Case Studies in Thermal Engineering 10 (2017) 325–334

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

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

Heat management methodology for enhanced global efficiency in hybrid electric vehicles

F. Claude[a], H.S. Ramadan[b,c,*], M. Becherif[b], L. Boulon[d]

[a] SEGULA MATRA Technologies, 25200 Montbéliard, France
[b] FCLab FR CNRS 3539, Femto-ST UMR CNRS 6174, Univ. of Bourgogne Franche-Comté/UTBM, 90010 Belfort, France
[c] Electrical Power and Machines Dept., Faculty of Engineering, Zagazig University, 44519 Zagazig, Egypt
[d] Hydrogen Research Institute, Université du Québec à Trois-Rivières, QC, Canada

ARTICLE INFO

Keywords:
Electric vehicle
Efficiency
Multi-stack
Fuel cell
Heat transfer management

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 CO_2 emissions from fuel combustion increase annually starting at 15.5Gt in 1975 to 32.1 Gt in 2015 [1]. In emerging countries, the witnessed CO_2 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 CO_2 emitter since 2006 reaching 8.3 Gt in 2012 (55.46 Mt CO_2 in 1950). Thus, the total CO_2 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 CO_2 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

* Corresponding author at: FCLab FR CNRS 3539, Femto-ST UMR CNRS 6174, Univ. of Bourgogne Franche-Comté/UTBM, 90010 Belfort, France.
E-mail address: haitham.s.ramadan@gmail.com (H.S. Ramadan).

http://dx.doi.org/10.1016/j.csite.2017.06.006
Received 17 March 2017; Received in revised form 4 June 2017; Accepted 20 June 2017
Available online 09 August 2017

Nomenclature

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

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 M€ 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 stepwise transition from today's fossil system to a CO_2 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

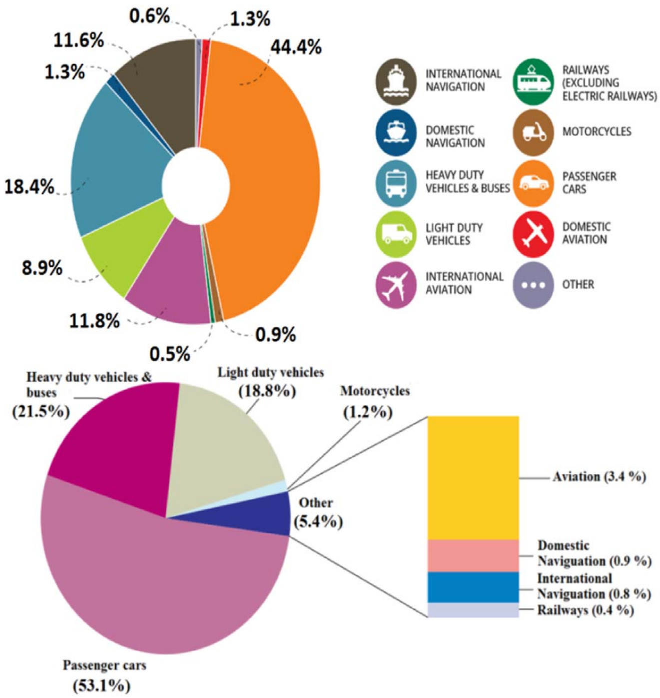

Fig. 1. Comparison of EU28 and US GHG emissions [10,11].