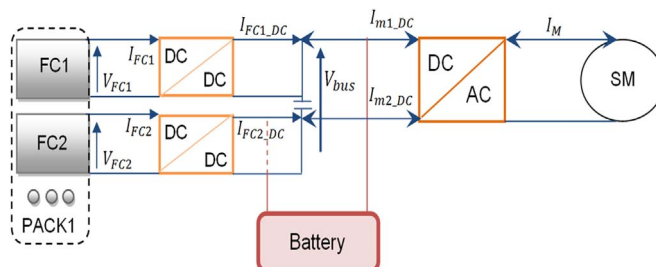


Fig. 2. Structure of hybrid sources.

This research principally discusses the benefit of using the multi-stack FC system and the particular architecture to control the energy. The TM inside the multi-stack FC coupled with the batteries power source.

3. System under study

In EVs, battery and FCs are used as a supplementary source of energy. One of the most important interests of using FCs is the byproducts of this zero CO₂ emission, such as water and heat. High rated power of using the unique FC can be more expensive and less reliable than multi-stack FC systems. In addition, the faulty stack replacement would be cheaper and easier in case of multi-stack FCs. However, the use of multi-stack FC system requires special TM. The considered system stands on preheating inter-stacks FCs using overheat to save energy and to improve the global system performance.

The structure of hybridization composed by FCs and battery is shown in Fig. 2.

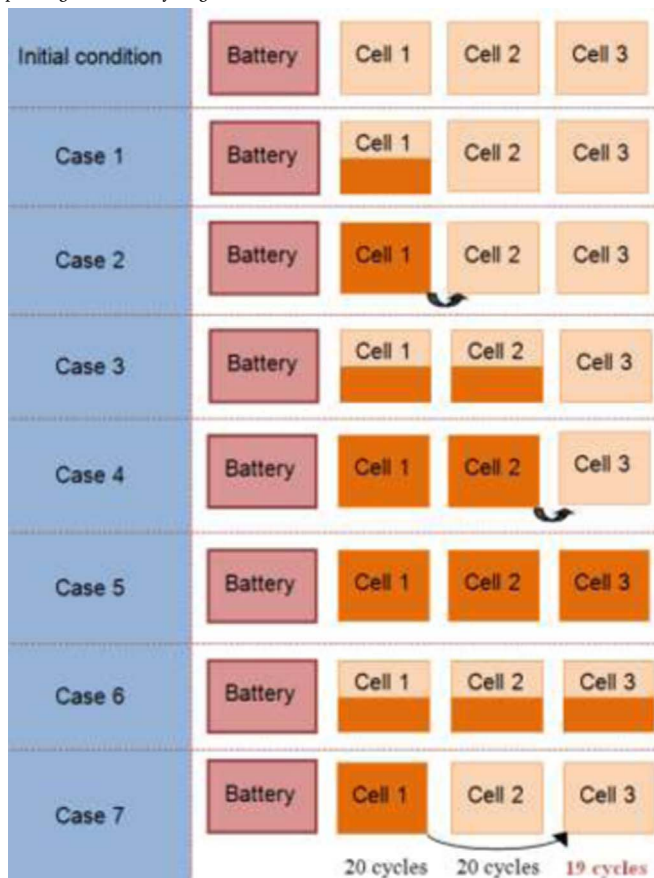
The power bus links the FCs to the electrical engines while the battery is directly connected to the bus. The converter monitors the requested power from FCs. In the electrical circuit, an isolated boost between the FC and the power bus is used for increasing the FC voltage and for matching the power bus. Moreover, a galvanic isolation allows protecting the FCs against any return of current during the battery charge by a deceleration of the Synchronous Motor (SM).

To design this structure and to obtain real time multi-domain coupling problem (electrical and thermal for instance), the Mathematical Temporal Calculation Simulation (MTCSim[®]) software is used. Developed by Segula Technologies in 2012, this software has been mainly employed to the development of new engines, energy management and components sizing. Using MTCSim[®], it is possible to dimension the electrical power needs of the system to simulate the relevant autonomy issue of the global setup. However, the difficulty remains the thermal transfer management in the multi-stack system.

4. Heat management procedure

One of the most important advantages of the multi-stack configuration is the possibility to use several FC with average power and not their maximum. This solution impacts on efficiency enhancement as FCs have better efficiency at lower power. The activation of several FCs allows to separate the global power demand and to use each FC at lower power and better efficiency in contrary of using

Table 1
Operating mode and cycling enhancement.



at its full high rated power.

To maximize FCs life span, the number of cycles start/stop of each cell need to be minimized because it is directly tied to the lifespan of the cell (500–1000 cycles). FCs energy contribution is reduced instead of switched off during in a lower power demand phase (deceleration for instance). Different operating modes are depicted in Table 1.

During the FCs start-up, the battery is the only source of power. In case 1, the vehicle power demand only necessitate one FC associated to the battery. Cell 1 is activated and operates at optimal power. The power demand increase and requires using cell 1 at maximum power. To minimize its use and to maintain the best efficiency as possible, cell 2 is active to relieve the first one and operates both of them at average power (case 2 and 3). Case 4, 5 and 6 illustrate the same scenario when power demand increase again.

Finally, a cycling system can be included to enhance the global FCs life span. With the identification of the number of cycling of all FCs, it is possible to activate the less stacks used in a multi-stack FC to save others as in case7.

This configuration implies to consider each FC independently, even in a same stack. FC needs to be activated and heated separately as their use will depend on the instantaneous power demand. In the multi-stack configuration, the FCs may be separately replaced due to the parallel installation. In case of a faulty FC stack, the other healthy stacks can be used for allowing the car reaching a safe place.

The TM of multi-stack FCs system is complex as each FC needs to be managed independently in terms of heating, cooling and power delivery. In addition, each FC has its imposed start-up time so the TM needs to be efficient as possible and the FCs should be maintained at their optimal temperature range at the same time. Therefore, the management of the excess heat may allow to heat faster the next FC. This excess has to be lead with the heating process to avoid any overtaking of the FC maximum temperature. To realize these conditions and to enhance FCs lifetime, the control system and a FC activation law proposed in this study is depicted in Fig. 3.

To deliver the minimum power, FC needs to be heated at T_{min} (23 °C at least). During this time of start-up, the battery will provide the vehicle demand. Beyond this temperature, the FC becomes active and starts to deliver power and the self-heating process. The FC can reach the optimal temperature range (around 70 °C) by using its own produced heating. The excess heat can be transmitted and used by the next FCs and so on. This management constitutes the TM of FCs presented in Table 2.

5. Thermal management system

To simulate the cooling and heating issues, the TM scheme has been implemented in MTCSim©. The FC temperature increases and the optimal temperature stabilization are represented by transfer function as thermal inertia. The FC temperature depends on the fluid and the ambient temperature associated to flow rate. When several FCs are implemented in the thermal model, the impact of the excess power of one is observable on the next and so on.

The TM procedure of the MTCSim© simulation is described in Fig. 4 and Table 3. The first FC needs to be heated to 23 °C to start its internal heating. The external heating can be stopped around 30 °C. The cooling is started when the cell temperature reaches 60 °C. At this point, the internal heating decreases and the cooling process aims is to maintain the FC around its optimal temperature (68.8 °C in the numerical simulations).

The excess heating power delivered by the first FC is the difference between the power used for heating and the one needed to cool itself. This excess is transmitted to the next FC that will use it as replacement of the external electrical power. The internal heating power required will be inferior to the first cell and more excess power will be transmitted to the third one and repeatedly cell to cell.

In [33,34] de Bortoli et al. have proposed a thermal management of a multi stack FCs system. Although the considerable

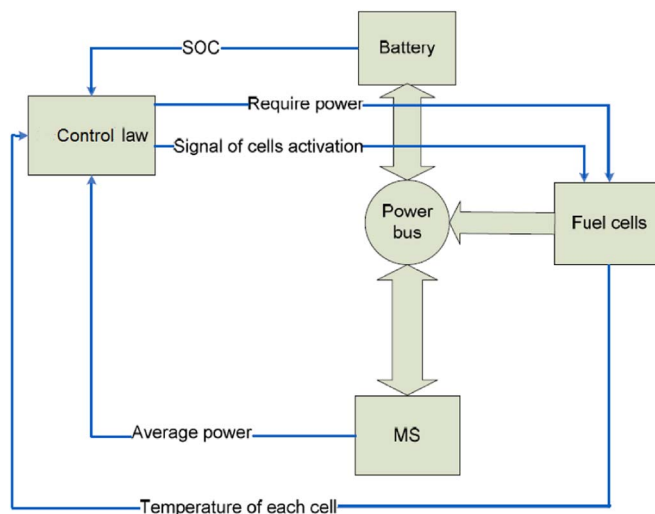


Fig. 3. Multi-source FC control system.

Table 2
FCs and battery activation laws.

FCs	
$T_{cell} > T_{max}$	FC cooled and excess of temperature used to preheat a second FC
$T_{min} < T_{cell} < T_{max}$	FC power delivers at optimal temperature range
$T_{cell} < T_{min}$	FC heated to deliver power
Battery	
SOC > 90%	Battery is priority and FC activated function at low power.
25% < SOC < 90%	A linear variation of power demand is established. FCs are activated and function at certain power in consequences
SOC < 25%	Battery safety limit. FCs provides the total power demanded by the vehicle

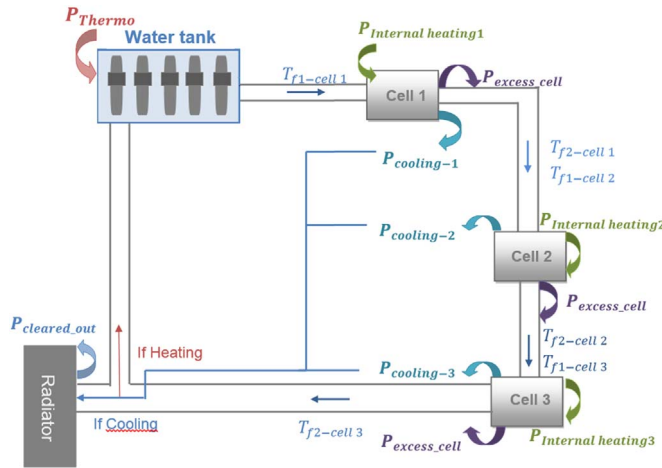


Fig. 4. Thermal regulation diagram.

Table 3
Thermal regulation conditions.

T_{cell}	$< 30^{\circ}C, P_{thermo} > 0$	External heating
	Otherwise, $P_{thermo} = 0$	
	$\geq 23^{\circ}C, P_{internal_heating} > 0$	Internal heating
	Otherwise $P_{internal_heating} = 0$	
	$\geq 60^{\circ}C, P_{cooling} < 0$	Cooling
	Otherwise $P_{cooling} = 0$	

simulation results, the authors have not taken into account a real heating system process and the external conditions over the FCs heating issues. In this study, the proposed TM method proposed is based on a real thermal architecture as water exchanger and shows interesting results. The advantage of using a multi-stack system on the heating system is highlighted. The FCs direct impact on efficiency and lifetime is shown.

To understand the relation between FCs heating, lifetime and efficiency, it is important to know that the FC stack efficiency depends on the electrical power delivered and the power consumed by the fuel (hydrogen).

$$\eta_{stack} = \frac{P_{stack}}{P_{H2}} \tag{1}$$

P_{stack} is depending on the intensity and voltage of the FC:

$$P_{stack} = I_{stack} \times U_{stack} [W] \tag{2}$$

On the other hand, the stack intensity is linked to the temperature by a relation given par a FC professional Ballard [35]:

$$T_{optim} = I_{stack} \times (0, 53 + 26, 01) + 273, 15 [K] \tag{3}$$

with Eqs. (1)–(3), it easy to understand that the FC delivered power depends on the intensity and temperature of the FC and that the optimal temperature will lead to the optimal power and the optimal efficiency:

$$\eta_{stack}(I, T) = \frac{P_{stack}}{P_{H2}} \leftrightarrow \eta_{stack-Optim}(I, T_{optim}) = \frac{P_{stack-Optim}}{P_{H2}} \tag{4}$$

Eq. (4) clearly links the temperature and the efficiency. It illustrates the importance of the proper TM to extract the FC optimal power. The two parameters are also linked to the FC lifetime. Using the FC on its optimal properties allows reducing the membrane degradation and enhancing the durability of the FC [33–41].

6. Simulation results

The first study led was the effect of external temperature (T_{ext}) on the TM parameters for one FC. The thermal regulation system depicted in Fig. 4 was implemented into MTCSim[®] to obtain Fig. 5 results.

Fig. 5(a) shows the limit between the heating and the cooling around $T_{ext} = 30^{\circ}C$ which is the temperature limit to use the external heating ($at T_{cell} > 30^{\circ}C, P_{thermo} = 0$). When the external temperature is warm enough, the external heating is no longer necessary because the FC is already at its start-up temperature and can heat itself. That explains the drop of P_{thermo} and the water flow decreasing to reach $0 m^3/h$.

For $T_{ext} > 30^{\circ}C$, the cooling is gradually superior to the heating and more excess power can be transmitted to the next FC. The cooling power is negative because the power needs to be evacuated. The FC is not literally cooled, However, a part of the power is evacuated to maintain the FC at its optimal temperature.

Fig. 5(b) depicts the FC and thermal fluid temperature evolution at $T_{ext} = 10^{\circ}C$. The evolution is very interesting and highlights the TM conditions (Internal heating starting at $23^{\circ}C$, and External heating stopped at $30^{\circ}C$). Fig. 5(b) depicts that the FC reaches its optimal temperature after around 70–75 s but still undergo few variations. The temperature is stabilized after 100 s.

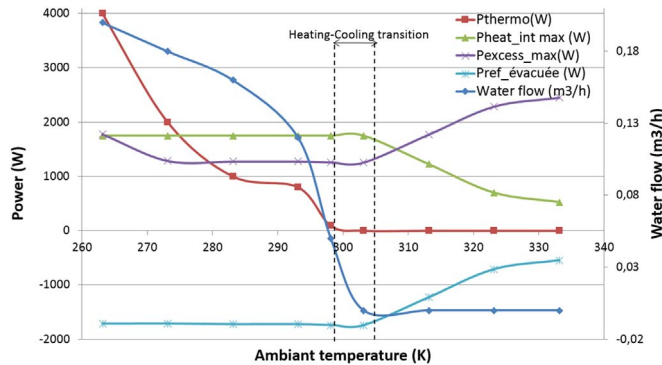
The (T_{f1} and T_{f2}) curves refer to the fluid temperature in the FC (entry and exit) respectively. The fluid entry temperature is considered as a constant source and the fluid exit is calculated as shown:

$$T_{f2} = T_{f1} - \frac{P_{thermo} \times 3600}{\rho \times Cp \times q_{water}} [K] \tag{5}$$

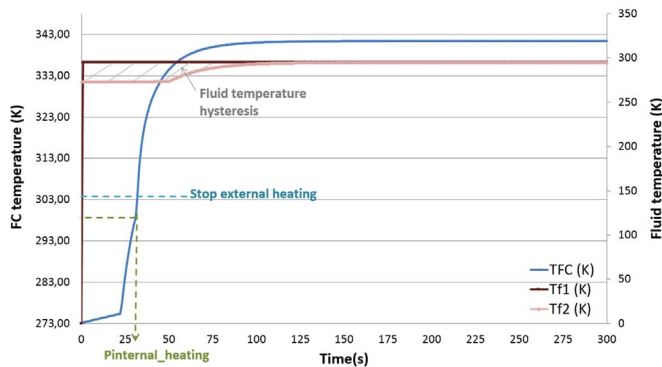
The fluid temperature hysteresis observable is characteristic of an exchanger regulation and explains the variation of T_{cell} .

A second study is realized, based on the same numerical simulation model, but considering three FCs. The study aim is to observe this time the importance of the excess power transmitted from one FC to another on the heating duration of the FCs. The principle is to reduce this duration cell by cell. The duration of the system heating is very important because it conditions the warm-up time of the entire system and the rapidity of the multi-stack FC system to respond to the vehicle power demand.

In Fig. 6(a), the temperature of the different FCs (T_{FC1} , T_{FC2} and T_{FC3}) increase respectively from 273 K to their steady state values



(a) Thermal regulation parameter's evolution at T_{ext} variable.



(b) T_{cell} , T_{f1} , T_{f2} evolutions at $T_{ext} = 10^{\circ}C$.

Fig. 5. Numerical simulation analysis of TM at 1 cell. (a) Thermal regulation parameter's evolution at T_{ext} variable. (b) T_{cell} , T_{f1} , T_{f2} evolutions at $T_{ext} = 10^{\circ}C$.

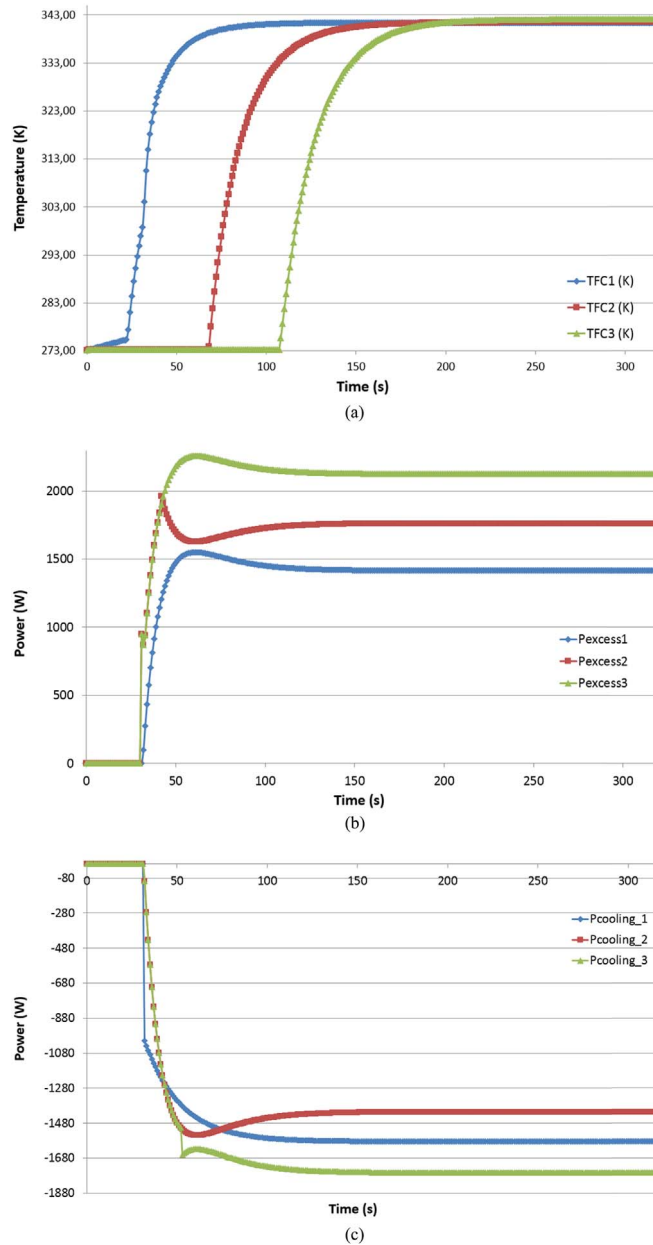


Fig. 6. Dynamic performance during TM for 3 FCs. (a) FCs Excess Power evolution at $T_{ext} = 10^\circ\text{C}$. (b) FCs Cooling Power evolution at $T_{ext} = 10^\circ\text{C}$.

Table 4

Extrapolation of the gain duration for a complete multi-stack FC system at $T_{ext} = 10^\circ\text{C}$.

Warm-up gain FC2 (s)	0.1	1.3%
Warm-up gain FC3 (s)	9.1	12.3%
Warm-up gain FC4 (s)	19	25.3%
Numbers of FC for the system considered	10	
Warm-up gain for 2 packs of 3 FCs	18.2	
Warm-up gain for 1 packs of 4 FCs	19	
Warm-up gain entire system (s)	37.2	5%

of about 333.8 K. The requested time to reach these value are not the same for the three FCs. From Fig. 6(a), the warm-up duration of the 3 FC can be observed. The first remark is that a duration gain is observable between the first cell and the second and even more important between cell 2 and cell 3. The second observation is the time delay between the activation of the first, second and third cell.

The temperature of cell 2 cannot increase as long as the first one does not reach 23 °C at least and start its internal heating. Few time after the activation temperature reached by the first cell and when the cell provide enough power to warm and transmit excess power to the next one, the temperature of the second cell starts to increase and so on. At $T_{ext} = 10^{\circ}\text{C}$ for example a gain of 0.1 s is observed between the warm-up time of the first and second FC. The gain begins to be significant at 3 FCs as the gain between the third FC and the first is around 9.1 s. The results shows promising benefit for an overall multi-stack FC system.

Fig. 6(b) illustrates the evolution of the excess power (at $T_{ext} = 10^{\circ}\text{C}$) for the three FCs. Obviously, the power is higher for FC3 than FC2 and FC1. Therefore, the excess power of a multi-stack system can be properly used.

The excess power increases with the decrease of the internal heating power. The dynamic performance steady state stability is reached. The same evolution is observed in Fig. 6(c). The cooling power increases as a part of the heating power should be evacuated from the system to maintain the FC at its optimal temperature.

Finally, an extrapolation of the total gain of warm-up for the overall system can be proposed as introduced in Table 4. From the system analysis presented in Table 4, 10 FCs of 3 kW each are used. The system is split into two packs of three FCs and one of 4 FCs. Each pack of three FCs can gain up to 9.1 s. Therefore, a gain of around 18.2 s is reached for both packs.

The extrapolation performed on a fourth cell allows considering the warm-up gain of the single 4 FC pack of around 19 s. For the two packs of three cells, the warm-up gain reaches 12.3% than a single FC and up to 25.3% for the 4 FCs pack. If the entire system is considered the gain can be around 5% for the warm-up which is not neglected.

To conclude, two main properties of the multi-stack FC have been highlighted in the study. First, the importance of the proper thermal management for a warm-up gain of the system. Second, the FC temperature can be maintained at its optimal temperature. Accordingly, the lifetime enhancement can be reached using more carefully the FCs. Indeed, the global efficiency and management of the system is upgraded as the multi-stack system is more quickly available to respond of the vehicle power and energy demand. The second one affects the multi-stack FC efficiency as the delivered power is directly linked to the temperature and so is the efficiency. Maintaining by a proper TM of the FC temperature as close as possible to the FC optimal temperature leads to an enhanced delivered power and efficiency.

7. Conclusions and perspectives

The paper presents a real interesting advance towards the understanding and the improvement of the multi-stack FC system. Based on the numerical simulation results via MTCsim[®] software., the multi-stack FC integration is considered as an ideal solution to increase the FC vehicle efficiency thanks to the possible proper heat management and the thermal dissipation recovery. Moreover, the activation response time of each FC and the life time of each FC rise thanks to a management activation process of each/all FC.

With a 25.3% heat gain for the FC4 and 5% for the overall HEV system, the thermal management solution shows that the FCs overheat recovery is an innovative solution for improving the overall efficiency of the multi-stack FC system integrated into HEVs.

The forthcoming studies will mainly focus on the experimental validation of the proposed TM approach for the feasibility of the proposed system, lifespan enhancement, cycle, efficiency and reliability of the EV. In such study, the different parameters uncertainties such as degradation rate, real lifespan etc.... will be accounted for. In addition, the different advanced control methods can be applied to the system for reaching enhanced dynamic responses.

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