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Experimental evaluation into novel, low cost, modular PEMFC stack

Paul Scott*, Dr. R.K Calay, Dr. Y.K. Chen,

Sustainable Energy Technology Centre, University of Hertfordshire, United Kingdom, AL10 9AB

Abstract

The Polymer Electrolyte Membrane Fuel Cell (PEMFC), despite being regarded as an ideal replacement to the internal combustion engine, is still not an economically attractive pri-mover due to a number of key challenges that have yet to be fully resolved; some of which include degradation to cell components resulting in inadequate lifetimes, specialised and costly manufacturing processes and poor gravimetric/volumetric energy densities. This paper presents a novel stack concept which removes the conventional bi polar plate (BPP), a component that is responsible for up to 80% of total stack weight and 90+% of stack volume in some designs [1]. The removal of said component not only improves the volumetric and gravimetric energy density of the PEMFC stack but drastically reduces the cost of the stack by removing all costly manufacturing processes associated with PEMFC component machining while the functionality of the traditional BPP is still retained by the unique stack design. The stack architecture is first presented and then the characterisation of the PEMFC is shown over a wide range of operating scenarios. The experimental studies suggest that the performance of the new design is comparable to that of traditional stacks but at significantly less cost price.

Keywords: PEM; stack; novel; architecture; experimental

* Corresponding author. Tel.: +44(0)1707 284772
E-mail address: p.e.scott@herts.ac.uk

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1. Introduction:

Despite liquid electrolyte fuel cells already a commercially available and viable product for medium to large scale stationary applications it is widely regarded that the PEMFC is one of the most promising solutions for clean and sustainable power production for future generations that will reduce our dependency on fossil fuels. The PEMFC is particularly attractive due to its simplistic operating principle and low operating temperature and its versatility to meet a wide range of applications over a large power demand spectrum without the need for much modification to either stack or overall system design [2, 3]. Despite the considerable research and many feasibility studies undertaken on the PEMFC over various applications the PEMFC is only just reaching a stage where it can be classed as commercially available, yet still not economically viable; a situation the fuel cell must be in before it can be considered as a suitable alternative to traditional pri-movers. Despite the simplistic operation which has made the PEMFC so favourable as an alternative pri-mover, it is fraught with a number of inter-related technological and operational issues which has led to the slow development of the PEMFC which must be resolved before widespread commercialisation is realistic [1]. Technological issues include material selection and subsequent manufacture of components while operational issues include optimisation of influential operating parameters and also prevention and management of component degradation within the fuel cell which directly relates to the durability and operational lifetime of the stack.

In 2005, the US Department of Energy (DOE) revised cost and performance targets for PEMFC components to be reached by the year 2015. These targets are summarised in *table 1*. These targets are set for 500, 000 per year 80 KW PEMFC stacks and based on automotive applications [4,5]; however in order for these targets to be met a paradigm shift is needed in stack design philosophy, material selection and fabrication techniques which have not yet been seen.

Table 1: US DOE cost and performance targets 2015.

Characteristic	**Units**	**2015 target**
Cost * [4]		
• System	US$/KWe	30
• Bi Polar Plates	US$/KWe	3
• Electrocatalyst	US$/KWe	3
• Membrane	US$/$m^2$	20
• Stack	US$/KWe	15
Durability [5]	**Hours**	
• Automotive		5, 000**
• Domestic		40,000

**Based on production of 500, 000 unit/year 80KW stacks*
***inclusive of load following/start stop cycles (~150, 000 miles)*

One component in particular, the Bi Polar Plate (BPP), is responsible for over 30% of stack costs alone and contributes to over 60% of stack weight in some fuel cell designs and almost entirely all of the

volume of the stack in the majority of stack designs [6]. Here, a novel modular fuel cell stack is presented which has removed the BPP from the planar PEMFC stack resulting in a fuel cell stack that has improved the volumetric and gravimetric power density to that of a more traditional counterpart.

2. Design changes

The new novel concept involves a series of identical chambers that provides a singular gaseous stock to two cells simultaneously with the fuel and oxidant alternating in each chamber. While only a single gas is fed into each repeated chamber, planar repeating cells is achieved by simply shifting cell boundaries to the middle of each chamber thus ensuring fuel and oxidant on either side of each MEA sandwiched between the repeating chambers.

Instead of a typical Anode –Membrane – Cathode/ Anode –Membrane- Cathode repeating configuration between the MEA of one cell through the BPP to the next cell in a traditional planar fuel cell, the following configuration is utilised; Anode- Membrane – Cathode / Cathode- Membrane – Anode/ Anode – Membrane- Cathode ... whereby electrical continuity is achieved using perforated current collecting plates that allow for external connections in a series arrangement (and parallel if required) while also allowing a fault tolerant system to be implemented. This also means that the same initial sizing parameters, specifications and equations can still be used as with a traditional planar stack.

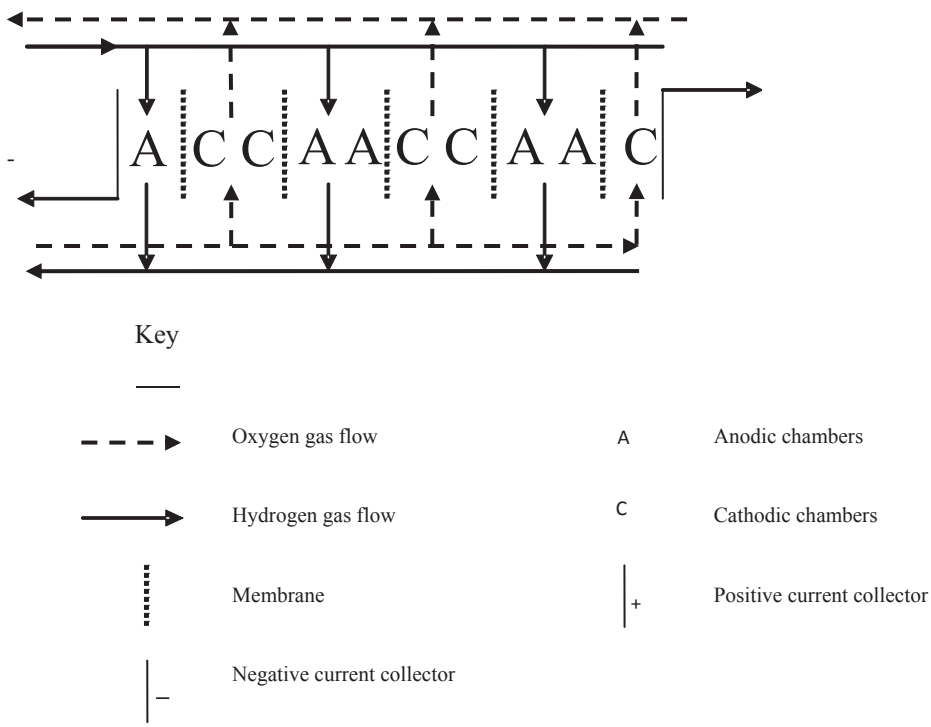

Figure 1: Schematic of novel stack architecture arrangement

External manifolds provide fuel and oxidant either side of the casing in a U arrangement. The stack has been designed with simplicity and manufacturability in mind and as such the main stack body compromises of just two components which have been mirrored on its inner planar face to create the overall stack components resulting in minimal need for change to the manufacturing processes. The novel design concept of the chamber means that the integrated chamber can be used for both gas streams by simply rotating the component by 180° thus ensuring the same repeatability that was achieved with the traditional BPP. The manifolds for both gas streams are symmetrical about the inner face of the manifold and are co-ordinated in relation to the chamber design. Within each chamber, an integrated insulating interdigitated flow topology is utilised to aid even gas distribution within the chamber and to the Membrane Electrode Assemblies (MEA's).

The nature of the flow topology means that both diffusive and forced convection gas transfer mechanisms aid mass transfer to the reaction sites but also help to remove product water from the GDL and centralised flow field. Coated Stainless steel BPP has been shown to meet material and cost targets set out by the US DOE and in particular can withstand the harsh acidic operating environment inside the PEMFC without significant oxide formation and metal ion dissolution, both of which are detrimental to fuel cell lifetime and performance [3,7].

Titanium Nitride (TiN) has been shown to reduce metal ion dissolution and contact resistance compared to that of uncoated SS while reducing the voltage decay to that of almost Graphite [3,8]. Here, perforated Stainless Steel (SS) plates with a TiN coating are used as the current collecting plates for each fuel cell which are housed within the repeating chamber. Perforations allow the gas to flow from the gaseous chamber to the GDL of each MEA sandwiched on either side of the chamber. The high density of the SS is offset by the perforations and the considerably thinner sheets to that of the Graphite, despite SS having a density ~x4 to that of Graphite. The simplified nature of the stack has meant that the compressive end plates are identical whether at the front or rear of the stack further reducing the machining processes required to produce the fuel cell stack.

The compressive end plates and the external manifolds' novel design form a gas tight seal between the two end plates and the stack chambers, ensuring no gas mixing or venting to the atmosphere can take place.
The changes to the stack architecture has led to a fuel cell stack that has removed the BPP while also reducing stack size and weight, improving the volumetric and gravimetric power densities of the PEMFC utilising materials that are ideal for mass manufacture but also suitable within PEMFC environment.

3. Experimental

Here, a six cell 210 W (Pelec@nominal) modular PEM fuel cell stack was manufactured, assembled and characterised. The stack utilises 6 x 100cm^2 Active Area Nafion®117 five layer MEA with a Pt loading of 0.4mg/cm^2 on Carbon Black with Carbon paper used as the Gas diffusion layer, sourced from Electrochem Inc. For the prototype fuel cell stack, Acrylic (Perspex) was chosen as the material for chambers, external manifolds and internal flow field sections. Repeating chambers and external manifolds were manufactured out of house by Penta Precision Engineering® using CNC milling machines. The designs of the chambers and manifolds are such that they are ideal to mass manufacture injection moulding techniques.

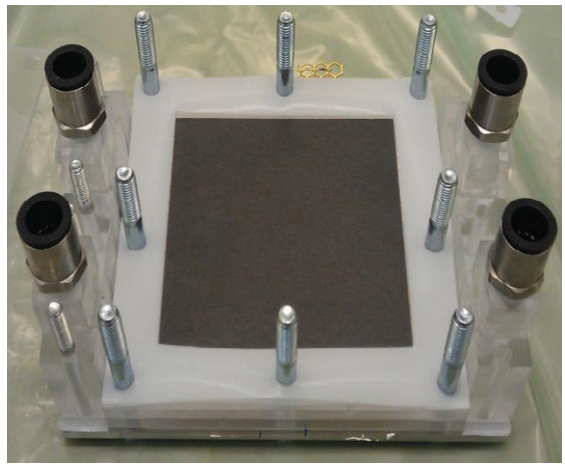

Figure 2: Assembly of PEM fuel cell stack

Interdigitated internal flow field sections were manufactured in house using a CNC milling machine, where the interdigitated design is mirrored about the planar face, resulting in the same flow field design on both faces of the acrylic section. The flow field section is the same size as the active region of the chamber, where they are coupled via an interference fit. SS 316 was used as the current collecting plates for both anode and cathode which was purchased in pre fabricated perforated sheets which were then made to size using a laser cutter. The sheets were then coated with a ~2μm TiN layer via electron beam evaporation physical vapour deposition process by TecVac® coating services. Compressive gaskets were positioned between compressive end plates and external manifolds and between each repeating chamber. The gaskets vary on design however were both made from PTFE, with thickness 160μm +/-10μm. For initial proof of concept, the end plates have been made from SS304; however, it should be noted that future stack designs will incorporate light weight compressive end plates as part of continual design improvement process. The stack is clamped via 8 x 8mm SS bolts through the central chamber casing and 8x 5mm SS bolts through the external manifold casing. Fluid connections are made via 12mm OD push fit connections. External connections are made via the current collecting plates which protrude out of the repeating casings. The interconnects allow either a series, parallel, or both configuration within the fuel cell stack allowing complete flexibility depending on the power requirements of the application. During the prototype phase, interconnects were made from heavy duty insulated Copper cabling with a unique electrical coupling to the current collecting plates to reduce interfacial resistances. Here, the connections were made in a traditional series configuration, The 6 cell modular fuel cell stack is shown below in *figure 3*.

In order to evaluate the performance the fuel cell stack was assembled and characterised in house. A CompuCell gas management system, purchased from Electrochem Inc, was used to control, humidify and monitor both the fuel and oxidant gas streams. A TDI Dynaload RBL800W was used for the load demand on the fuel cell stack of which power, current, voltage could be tested in a constant mode. The proprietary PowerStation software was used to control gas flow, humidification, electronic load and data capture of all experimental variables during the testing phase. A stand alone Agilent bench-top digital multimeter coupled with an Agilent multiplexer unit was assembled, configured and commissioned for use a cell voltage monitoring unit to measure the voltage distribution within the stack. Datalogger 3 was used for cell voltage data acquisition.

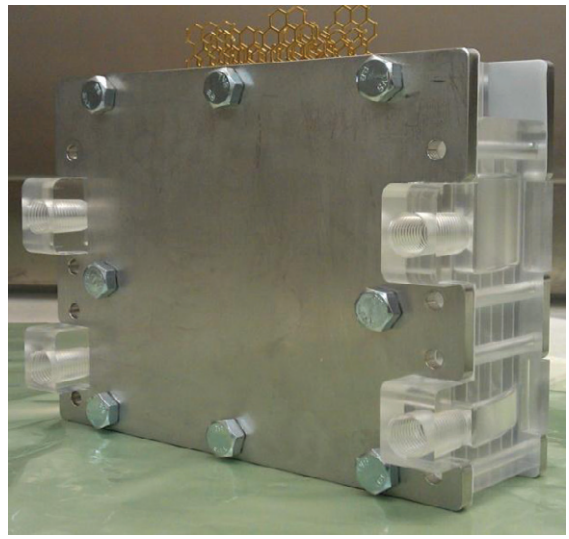

Figure 3: Novel PEM fuel cell stack

4. Results and discussion:

Operating temperature of the fuel cell, temperature of reactant gases, stoichiometric ratios (λ) of reactant gases where varied to characterise the fuel cell stack. Due to the nature of the humidification process, both the fuel and the oxidant were humidified to a Relative Humidity of 100% for all testing sequences. Of particular interest was the overall maximum electrical power produced from the novel fuel cell stack shown in *figure 4* Stack peak power was measured @ 234.56W, with a power density of 0.390 W/cm^2 and a nominal electrical output ($0.6Acm^{-2}$) of 210W. While the overall performance of the fuel cell stack was satisfactory there were issues in maintaining even voltage distribution across all of the cells within the stack under various operating conditions and loading (both steady and unsteady). For cell measurement, cells in the stack were numbered 1-6, from back of stack towards the fluid connections and each cell was connected to the voltage multiplexer via connections to the anode and cathode of each cell using twin core coaxial cable to prevent electromagnetic and radio frequency interference. Here, both the voltage distribution and the steady state performance of the cells within the stack are examined. The fuel cell stack was imposed under a voltage of Vstack=3.6V for 1440 minutes with polarisation curves taken at 0mins, 720mins and 1440 mins. The voltages throughout the testing [excluding polarisation curve sequences] are shown below in *figure 5*.

Whilst the fuel cell was kept at 3.6V, cells 5 and 6 were erratic during different stages in the testing process. After pol.1@t=0mins, cell5 took 320 minutes to rise from an operational voltage of ~0.3V to that of the Pnominal of ~0.6V required per cell. As seen in figure 5, cells 1-4, 6 operated between 0.66-0.73V in order to compensate for the low voltage seen in cell 5. Of the cells to compensate, cell 2 was consistently at a higher operating voltage approximately operating at >0.7V for over 700 minutes. After 320mins, cell5 begins to stabilise towards that of Pnominal, bringing the operating voltages of cells 1-4, 6 towards that of the desired 0.6V per cell. However, it can be seen that cell5, despite a rise in operating voltage remains consistently lower than the respective cells in the stack, with a 0.06V drop in operational

voltage compared to that of cell2. After 320 mins, the cells have a period of stabilisation where all cell voltages are within 0.1V tolerable range.

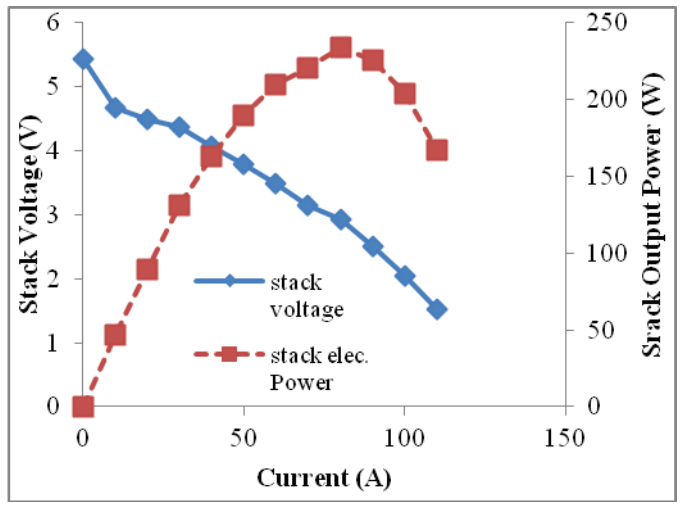

Figure 4: Max voltage and power curve for fuel cell stack [Tcell=75°C; H2/air @100% RH; Pstack(abs) 1.2Bar(H2/air); stoichiometric ratios: H2λ2;airλ3]

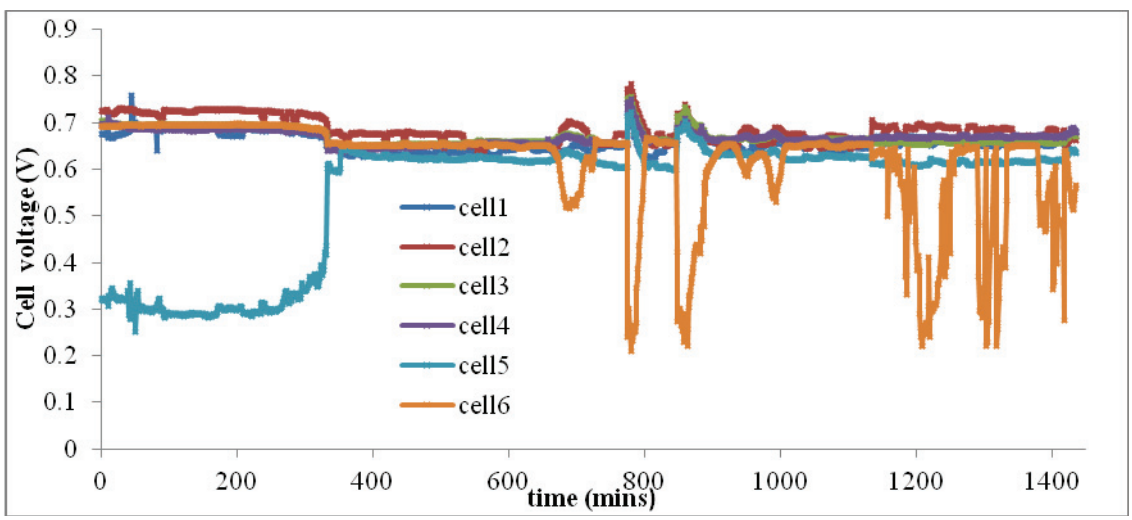

Figure 5: Cell voltages during steady state testing @ Vstack=3.6V [Tcell=75°C; H2/air @100% RH; Pstack(abs) 1.2Bar(H2/air); stoichiometric ratios: H2λ2;airλ3]

After pol.2 @t=720mins it can be seen that cell 6 now is considerably unstable with regions of significant cell voltage drop close to the emergency shut down voltage of 0.2V. The gradual drop in voltage followed by sudden drop of voltage is characteristic result of flooding first within the GDL, seen

by a gradual decrease in cell voltage followed by flow channel blockages resulting in a significant drop of reactant gas concentration leading to starvation to the cell. This is in agreement with the results found by Fouquet [9] where sudden voltage drops were also seen as a result of water blockages. As the pressure builds up inside the flow channels the water is then removed, eventually restoring the performance for a period of time. Cells 1-5 compensate the fluctuations in voltage of cell 6 to maintain the desired Vstack =3.6V, however in doing so set up a quasi- dynamic phase where cells are consistently varying in response to the changes to cell6. The cyclic voltages of cells 5 and 6 suggest that bulk reactant gas distribution is responsible for the varying performance in these cells. It can be seen that performance of the fuel cells are satisfactory if reactant gases reach the active areas of the membrane, which suggests that bulk distribution of reactant gases is suitable, if somewhat rich, towards the rear of the stack as seen by the consistent performance throughout of cells1-4. In particular, an oxidant gas chamber that supplies both cell 5 and 6 simultaneously is considered to have ineffective gas bulk flow into the chamber to provide adequate reactant gas at higher current densities, as seen by the poor output of either cell 5 or cell 6 after a polarisation test. The concern lies in degradation mechanisms acting on both the affected cells and the supporting cells as a result of the cyclic performance of cell 6. Cell 5 and 6 are likely to suffer from gas starvation mechanisms that can result in Carbon and Pt particle oxidation, or cell potential reversals while the repeated cyclic potentials found in the supporting cells are also likely to result in catalyst layer oxidation at higher potentials, as seen by cell 2 maintaining an operational potential of >0.7V.

Upon inspection of the stack it was found that there was considerable water coalescence inside the interdigitated flow field of cell 5, which would explain the erratic cell performance during the second steady state phase. In light of this, a revised CFD model is being developed to improve the fluid model of the two phase flow found inside the fuel cell.

5. Conclusions:

A novel PEMFC stack has been designed, assembled and experimentally validated. The fuel cell architecture has lead to the removal of the BPP and instead a series of chambers that supply a reactant gas to two cells simultaneously via an external manifold has been utilised. All components inside the stack can be manufactured using mass manufacturing techniques and as such the stack lends itself to becoming a low cost PEMFC stack, moving away from the costly and complex manufacturing processes typically seen with Graphite BPP. Characterisation has shown that the stack can yield outputs similar to current fuel cell stacks with a maximum power output of 234.56W for 6 cells, equating to a power density of 0.390W/cm^2, however, extended operation at a steady state load saw operational issues with cells 5 and 6 which resulting in a quasi dynamic loading on the supporting cells despite a steady state loading. The bulk gas flow into an oxidant gas chamber that simultaneously supplies the oxidant to cells 5 and 6 was identified as the issue. As a result, a revised CFD model will be set up to improve the analysis of two phase flow within the external manifold to increase the flow into the problematic chamber. The next phase of work includes further weight savings to the stack and electrochemical analysis.

Acknowledgements

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