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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 factors including financial constraints, performance requirements and competition regulations. Table 1 provides a summary of the technology adopted to date.

There are several hybridisation strategies available to the designers of such vehicles and the choices made so far by the IRG team reflect these. IRG01 and IRG03 are examples of 'battery-heavy' hybrids [1] in which the fuel cell acts as a low-power range extender and the majority of vehicle peak power is provided by an energy storage system. For example, in IRG01 and IRG03, the fuel cell provides just 3% and 5% of vehicle peak power, respectively.

This is in contrast to the 'fuel cell heavy' hybrid (at the opposite extreme) in which the peak power is provided by a large fuel cell. In this strategy the fuel cell must follow transient loads in the same way as an internal combustion engine does in a conventional road vehicle.

In both strategies the cost of providing the peak power with a large fuel cell versus the cost of providing sufficient energy storage in an accumulator must be optimised. Indeed it has been demonstrated that the lowest cost solution is more likely to be found between these two extremes [2,3].

IRG02 is a compromise between the two extremes, its fuel cell providing the vehicle's average power consumption (roughly 25% of peak power). In this configuration the energy storage system (two banks of 165 F:48 V Maxwell ultra-capacitors) acts as an energy buffer, smoothing the transient power demands from the motors. The energy storage system accepts rapid charging during regenerative braking (when the vehicle's electric motors are used as generators, braking the car) and provides supplementary power to the motors during periods of hard acceleration. 'Round trip' efficiencies better than 50% have been demonstrated for these systems at Imperial College.

It is anticipated that IRG05 will be the first vehicle to utilise the fuel cell system described in this paper. The working prototype described in this paper was developed this academic year (08/09), the second generation system suitable for a vehicle will be developed in the academic year 09/10, which will be integrated into IRG05 in the 2010/11 academic year.

Based on modelling and optimisation work it was found that a hybrid configuration similar to that used on IRG02 (in which the fuel cell provides the vehicle's average power demand) would be most appropriate for the Formula Student competition. Such an arrangement would reduce the energy storage requirements for the competition's 'Endurance' event whilst ensuring a sufficiently high peak power was available for the 'Sprint' and 'Acceleration' events [SAE International, 2008]. A net fuel cell output in the region of 13.5 kWe was predicted from vehicle modelling over the race duty cycle, and has therefore been adopted as the development target for the IRG fuel cell system.

2.3. System architecture and fuel cell stacks

A fuel cell stack requires additional supporting components in a fuel cell system to enable it to function. These components are known as the balance of plant (BOP) and consist of the following subsystems:

1. Air system
2. Hydrogen system
3. Cooling system
4. Control system

An artificial constraint that was imposed upon the project was the limitation of the maximum gross power of each fuel cell stack to 10 kW in order to conform to laboratory safety regulations. This meant that two separate fuel cell stacks were required for the net 13.5 kW system required, to enable initial testing with a single stack to be performed in the laboratory at Imperial College London. Future testing of a complete system with two stacks will be done off-site.

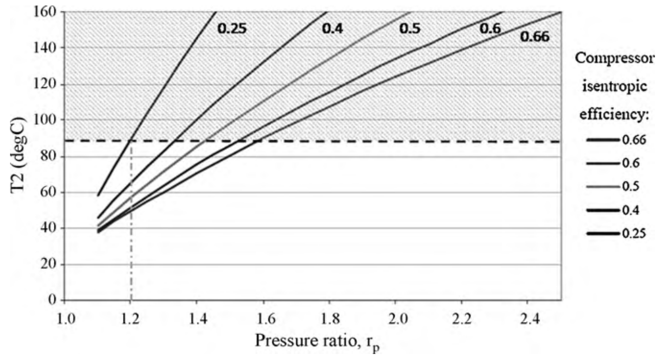

Fig. 1. Effect of pressure ratio and isentropic efficiency on compressor outlet temperature, T_2, assuming standard inlet conditions of 25 °C. The horizontal dashed line marks the 90 °C inlet temperature limit for the Nafion® membrane based Perma Pure FC series humidifiers recommended by NedStack.

In all PEMFC systems a proportion of the fuel cell stack's gross power output is consumed by the ancillary balance of plant components required for its effective operation [15]. These ancillary components include each of the subsystems 1–4 listed above. In order to provide a given net system power, the fuel cell stacks must therefore be sized to meet both the system and balance of plant power requirements.

2.4. Air system

The fuel cell stacks require a cathode stoichiometry of more than two, requiring the chosen compressor to supply up to 1 m^3 min^{-1} of dry, oil-free air to the humidifier. The nominal operating pressure of the stacks is 1.2 bar (absolute). The additional requirement for a low-cost component which could be used at various operating points led to the selection of an Eaton M24 roots-type supercharger.

Fig. 1 shows the effect of pressure ratio and isentropic efficiency on compressor outlet temperature. The range of isentropic efficiencies plotted covers the supercharger's full operating range. Fig. 1 demonstrates that the supercharger's output temperature should be acceptable throughout its operating range when supplying a NedStack fuel cell stack at a pressure ratio of 1.2. If a higher pressure stack had been used, it would have been necessary to include a heat exchanger to reduce humidifier inlet temperature.

A particulate filter was installed upstream of the supercharger inlet. Following consultation with NedStack it was agreed that the hydrocarbon contamination expected from an Eaton M24's sealed bearings was sufficiently low to justify omitting an additional downstream filter, which would have introduced a significant additional pressure drop. In order to mount the selected air system components on the main test rig a number of mechanical components were designed and manufactured, including the motor/supercharger mounting and outlet manifold.

The supercharger mounting system was designed to allow simple adjustment of the drive belt tension whilst ensuring that its position could be locked-off securely using a clamping bar. Guide blocks were fitted to the underside of the adjustable sled to ensure that belt alignment was maintained at all times. The compressor outlet manifold was produced in alumide (an aluminium filled polyamide rapid prototyping material) using the selective laser sintering (SLS) method.

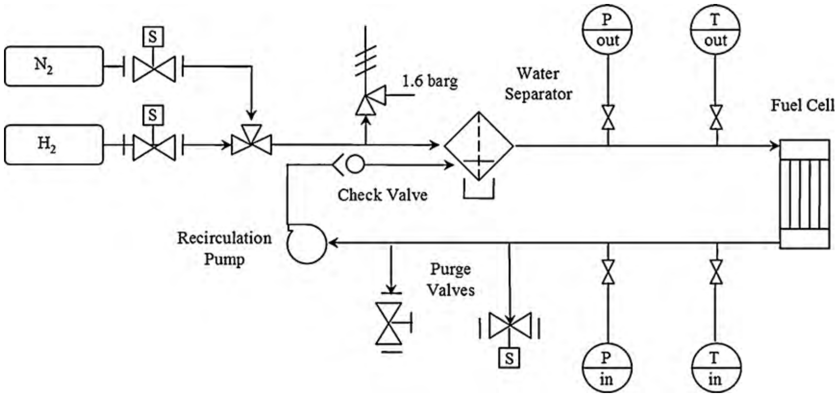

Fig. 2. Hydrogen system arrangement showing recirculation loop.

2.5. Hydrogen system

On the cathode, stoichiometries higher than one are conventionally achieved by adopting a flow through configuration for the air system [15]. Consequently a fraction (typically 80% or more), of the oxygen in the air supplied by the compressor will still be present in the fuel cell's exhaust. The equivalent arrangement would clearly be unacceptable at the anode, where such a loss of fuel would reduce fuel efficiency.

A recirculation system must therefore be used in order to obtain stoichiometries above one whilst keeping losses acceptably small as shown in Fig. 2. For this purpose, a small diaphragm pump was specified. This feeds the fuel cell exhaust gases back into a water separator where they are mixed with the cold, dry hydrogen entering the system. In this configuration, the pump's main purpose is to overcome the small pressure drop between the anode inlet and outlet and it therefore consumes far less power than the air compressor. A check valve is positioned between the diaphragm pump and water separator to prevent backflow.

2.6. Cooling system

2.6.1. Summary

Both fuel cell stacks are fed coolant, water, from a common reservoir, with the coolant circulated by a single pump. They are arranged in parallel, as shown in Fig. 3, to ensure that their temperature profiles are uniform. This is important in order to ensure both stacks operate with similar reactant relative humidities; a factor which plays a major role in cell performance and is strongly influenced by stack temperature.

To maintain acceptably low levels of cell-to-cell current leakage through the coolant, its conductivity must be reduced below specified limits, typically 50 μS cm^{-1}. This is equivalent to a minimum resistivity of 20 kΩ cm^{-1} and can be achieved by the use of deionised water as a coolant. In order to prevent the coolant's conductivity rising as ions are leached from metallic components like the radiator, a deionising filter is installed in the loop. Furthermore, plastic fittings are adopted wherever possible and all metallic components are specified in 316 stainless steel or aluminium.

2.6.2. Requirements

Two NedStack 9.5 kW fuel cell stacks were selected as the most appropriate trade-off between power requirements, cost and vehicle packaging. Vehicle performance simulations predicted that an average power of between 10 and 12 kW would be required in order to surpass the best performance of historical Formula Student petrol combustion engine powered vehicles in the endurance event (18 laps of 1.25 km, taking approximately 30 min). Assuming a fuel cell system parasitic load of 25–30% two 9.5 kW stacks would provide between 13 and 14 kW of net power, which would be sufficient considering other parasitic loads on the vehicle could approach 1 kW.

The conditions for the cooling system for the fuel cell stacks are given in Table 2.

2.6.3. Design process

The first iteration was designed to cool both the fuel cell stacks and the air supply to increase overall fuel cell system efficiency. The initial cooling system design was based on a single coolant loop consisting of an air-to-water heat exchanger, deionising (DI) filter, pump, bypass valves and a fan and radiator.

The bypass valves over the heat exchanger and the radiator are used to control the proportions of coolant flow through the respective components, controlling heat transfer which takes place. Increasing the proportion of flow through the component increases heat dissipation. The filter is placed in parallel to the fuel cell stacks rather than in series to avoid a pressure drop across the filter. The maximum flow rate allowable through a filter of realistic size would also significantly limit the maximum coolant flow rate if attached in series.

To simplify the control system, a two loop system to cool the air supply and stack separately was considered. However, whilst controlling the various temperatures would be straight forward, the disadvantage was that a separate pump, radiator and fan would have been required, adding weight.

Therefore a third design incorporating the separate loop for cooling the air supply was developed further as it was considered most viable given the very tight time constraints (less than 6 months for design validation, construction, testing and integration). The air-to-water heat exchanger in the air supply water coolant loop was replaced with an air-to-air heat exchanger to give an open air-coolant system. This reduced the weight and cost of the system as it eliminated the need for the second pump, radiator and fan and additional tubing, connections and water coolant. For the stack cooling loop, problems concerning the mixing of different temperature fluids at the stack and filter exit junction were identified and as a result the filter was repositioned before rather than in parallel with the stack, which considering the dual stack design

Table 2
Key parameters for the fuel cell stack cooling system.

Capacity	>20 kW (minimum)
Medium	Demineralised water
Pressure difference	<0.5 bar
Operating temperature	65 °C
Temperature window	dT < 10 K

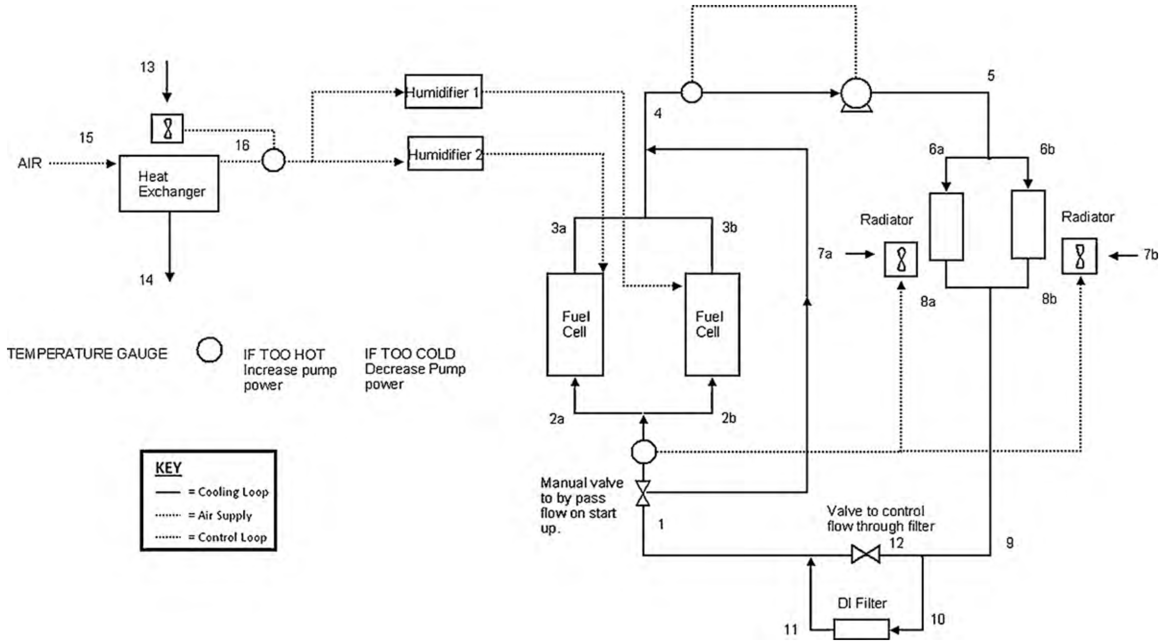

Fig. 3. Final cooling system design.

also meant only a single filter would be required. The schematic of the final design is shown in Fig. 3.

2.6.4. Control

After testing with basic flow gauges it was concluded that varying the flow rate with the pump did not provide good control over the heat transfer. It was discovered that heat transfer could be managed by monitoring the inlet and outlet temperatures of the fuel cell coolant and controlling the radiator fan speed; which meant coolant flow gauges did not need to be incorporated into the system. The arrangement of the components, sensors and control loops are shown in Fig. 3.

2.6.5. Air supply cooling

The air-to-air heat exchanger and fan effectively act as a radiator to cool the air supply. As the purpose of cooling the air supply is to assist the humidification process, the heat exchanger and fan are situated before the humidifier. Similar to the stack coolant control method, the air temperature was monitored after the heat exchanger and control achieved by varying the fan speed.

2.6.6. Fuel cell cooling loop

Fig. 3 shows two radiators in parallel; however, a single radiator may be sufficient for the system as long as it has a large surface area for heat dissipation and that the fan is powerful enough. The deionising (DI) filter is positioned directly before the fuel cell stacks to ensure that the water flowing through the stacks is deionised. The filter is also positioned parallel to a valve in order to ensure a fixed proportion of coolant flow through the filter. To avoid contaminated water flowing through the stack and causing damage, all of the coolant must pass through the filter during start-up of the fuel cell stack. This is achieved by cutting off the flow to the stack at start-up using the manual bypass valve placed across the fuel cell and passing the entire flow at reduced flow rate through the filter.

2.6.7. Testing rig

In order to test the cooling system, a test rig able to simulate up to 26 kW of heat produced by the fuel cells was designed and built.

The most practical design which suited the budget and timeline of the project was the heating of a tank of water using several standard 3 kW domestic boiler immersion heaters and passing the coolant loop water through the tank to be heated. To simulate heat production from single and double fuel cell stacks a minimum of 5 and 9 heaters are required, respectively.

Testing of the fuel cell cooling system was then carried out using the designed test rig. After completion of these tests, a set of performance data was transferred to the control system. Complete fuel cell system tests were then performed integrating all the balance of plant systems with the fuel cell. The cooling system was allocated the bottom shelf in a server cabinet as shown in Fig. 8. The cooling system was mounted on the bottom shelf as a precaution to avoid damage to the other systems in the event of a leak.

2.7. Control

2.7.1. Introduction

Several different products were considered for the fuel cell system's control and data acquisition duties. National Instruments and Yokogawa products were selected for the initial development phase of the project. The team already owned much of the CompactRIO hardware required for this system and National Instruments were prepared to offer substantial discounts on the remainder, in addition to free on-site technical support. As such, adopting this proven technology presented a low-cost, low-risk option.

Yokogawa's loan of an eight-channel 'Datum-Y' data acquisition unit free of charge allowed for separation of input signals into two groups:

1. Those which are critical for control and condition monitoring of the fuel cell system when mounted on IRG05 and which would be logged by the CompactRIO.
2. Those which would provide useful additional insight into system performance during lab testing and would be monitored with the Yokogawa Datum-Y unit.

The CompactRIO embedded control and data acquisition platform consists of three functional elements/groups: a 400 MHz processor which runs LabVIEW programs in real-time, a field-programmable gate array (FPGA) which is used to read and write to individual

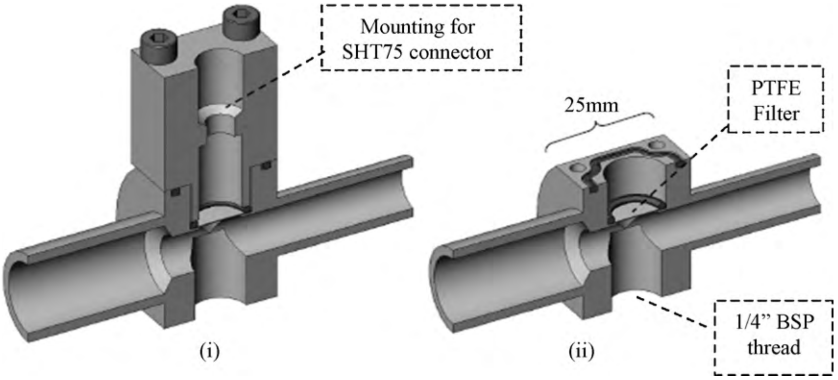

Fig. 4. Section views from humidity sensor design (in configuration used at the anode inlet and outlet): (i) with and (ii) without sensor housing installed.

module I/O channels and perform parallel LabVIEW operations in hardware, and a set of user-selectable input/output 'modules' allowing custom I/O configurations to be produced.

2.7.2. Control

The objective for this element of the project was to develop a single computer interface which could be used to adjust key variables, monitor system condition and log data during lab testing of the IRG fuel cell system. Due to budgetary constraints, it was necessary to develop this system for the minimum possible cost whilst ensuring it was sufficiently robust to be transferred directly from the lab onto IRG05.

2.7.2.1. Hardware. First it was necessary to identify each of the parameters which must be controlled or monitored and a means for interfacing them with the CompactRIO. The selection of sensors for a few of the most important signals is described to provide examples of the work conducted.

2.7.2.2. Temperature measurement. K-type thermocouples were adopted for all temperature measurements with standalone data-logging modules already available. This meant that development of the CompactRIO data acquisition system and bench testing of, e.g. the cooling systems could take place concurrently.

2.7.2.3. Pressure measurement. A number of sources of 0–4 bar pressure transducers with pre-calibrated analogue voltage outputs were investigated.

Omega Engineering PMX219 pressure transducers were chosen on a cost basis and were specified with 0–10 V output voltage range in order to make them compatible with the various general purpose analogue input modules offered by National Instruments.

To make future reconfiguration as simple as possible a standard 1/4 in. BSP parallel (G) thread and DIN electrical connectors were used for all transducer installations.

2.7.2.4. Humidity measurement. Accurate relative humidity measurement has been identified in the literature as a particular challenge [16], especially when monitoring transient systems. One technology offering particularly fast response times (time constant, Z, quoted by manufacturer as 8 s) and high accuracy (±2% up to 90% relative humidity) is the Sensirion SHT75 series of capacitive humidity probes. These devices have the additional advantage of being small enough to be packaged within conventional 1/4 and 1/2 in. gas fittings.

For the IRG fuel cell system, attempts were made to overcome problems with flooding of these sensors. When contacted, the manufacturers recommended the use of their own hydrophobic PTFE filter caps to combat the flooding problems experienced. However, it was found that the mountings of these components could not be made sufficiently gas-tight to maintain an acceptable hydrogen seal.

To remedy this, a new fitting was designed in aluminium, capable of accommodating a suitable PTFE filter and providing a proper gas seal thanks to the inclusion of a Viton O-ring between its two mating halves. An additional feature of these fittings' design was their use of a four-way 1.27 mm pitch socket terminal to connect output leads to the sensor, rather than the soldered joints which had been used in the past. This made replacement of individual humidity sensors during routine maintenance much quicker and easier.

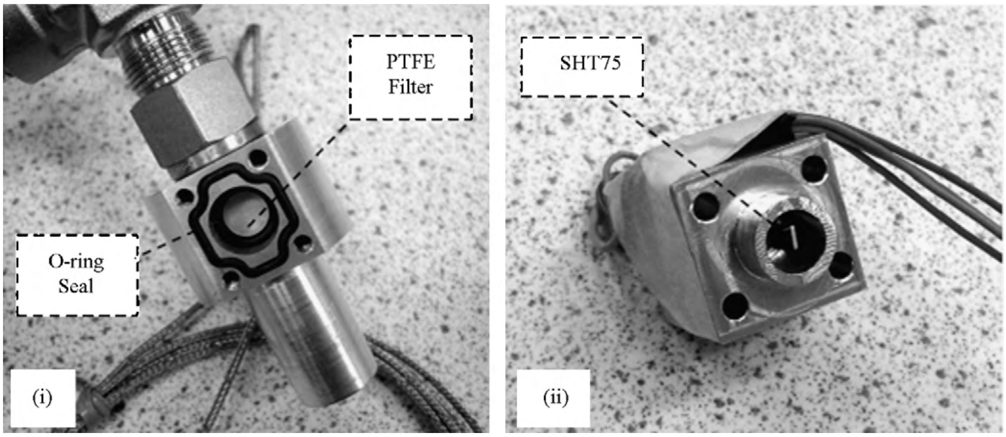

Fig. 5. (i) Photograph of humidity sensor housing with PTFE filter and O-rings installed. (ii) Photograph of humidity sensor fitting with SHT75 installed.

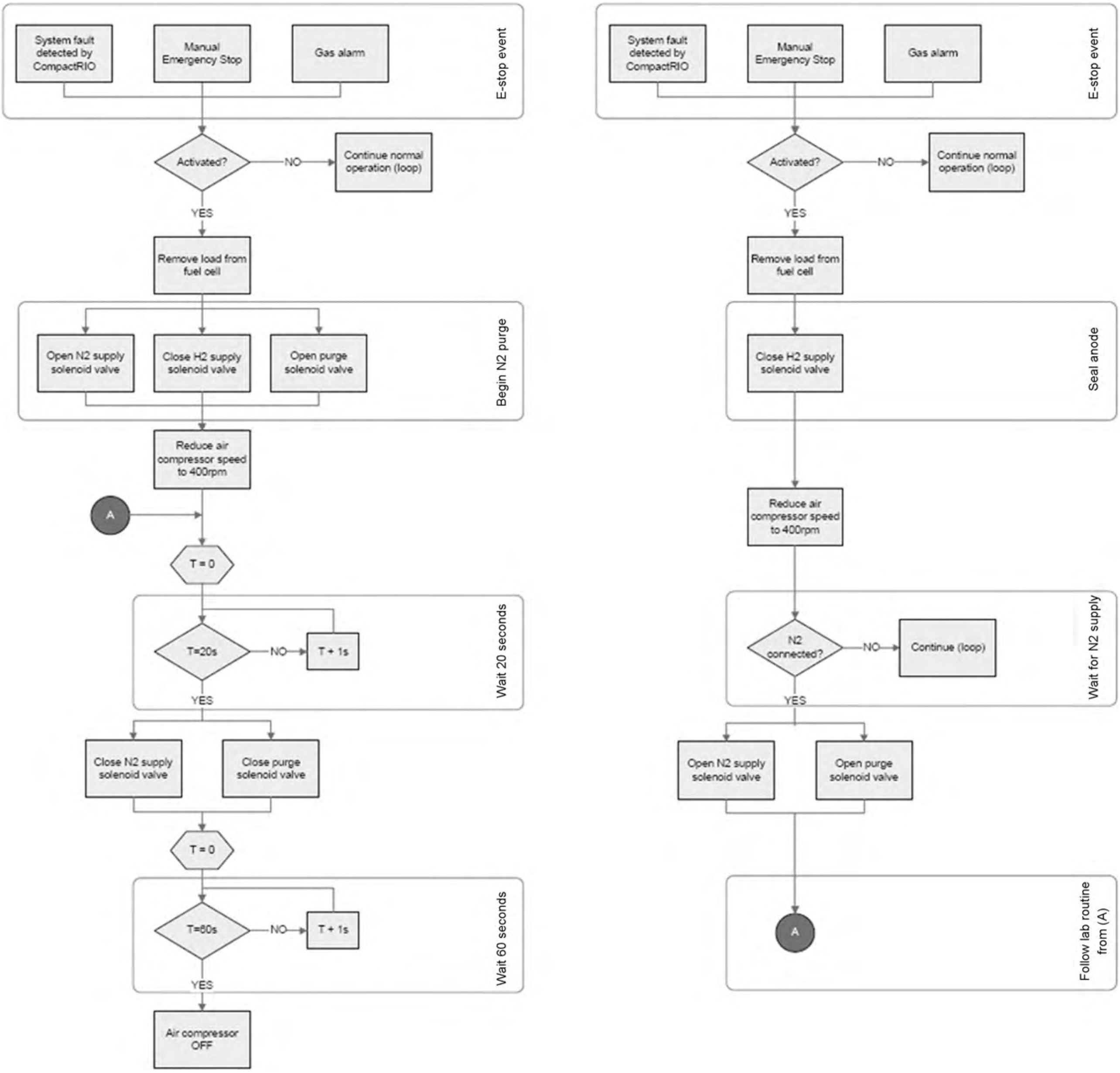

Fig. 6. Emergency stop routines developed for use (i) in laboratory and (ii) on IRG05.

After seeking technical advice from Sensirion and Millipore (a manufacturer of PTFE filter materials) a 1 μm pore diameter hydrophobic PTFE filter material was specified and free samples ordered. Fig. 4 shows a section from the fitting design and Fig. 5(i) and (ii) photographs of the completed components. Note that the aluminium fitting also serves as a 3/4 to 1/2 in. tube adaptor, saving weight over Swagelok's equivalent stainless steel component.

Once installed in these fittings, the sensors were found to be very reliable, providing they were kept in the vertical orientation. Trial installation of the fitting in the opposite configuration led to flooding of the SHT75 sensors as puddles of condensate were able to form on the surface of the PTFE filter as shown in Fig. 4.

2.7.2.5. Flow measurement. Whilst mechanical or electronic control valves can be used to achieve very rapid changes in anode mass flow rate (because they are supplied from a large, high pressure reservoir of gas in the hydrogen cylinder), the air compressor response is retarded by the inertia of the supercharger. As such, the rate at which oxygen can be supplied to the cathode of a fuel cell becomes the limiting factor when current demand is increased rapidly. For this reason, it is common to adopt 'cathode control' in PEMFC systems. In order to achieve effective control of cathode flow rate it is important to be able to measure it accurately, for which an ABB FV4000 air flow meter was used.

2.7.3. Emergency stops

Formula Student race cars have relatively short operating lives, during which they will be driven a fraction of the mileage covered by a conventional road vehicle between services. It is therefore interesting to consider whether there are any opportunities to achieve improvements in vehicle performance at the cost of acceptably small reductions in the fuel cell stack's rated 10,000 h life.

NedStack recommend purging the stack's anode with humidified nitrogen when performing a controlled shut-down. However, discussions indicated that exceptions could be made in the case of an emergency stop event, when it would be acceptable to hold the stack at open circuit voltage for a short period before the purge was performed. However, the resulting reduction in fuel cell performance is not well understood.

If the IRG fuel cell system were to be transferred from the lab to the car without modification, it would be necessary to provide a nitrogen cylinder and regulator for purging duties. This would add significantly to the existing system's weight.

2.8. LabVIEW interface

Restrictions on the length of this paper mean that it is not possible to provide detailed explanations of the LabVIEW codes generated in order to produce the system interface; only the key points are discussed below.

A real time virtual interface (VI) front panel is used to control all system set-points and for monitoring basic information on system condition. Various system parameters were logged directly into a text output file on the host's hard-disc. The Host Computer VI also provides more detailed information on system temperature and pressure trends via its multiple graphical outputs, each of which is updated every 500 ms.

Fig. 6 shows the flow diagrams, which describe the emergency stop routines developed as part of this project. The 'laboratory' routine is currently implemented on the CompactRIO via a flat sequence structure within the Real Time VI. This contains a conditional whilst loop which terminates when an alarm signal is received from the gas alarm, a manual switch or on detecting a system fault. This triggers the automatic shut-down sequence.

2.9. Model development

A dynamic, control-oriented PEMFC system model was developed in order to improve the understanding of the stack and BOP interactions and to enable the implementation of a complete fuel cell system controller in the next phase of development. In order to achieve fast power response to rapid changes in load that occur in a racing situation whilst also maintaining an efficient operation, reactant flow rate, total pressure, reactant partial pressure, temperature and membrane humidity are the main parameters that need to be regulated by a fuel cell system controller.

In the application described in this paper the fuel cell system is hybridised with supercapacitors which should reduce rapid changes significantly. The opportunity to design a simpler fuel cell system will therefore be explored by incorporating the supercapacitors into the fuel cell system model rather than designing the fuel cell system separately from the vehicle.

Control engineering is often an underestimated task in the development of fuel cell systems since many actuators, which are interacting with each other but operating independently from each other, are necessary to guarantee an optimised and fail–safe system operation. Unlike conventional internal combustion engines used in vehicle applications, the majority of the components that form the BOP are not mechanically coupled. As a result, these components have to be controlled by additional controller devices with adequate sensors and actuators and the dynamic behaviour of the complete fuel cell system is not only reliant upon the transient behaviour of its components, but it is also strongly affected by the quality of the control layout.

It was found that, ignoring very fast electric dynamics, the transient behaviour is dominated by mass transport in the air delivery system. Therefore, control system design focussed on the air supply system, with a control objective of maintaining the optimal oxygen excess ratio and preventing oxygen starvation that might occur during rapid changes in the load current.

Although very complex models of, for example, the fuel cell membrane–electrode-assembly (MEA) exist, only a few publications in the literature focus on fuel cell modelling from a system perspective. Mathwork's SIMULINK was used to develop a complete model of the PEMFC system using block diagrams to represent the different components of the direct-hydrogen, pressurised and liquid-cooled PEMFC power plant. A lumped-parameter, semi-empirical modelling approach was adopted using physical principles such as electrochemistry and thermodynamics, mechanics and lumped-parameter fluid dynamic principles.

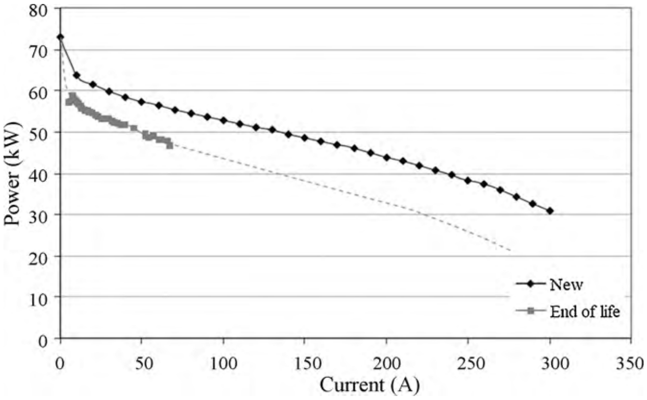

Fig. 7. Polarisation curves provided for new and the 'end of life' NedStack P9.5 stack provided for testing, squares overlaid are the results obtained from initial tests.

In order to not over-complicate the model and system simulation, only dynamic effects which are related to the automotive control problem were included. The very fast electrical dynamic effects taking place inside the fuel cell for instance were ignored. The electrical performance of the PEMFCs was simply represented by a polarisation curve. Empirical modelling by mapping the fuel cell voltage as a function of various contributing variables was adopted as it has advantages in practical applications [17]. Moreover, the balance of plant components were either modelled from first principles (e.g. DC brushed electric motor, dynamic response of compressor) or based on empirical data (e.g. compressor speed–mass flow relationship). The developed model then permitted the behaviour of the BOP to be analysed in detail by means of computer simulations under different conditions of load current, pressure of reactant gases, temperature, stack voltage, etc. Sample results from the developed model agreed with experimental data found in the literature and confirmed that the air system has the largest effect on the dynamic response.

2.10. Testing

All tests involving hydrogen gas were performed in the Imperial College Fuel Cell Laboratory. In preparation for system tests, a large server cabinet was sourced to safely house the stacks and BOP. Shelves were fitted; one for each of the subsystems, as shown in Fig. 8.

Fig. 7 shows results from testing of the 'end of life' P9.5 fuel cell stack provided by NedStack, with data from a new stack included for comparison. The 'end of life' stack had undergone rigorous testing for many thousands of hours and was provided to mitigate the consequences of BOP failure during initial testing.

Testing was conducted using a programmable, water-cooled Dynaload load bank (WCL488 Master 12 kW). To maximise flexibility during lab tests, each of the balance of plant components was run from a mains power supply rather than drawing its power directly from the fuel cell stack. As a result any desired stack loading may be simulated, from a few watts up to the stack's rated power.

All control and data acquisition systems functioned reliably throughout the 10 h of testing conducted to date. Useful data was collected from the cooling system which has allowed calibration of the feed-forward element of the fan speed control.

Table 3
High-level bill of materials showing major fuel cell system components.

Component	Manufacturer	Qty.
Fuel cell stack	NedStack	2
Cooling system		
Centrifugal water pump	Jabsco	1
Radiator	Ford	1
Hydrogen system		
Diaphragm recirculation pump	Gardner Denver	2
Solenoid valves	Burkert	4
Water separator	Custom designed	2
Mass flow meter	Bronkhorst	2
Valves and fittings	Swagelok	(Various)
Air system		
Compressor	Eaton	1
Motor	Lemco	1
Air filter	Pipercross	1
Flow meter	ABB	1
Humidifier	Perma Pure	2[a]
Control/data acquisition		
Controller	National Instruments CompactRIO	1
Pressure transducers	Omega	10
Humidity sensors	Sensirion	4
Thermocouples	Various	10
Hydrogen sensors	Figaro	2

[a] Option to reduce to just one humidifier if performance is adequate.

No balance of plant failures were experienced during testing.

2.11. Costs

Initial cost estimates for the completed system were of the order of £40,000. However, the fuel cell system team was only allocated £3,900 in 2008/9 due to financial constraints. Therefore budgetary constraints have had a significant impact on the decisions made throughout the project. It has only been possible to build a working fuel cell system because of generous sponsorship support. The final system cost is anticipated to be £39,000.

2.12. Final design

Table 3 describes the top level bill of materials in the final design. Fig. 8 is a photograph of the completed fuel cell system during testing, and Fig. 9 is a schematic of the final design.

3. Future development

A number of areas have been identified as having strong potential for further development, with the aim of improving the IRG fuel cell system's performance before it is installed on the vehicle during the 2010/11 academic year. Furthermore, given that the system is currently configured for laboratory testing, more work is required before vehicle-mounting is feasible.

3.1. Balance of plant optimisation

Firstly, any reductions of the balance of plant's weight and/or power consumption would clearly be advantageous for this application; especially if savings are made at the system's 'racing' operating point. This would help improve system efficiency and allow a higher specific power to be achieved.

A number of opportunities for reducing balance of plant power consumption and/or weight present themselves, as detailed in the following sections.

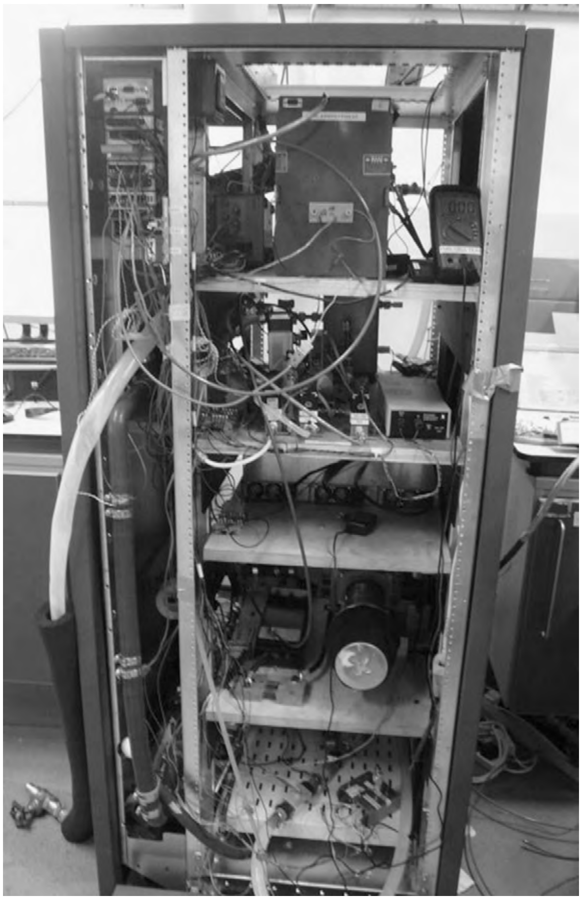

Fig. 8. Full fuel cell system assembly.

3.1.1. Replacement of air compressor

Despite proving excellent for laboratory testing, the Eaton M24 roots compressor is over-specified for this low-pressure application. The supercharger is capable of delivering considerably higher pressure ratios and flow-rates than the NedStack fuel cell stack demands and, as a result, is operated away from its peak efficiency.

Similarly the 11 kg, 16 kW (peak) Lemco LMC200 DC motor used to drive the compressor proved ideal for system evaluation but is wholly inappropriate for mounting on a vehicle.

3.1.2. Elimination of hydrogen recirculation pump

It has been demonstrated that ejector pumps can provide an effective means of recirculating hydrogen to maintain anode stoichiometries above one [Sugawara, 2003]. If such a device was developed as a passive replacement for the existing diaphragm pumps then a significant weight saving would be made in addition to the reduction in parasitic power consumption.

3.2. Vehicle integration

3.2.1. Optimisation

Further testing will help establish the best operating point for the fuel cell, achieving a sensible balance between fuel economy and power density. This is an important consideration for the Formula Student competition because a significant number of points are awarded on the basis of fuel consumption.

3.2.2. Data acquisition

A number of the instruments used for data acquisition in the laboratory must be replaced with lighter, more compact equivalents

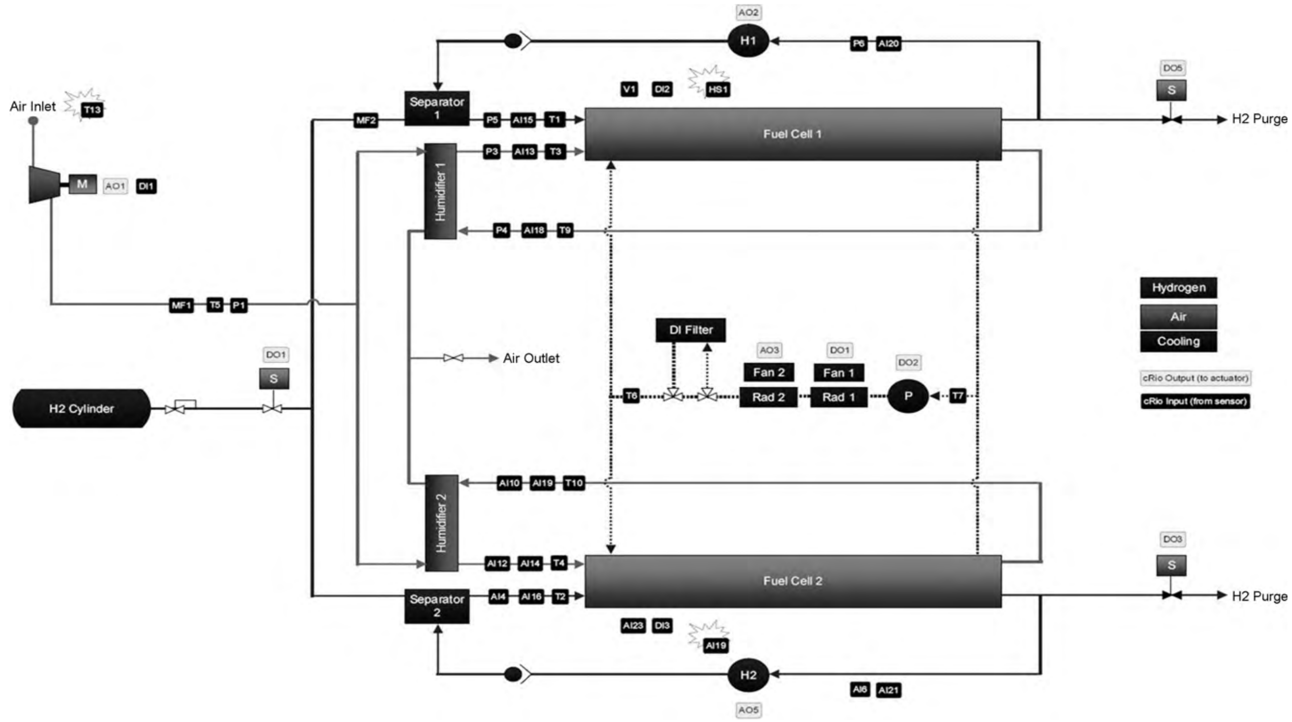

Fig. 9. Final fuel cell system configuration.

before they can be used on the vehicle. These include the industrial ABB FV4000 air flow meter and desktop computer currently used to log data. Air mass meters commonly used in car throttle bodies/inlet manifolds will be investigated as a low weight, low-cost replacement.

As demonstrated on IRG02, the CompactRIO can be configured to write data directly to a USB pen drive, removing the need for a host computer. Wireless connections to the CompactRIO have also been demonstrated, allowing remote condition monitoring; a tool which is of particular interest for this system, and should allow pit monitoring of the fuel cell system during racing.

3.2.3. *Packaging*

All of the fuel cell's balance of plant components must be safely packaged prior to mounting on IRG04. This is important to ensure that the fuel cell system can be installed and removed without unnecessarily disconnecting gas lines or instrumentation wires.

3.2.4. *Hybridisation*

The size of the vehicle's energy storage system will be specified based upon data collected from testing of IRG03 and IRG04. It is expected that the energy storage medium used in IRG05 will be supercapacitors and these will be significantly smaller than the battery packs used in IRG03 and IRG04, reflecting the larger fuel cell.

3.3. *Stack weight*

The NedStack P series was developed for stationary applications therefore it is expected that there will be extensive opportunities to reduce the weight of its mechanical components for an automotive application. In total, it is estimated that 17.5 kg (47%) of the P9.5's total 37 kg weight comes from mechanical fittings like the side panels and end-plates.

It is feasible that future variants of the fuel cell system could provide around 8.5 kW from a 40 kg system comprising of one stack with its own dedicated balance of plant. This would be a significant improvement in the power density ($\mathrm{kW\,kg^{-1}}$), compared to the system used on IRG02.

3.4. *Control system*

The fuel cell system model developed will be used to study different PEMFC system control strategies. Once an optimum control strategy has been identified it will be implemented in hardware on National Instrument's compactRIO (cRIO) to form the fuel cell system controller. The PEMFC system simulation running in SIMULINK can then be interfaced with the cRIO, i.e. the fuel cell system controller, in order to assess the hardware controller without risking causing damage to the real system. A user interface, easily established in LabVIEW, will allow all operational parameters to be monitored. Once it has been established that the fuel cell system controller operates satisfactorily, the PEMFC plant simulation can be replaced by the real system. Alternatively, a hardware-in-the-loop (HiL) approach could be adopted. The modelling, simulation and control project described here provides a basis for the development and implementation of a fuel cell system controller in both hardware and software by future IRG students.

4. Conclusions

Given a relatively modest budget and in less than 8 months, a team of undergraduate engineers successfully designed and assembled an operational high-power PEMFC system. Over £50,000 of sponsorship and help-in-kind was secured and long-term relationships have been initiated with many of the sponsors.

Individual subsystems were designed, independently tested on the bench, and then integrated into the whole balance of plant. Cell degradation mechanisms were investigated and used to inform the design of a LabVIEW based control system. This system was implemented using CompactRIO hardware and its performance assessed during initial testing. Successful testing was conducted using the balance of plant to support an end of life P9.5 Nedstack up to 3.1 kW of gross power. Performance of the stack using the balance of plant was identical to that provided by Nedstack. Potential long- and short-term system developments have been identified, several of which will be developed further next year.

In educational terms, the Imperial Racing Green project provides an opportunity for undergraduate students to work in a team based multi-disciplinary environment, developing cutting edge low carbon vehicle technology.

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