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Designing, building, testing and racing a low-cost fuel cell range extender for a motorsport application

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ABSTRACT

Imperial Racing Green is an undergraduate teaching project at Imperial College London. Undergraduate engineers have designed, built and raced hydrogen fuel cell hybrid vehicles in the Formula Zero and Formula Student race series. Imperial Racing Green has collaborated with its fuel cell partners to develop a 13 kW automotive polymer electrolyte membrane fuel cell (PEMFC) system. A team of undergraduate engineers were given a relatively modest budget and less than 8 months to design and assemble an operational high-power PEMFC system. The fuel cell system was designed to provide the average power required by the team's 2011 Formula Student entry. This paper presents the team's experience of developing and testing an automotive fuel cell system for a race application and plans for its future development and integration onto the vehicle.

1. Introduction

Imperial Racing Green (IRG) is a major undergraduate teaching project within the faculty of engineering at Imperial College London. IRG gives undergraduates hands-on experience in the design, development and construction of hydrogen fuel cell hybrid electric vehicles, which compete in Formula Zero and Formula Student giving undergraduates a chance to test their vehicles under challenging conditions. Vehicles are named with the following convention IRG0X where X denotes their number.

IRG02, the Formula Zero go-cart, is a hydrogen fuel cell supercapacitor hybrid and competed in the world's first hydrogen fuel cell powered race series in Rotterdam in August 2008 [1].

IRG03 is a hydrogen fuel cell battery electric plug-in series hybrid track car which was entered into Formula Student Class 1a in July 2009 and won the Autodesk Award for 'most effective/innovative design in engineering'. IRG03 was powered by a battery pack made up of 432 Kokam SLPB11043140 4.8 Ah (Kokam America, USA) cells in a 6P72S configuration (6 cells in parallel by 72 in series) to provide a 7.25 kWh battery pack with over 100 kW of peak power. The battery was hybridised with a 4 kW self-humidified polymer electrolyte membrane fuel cell (Pearl Hydrogen, China) operating as a range extender connected to the battery pack via a DC/DC converter operated in current control mode (Advanced Power Associates, USA).

1.1. Technology choice

Road transport today is responsible for a significant and growing share of global anthropogenic emissions of CO_2. Moreover, it is almost entirely dependent on oil-derived fuels and therefore highly vulnerable to possible oil price shocks and supply disruptions. Finally, using oil-derived fuels in internal combustion engines generates tailpipe emissions of pollutants such as PM_{10}, NO_X and VOCs which are harmful to human health.

Improving road transport requires all of these issues to be addressed. Managing demand and promoting co-modality can provide a partial solution; however, introducing alternative transport fuels and vehicles will also be necessary in order to achieve the objectives of reduced CO_2 emissions, energy security and urban air quality.

There are currently various barriers to the widespread adoption of both battery electric vehicles (BEVs) and fuel cell electric vehicles (FCVs); the most significant being technical, economic and infrastructural [2,3]. For BEVs the technical barriers are mostly associated with the battery technology itself [4], and a significant

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Table 1
Fuel cell systems used by Imperial Racing Green to date.

Vehicle	IRG01	IRG02	IRG03
Vehicle peak power (kWe)	40	40	100
Fuel cell module	Ballard Nexa	Hydrogenics HyPM HD8	Pearl Hydrogen PhyX 5000
Rated net output (We)	1200	8500	5000
Voltage at rated output (V)	26	48	60
Lifetime (h)	1500	3000	Not published
Mass (kg)	14	75	23.5
Physical dimensions (mm)	560 × 250 × 330	850 × 360 × 250	535 × 270 × 190
Specific power[a] (kW kg^{-1})	0.086	0.113	0.213
Power density[a] (kW L^{-1})	0.026	0.111	0.182

[a] Approximate values calculated from published data.

challenge is the relatively low energy density of batteries, which means that, for a reasonable range, they have to be large and therefore heavy and expensive. For example, with present technology a range of 200 km requires roughly 150 kg of lithium ion cells or more than 500 kg of lead acid batteries. This is a fundamental problem because the chemical storage of energy and its conversion into electric power are combined in a single device. In order to double the range, the power, energy, weight and cost must also be doubled. Energy density and hence range is less of a problem for FCVs, where chemical energy is converted into electric power in the fuel cell but the hydrogen fuel is stored in a tank. Hydrogen tanks are characterised by good specific energy (gravimetric energy density) but the energy density (volumetric energy density) is not so good, therefore achieving the range of a conventional gasoline vehicle with a pure FCV requires a bulkier hydrogen tank than the equivalent gasoline tank.

The cost of batteries and the logistics of recharging which provide additional barriers for BEVs, could at least be partly overcome by mass production of battery systems for road vehicles [5] and with schemes such as battery swapping [6], respectively. Fuel cells are also expensive and currently produced in very small numbers, but mass production should reduce their cost by an order of magnitude [7]. Refuelling a hydrogen tank only takes minutes whereas fully charging a battery may take hours, depending on the battery technology and the local electrical power limitation. However, electricity is already a widely used energy vector and building a recharging infrastructure for BEVs on top of the existing power grid is likely to be faster and lower risk than building a hydrogen production, transmission and refuelling infrastructure, of which very little exists today.

It is clear that both BEVs and FCVs can contribute to making road transport more sustainable but the barriers they face are somewhat synergistic. Although the advantages and disadvantages of battery and hydrogen fuel cell technologies have all been identified and discussed elsewhere [4,5,8–10] there is limited awareness of the strong synergies between them in road vehicle applications. Despite limited analysis comparing fuel cell and combustion engine range extenders for electric vehicles [11], BEVs and FCVs are still largely seen as mutually exclusive future options. Moreover, the most recent assessment of low carbon vehicles in the UK, the King Review [9], does acknowledge that a fuel mix including hydrogen and electricity is likely, but it implicitly assumes that this will be via different vehicle platforms, and not by a single vehicle with the capability to use both electricity and hydrogen. In response to this it has recently been demonstrated that a plug-in fuel cell hybrid electric vehicle (FCHEV) is likely to be cheaper than either the BEV or FCV, but only if it operates on both electricity and hydrogen with a down-sized fuel cell operating as a range extender [2,3]. Crucially an analysis of driving behaviour demonstrated that the rate of cost savings per kWh were high for the first 5–15 kWh of batteries, but showed a classic law of diminishing returns for larger battery packs [2]. In summary, it is possible to operate a plug-in hybrid vehicle as an electric vehicle for the majority of the miles driven in its lifetime (>80%) with a modest battery pack (5–15 kWh) and a single overnight charge. The cost of a fuel cell range extender, even with a more expensive fuel, is considerably less than the additional cost of the larger battery size (>50 kWh) needed to provide the range required to satisfy most consumer's demands. Therefore there is clearly a need to develop fuel cell systems for automotive applications that are of the correct size to deliver a vehicle's average power as a range extender rather than the peak power as the load follower.

The fuel cell system that is described in this paper is specifically designed for use in a motorsport environment, as both a means to demonstrate and test technology in a market that can accommodate higher costs than the mainstream automotive market and also to provide an exciting and motivating environment to train the engineers of the future.

2. System design

2.1. Challenges

The prohibitive cost, weight and poor durability of current PEMFC systems have been identified as key barriers to the proliferation of the technology, especially for automotive applications [12]. Focussing on durability, it has been demonstrated that load profiles and cycle frequencies have a major effect on fuel cell degradation rates [13], and more recently, that start-up and shut-down events also accelerate degradation [14]. This highlights a further advantage for the FCHEV as the fuel cell can be operated more often in a constant load configuration, with an accumulator (batteries or supercapacitors) providing the load following. This minimises unnecessary load following and start-up and shut-down events improving durability and lifetime.

However, whilst some attention has been given to the start-up and shut-down of large PEMFCs in passenger vehicles, no consideration has been given in the literature to their practical operation in a motorsport application. It is predicted that the start-up and shut-down requirements for a competition motorsport vehicle will differ from those for a fleet passenger vehicle, and further still from the fuel cell systems designed for stationary-power and forklift-truck applications previously used by the IRG team. A decision was therefore made to develop the fuel cell system for IRG's future vehicles 'in-house' with the intention of improving overall vehicle performance. Balance of plant design and operating and start-up/shut-down procedures necessarily became areas of key technical interest for the team. This paper provides an overview of the work conducted in order to develop the first prototype system in the academic year 2008/09.

2.2. History

Each of the team's existing vehicles was developed around a different PEMFC module, their selection being informed by various