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Non-planar architecture for proton exchange membrane fuel cells

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Abstract

PEMFCs traditionally rely on the use of sculpted graphite bi-polar plates and planar MEAs. A PEMFC design based on a non-planar electrode–membrane assembly and using non-conventional collector plates is described in this paper. The design achieves high volumetric power densities while maintaining low contact resistance and structural integrity. Several new methods for supporting the MEA, for collecting current and for sealing are described.

A technique and hardware developed for assembling the non-planar membrane–electrode assemblies are described and the performance of two prototype cells based on the new design is examined. Preliminary results demonstrating significant gains in volumetric power density are presented.

Keywords: Fuel cell; Membrane–electrode assembly; Power density; Metallic components

1. Introduction

Conventional PEMFC stack designs have been based on planar, repetitively stacked structures that use milled [1] or pressure-moulded plates [2] to deliver fuel and oxidant gases to the reaction sites. The materials of choice for these plates have included graphite, amorphous carbon, and carbon composite materials combined with resins and polymeric binding agents [3]. More recent work has considered stamped sheets made of titanium, stainless steel, and other metals.

During operation, the plates are exposed to acidic aqueous environments, with reducing and oxidizing atmospheres on the anode and cathode sides, respectively. The design constraints determining the choice of materials include

1. chemical and structural integrity,
2. electronic and thermal conductivity,
3. gas impermeability,
4. gravimetric and volumetric density,
5. cost,
6. manufacturability.

The first four items on this list are required to comply with application-specific criteria, and to maintain performance over extended periods of time (e.g. 5000 h for mobile applications, 40,000 h for stationary power generation). The last two items are related to market penetration, the implementation of mass-production schemes, and the competitiveness of fuel cell products with existing customer choices.

The level of relative importance on this list varies with the application. Cost and durability (lifetime), for example, are of paramount importance in mobile applications where fuel cells have to compete with advanced internal combustion engine technology. FC system designs for other applications (remote power, personal electronics, military applications, etc.) also have stringent but, typically, less demanding design, operation and cost constraints. In these applications there is considerable scope for new stack designs.

This paper presents a new stack design based on the waved tube cell (WTC) concept. This design is the physical embodiment of a novel fuel cell architecture aimed at developing high power density stacks that utilize non-carbonaceous materials, and continuously manufacturable components. This stack architecture provides intrinsically higher volumetric density, and the potential for significantly improved manufacturability and reduced cost.

1.1. Limitations of planar PEMFC structures

In conventional PEMFC configurations, shown in Fig. 1a, only a portion of the active area is exposed to the flow of reactants in the flow channels. At the points of contact, the porosity of the gas diffusion layer is reduced by the clamping pressure required to ensure perimeter sealing, prevent

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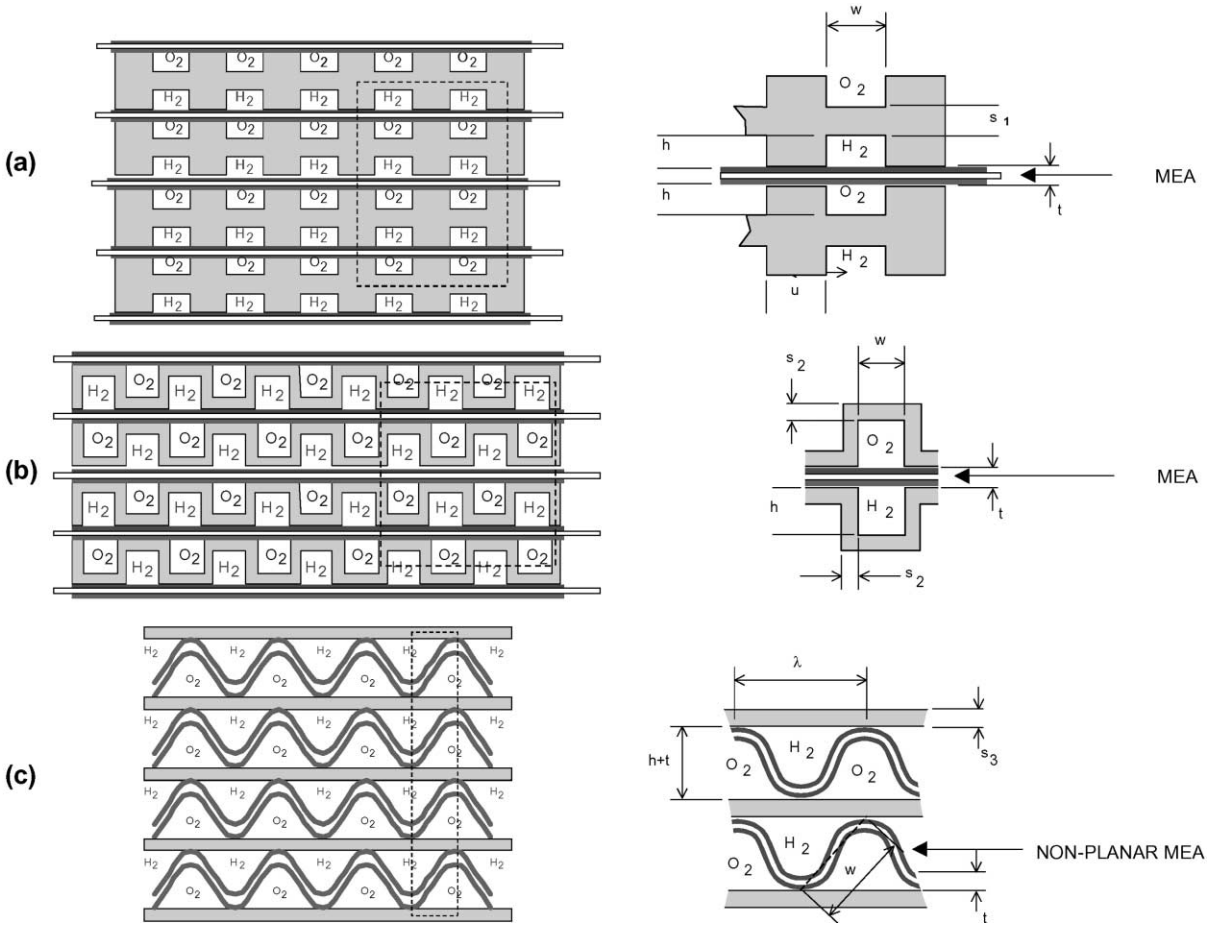

Fig. 1. Schematic stacks and blow-up views illustrating the progression from: (a) plate-and-frame architecture; (b) corrugated stack; (c) wave-tube cell concept with three-dimensional, non-planar MEA structure.

reactant leaks between adjacent channels, and reduce overall contact resistance.

Lower porosities result in hindered diffusion to the reaction sites under the points of contact between the flow field plates and the MEA. As a consequence, this particular design represents a trade off between larger exposed areas (i.e. larger current and power per unit active area), and larger contact areas (i.e. lower contact resistance and better support for the MEA).

From a manufacturing perspective, this plate-and-frame design is not unidirectional and relies on batch rather than continuous manufacturing processes. In addition, the creation of three distinct functional planes (oxidant, separator, fuel) implies the existence of redundant volumes within the fuel cell stack. This additional space, combined with the physical properties of graphite and graphite composites imposes limitations on plate thickness and, consequently, on the power densities achievable with plate-and-frame architectures.

The potential for volumetric power density increase through more effective use of space within fuel cell stacks has begun to be recognized. Examples of this progression include designs employing corrugated separator plates that are inherently thinner than their conventional counterparts [4,5]. Other efforts include banded structures and monopolar cell configurations [6,7]. Enhanced manufacturability has also been achieved by using moulded plates made of graphite composite materials [8,9]. In a separate publication, the authors have disclosed a space-efficient stamped separator plate that can achieve complex flow field geometries while minimizing stack volume [10]. The topology of a corrugated cell is shown in Fig. 1b; the higher volumetric density is achieved by collapsing the oxidant and fuel distribution channels onto a single plane.

1.2. A new PEMFC stack architecture

Despite the incremental improvements discussed above, plate-and-frame architectures perpetuate the use of planar MEAs, which are clamped between bi-polar plate elements of different geometries. The design of the first WTC prototype is based on a new approach for PEMFC manufacture that relies on non-planar waved MEAs (see Fig. 1c). The inherent advantage of non-planar electrode–electrolyte layers has been recognized before, and such designs have been proposed for high temperature fuel cells. This includes solid oxide fuel cells with a thin corrugated ceramic electrolyte

deposited on a honeycomb structure [11], and undulate electrolytes in molten-carbonate fuel cells [12]. These designs do not, however, suggest the use of undulate membranes–electrode-assemblies in PEM fuel cells, nor do they address critical design and manufacturing issues such as how to achieve effective manifolding and complex flow fields for reactant gas distribution.

Instead of starting with a flat membrane and building the cell/stack around it, the waved tube cell is based on a layered structure that extends the two-dimensional (planar) MEA functionality into a third-dimension. The associated fabrication process is one-dimensional and has the potential to be implemented in a continuous and automated mass-production scheme.

1.3. Theoretical volumetric power density gains

The topologies in Fig. 1 can be used to illustrate the volumetric power density associated with each of the three stack architectures. Assuming straight flow channels and neglecting manifolding space, the minimum volume, $V_{\min}$, required to expose an active area, wl, in a conventional plate-and-frame cell is given by

$$\frac{V_{\min}}{wl} = v_1 = \frac{(w+u)(2h+t+s_1)l}{wl} = (1+\alpha)(2h+t+s_1) \tag{1}$$

The width of the contact area, $u = \alpha w$, is usually comparable to the channel width (i.e. typically $\alpha \cong 1$). The corresponding expression for the corrugated cell in Fig. 1b is

$$v_2 = \frac{2(w+s_2)(h+t+s_2)}{w} \tag{2}$$

For the sinusoidal topology in Fig. 1c, the minimum volume can be adequately approximated by considering an equilateral, semi-triangular channel of side w:

$$v_3 = \frac{w}{2}\frac{(h+t+s_3)l}{wl} = \frac{h+t+s_3}{2} \tag{3}$$

A representative variation of the volume corresponding to each topology is shown in Fig. 2. The specific volume parameter range for each topology is generated by varying h, w, u and t over a range of values as indicated in the figure caption.

The progression from one topology to the next yields a decrease in the minimum volume required to expose a given amount of active area (i.e. $v_1 > v_2 > v_3$). However, the potential gains in volumetric power density for the waved cell can only be realized in practice by addressing significant challenges in MEA manufacture, sealing, manifolding, and current collection.

1.4. The challenges

A primary consequence of non-planar MEA strata is that, instead of relying upon channels in the separator plates to provide reactant conduits, large portions of the MEA can be shaped to serve as channels for reactant delivery. In its simplest embodiment, the resulting structure resembles corrugated cardboard. Fig. 1c illustrates how the MEAs could be configured as corrugated strata between planar separator plates.

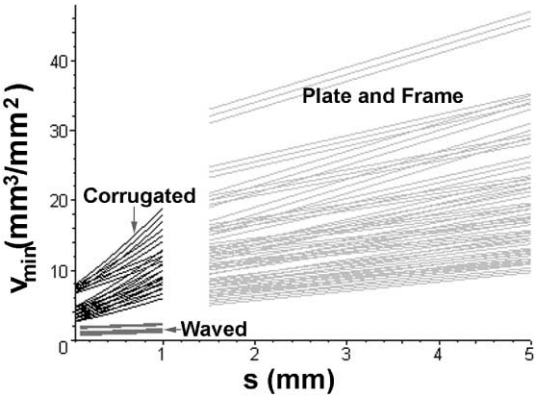

Fig. 2. Variation of the volume per active membrane area, $V_{\min}$, as a function of separator plate thickness for the three stack topologies. In all cases, $h \in \{1, 1.5, 3\}$; $w \in \{1, 1.5, 3\}$; and $t \in \{0.25, 0.50, 0.75\}$ (all dimensions in millimeter).

Some of the issues that need to be addressed for the effective implementation of the wave cell concept are: (i) manufacturing of non-planar MEAs, (ii) stiffening or structural support of the MEA to withstand deformation under the compressive forces required for proper sealing and good electrical contact, (iii) reduction of contact resistance between electrodes and separator plates, (iv) manufacturing of adequate perimeter seals, and (v) manifolding associated with co-planar, straight flow channels.

The fabrication methods for non-planar MEAs are the subject of a different publication. In general, these methods include manufacturing steps with precise control of the temperature, pressure, and feed rate required to bond catalyzed electrodes to the polymeric ionic conductor.

Structural integrity of the non-planar shape and good electrical contact require either modification of the standard MEA manufacturing and appropriate techniques to bond the MEA to the conducting separator plates, or re-design of the plates to provide internal structural support and ensure good electrical contact without the use of large compressive forces. In both cases, the authors have found that the addition of macroscopically porous current collectors to either the separator strata or the MEA provides a satisfactory result. The current collectors may be either attached to the separator strata or combined integrally with the MEA to form a bonded non-planar structure. In the former case, localized compressive forces are greatly reduced by spreading the electrical contact over the surface of the MEA. In the latter case, if the current collectors are attached, the compression force needed to hold the stack together is greatly reduced, because the separator strata and electrodes no longer need to be forced together to reduce contact

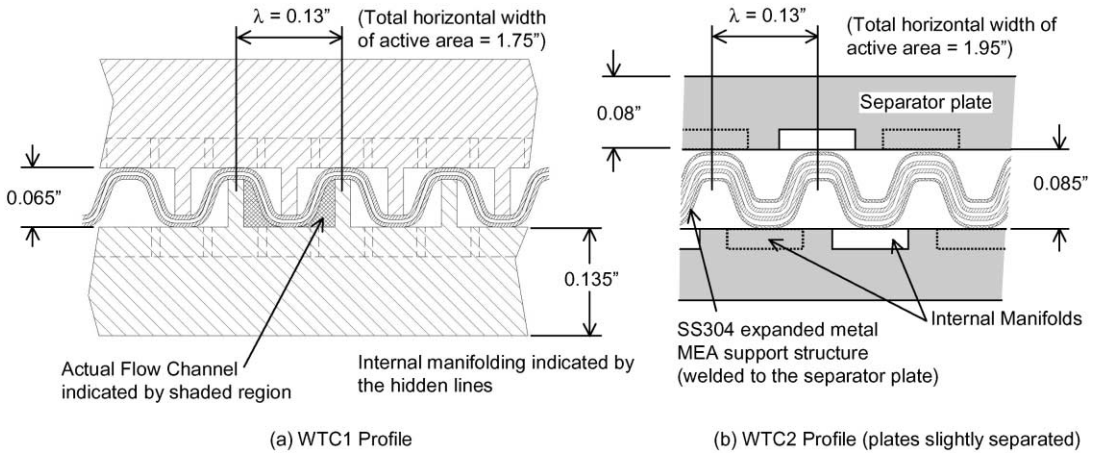

Fig. 3. Cross-section of the two WTC prototypes: (a) waved MEA is supported by ribbed graphite plates; (b) waved MEA is supported by waved expanded metal structure.

resistance and prevent leakage. Compressive force is required only to counteract the internal pressure of the reactant gases, and to ensure proper current transmission from one cell to the next. If, in the latter case, the current collectors are not attached to the separator strata, the inherent elasticity of an undulate MEA support structure (e.g. an undulate metallic mesh) may provide adequate electrical contact.

2. Prototypes

Two prototypes were developed to evaluate separately the impact of waving the MEA and introducing non-graphite collector plates with a non-conventional structure. The first prototype (WTC1) used bi-polar plates made of graphite, and an undulate MEA manufactured in our laboratory using a custom designed waving apparatus. This design, shown in Fig. 3a is similar to the structure disclosed by Futoshi et al. in 1996 [13,14]. The second prototype (WTC2) is shown schematically in Fig. 3b. This second prototype used the same type of MEA used in WTC1 but, in this case, the current collectors were made of macroscopically porous stainless steel materials (304SS expanded metal). These materials were formed into a profile that matched the MEA's undulate surface.

The straight flow channels generated in WTC1 had quasi-triangular cross-sections that were defined by the undulate MEA and the plate walls. Reactant flow re-direction was achieved by placing custom-designed manifolding gaskets underneath the bi-polar plates as shown in Fig. 4. With this configuration, the flow pattern could be easily altered by using different gaskets. The performance data presented here correspond to a single serpentine path and parallel co-current flow of reactants.

Unlike WTC1, in which current collection was highly localized, WTC2 spread the contact over the surface of the MEA. Good electrical and thermal contact between the current collectors and the separator plates was achieved by spot welding the contact points to the flat plates. Fig. 5 shows a close-up of the welding technique and a photograph of the assembled plate. In both prototypes, perimeter sealing was accomplished with non-planar, moulded silicone gaskets manufactured in our laboratory.

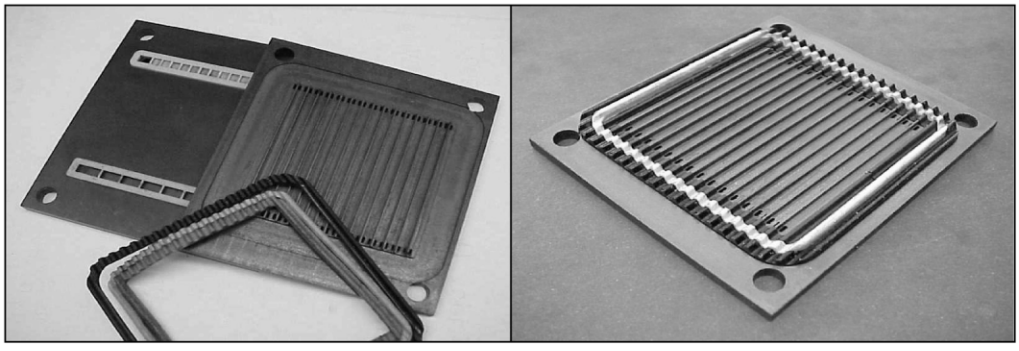

Fig. 4. WTC1 prototype sub-assembly showing (left) the manifolding gasket, seals and bi-polar plate and (right) the assembled half-cell.

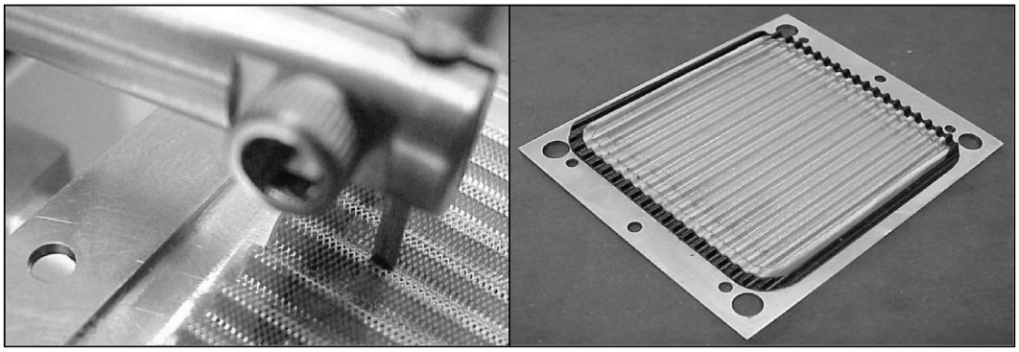

Fig. 5. Detail of the spot welding technique used to attach the expanded mesh screen current collectors to the separator plates (left), and the finished half cell for a WTC2 half-cell (right).

3. Experimental results

Baseline data were obtained by characterizing the performance of a conventional planar cell, consisting of graphite plates with single serpentine gas flow channels (channel width = depth = 1.59 mm) and with an active area of 30 cm^2.

A polarization curve was obtained using these flat plates and a standard MEA manufactured by Ballard Power Systems (30% PTFE/Carbon Fibre paper electrodes, Nafion® 117, and 4 mg Pt/cm^2). The resulting polarisation data were used to compare the performance of WTC1 and WTC2 under similar operating conditions.

Figs. 6 and 7 show the pressure drop characteristics for both prototypes. The higher pressure drop observed in WTC1 was a result of smaller channel cross-sections, gasket deformation (which resulted in partially blocked flow paths at the manifolds), and a tortuous path defined by multiple flow direction changes. All these issues have been addressed by our current efforts. Despite the higher pressure drop, WTC1 was operated at relatively low reactant utilization ratios (i.e. high stoichiometries). Higher flows were required to compensate for water management limitations in both the planar cell and WTC1. The pressure drop in WTC2 was lower than those observed in the planar cell and WTC1 and, as a result, the flows required to avoid flooding were even higher (see Table 1). Cross flow between adjacent channels was also detected and, accordingly, larger clamping pressures were required in WTC2. From the results in Fig. 7, we conclude that this problem arose due to mismatching profiles between the current collectors and the undulate MEA.

Figs. 8 and 9 show the measured polarisation curves for WTC1 and WTC2. The current densities in the three prototypes were normalized by the total active area in each cell, rather than by the projected (planar) areas. The area of contact in WTC1 was smaller than the corresponding area in the planar cell and, as a result, the current paths in the gas diffusion layer were longer and current collection was highly localized. As can be seen, the performance of WTC1 in the ohmic region was comparable to that obtained with the planar cell (albeit at higher clamping pressures). Ohmic losses due to high contact resistance were evident in the

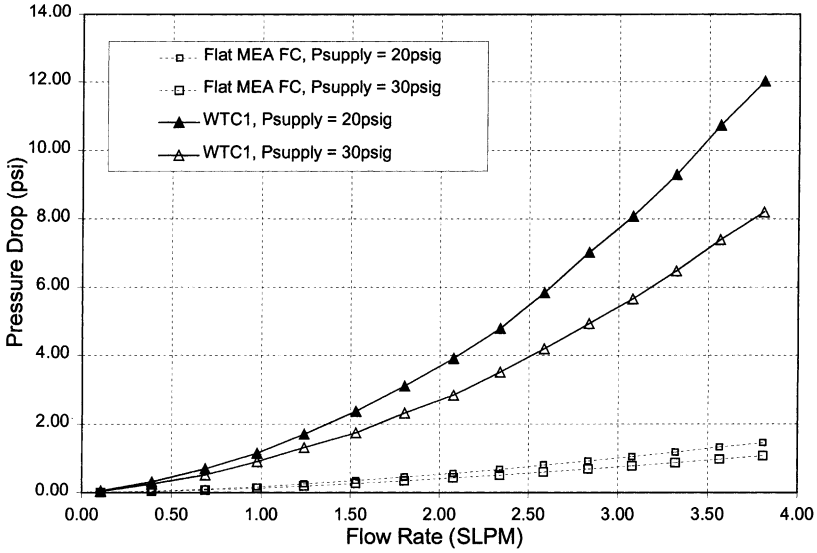

Fig. 6. Pressure drop characteristics for WTC1 and comparison to plate and frame cell with flat MEA.

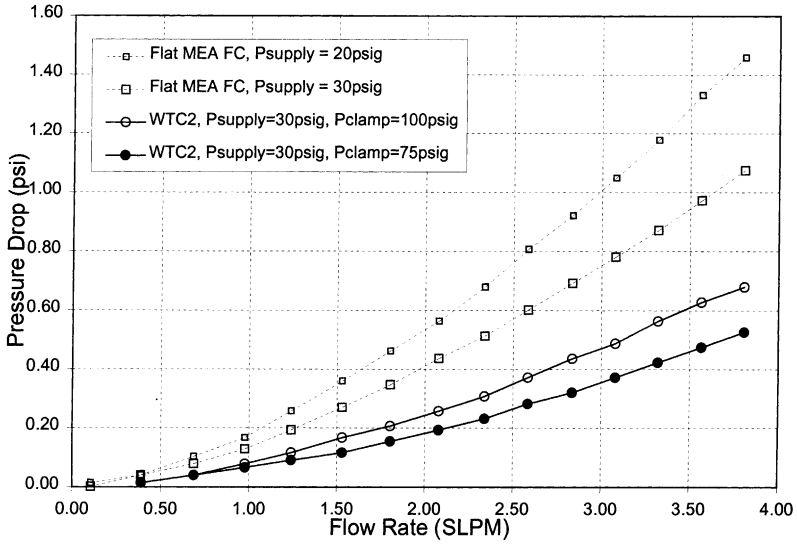

Fig. 7. Pressure drop characteristics for WTC2 and comparison to plate and frame cell with flat MEA.

Table 1
Summary of test conditions and operating parameters

	Planar cell	WTC1	WTC2	Comments
Reactant pressure (psig) (Air){H_2}	(30) {30}	(30) {30}	(30) {30}	±0.5 psig
Reactant temperature (°C) (Air) {H_2}	(90) {90}	(90) {90}	(90) {90}	As measured at the humidifier module
Reactant stoichiometry (Air) {H_2}	(4-5) {4-5}	(4-5) {4-7}	(5-10) {5-10}	Typical stoichiometric ratios
Coolant temperature (°C)	80	80	80	
Clamping pressure (psi)	80	100	135	Cross flow between adjacent channels
Channel cross-section (mm^2)	2.52	1.57	2.45	
Flow path length (cm)	91.4	88.4	83.8	
Cell surface temperature (°C)	75	75	75	

results for WTC2. Higher clamping pressures were required to reduce these losses and obtain the results shown in Fig. 9.

Fig. 10 shows the measured volumetric power densities for WTC1 and WTC2, and compares them to the corresponding baseline values. These results were obtained with a traditional membrane material (Nafion® 117) and relatively high catalyst loadings. The gains in volumetric power density are evident. We note that the baseline values do not represent

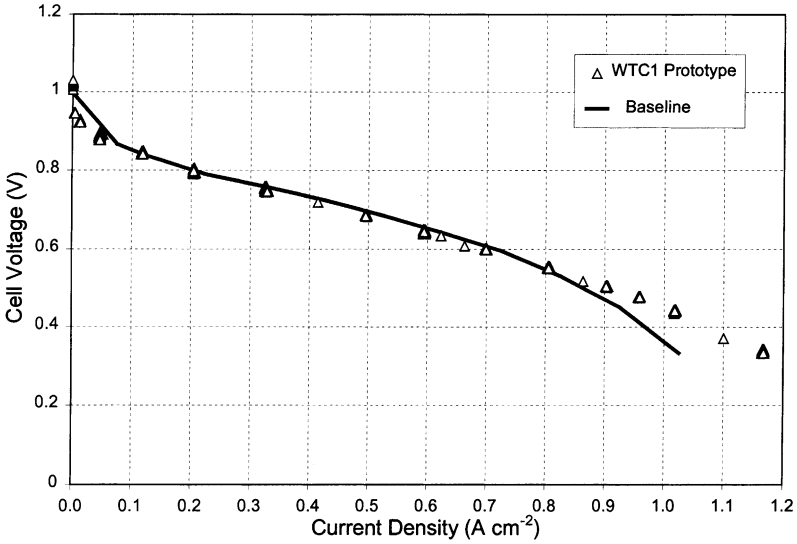

Fig. 8. Polarization curve for WTC1 and comparison with baseline plate and frame cell.

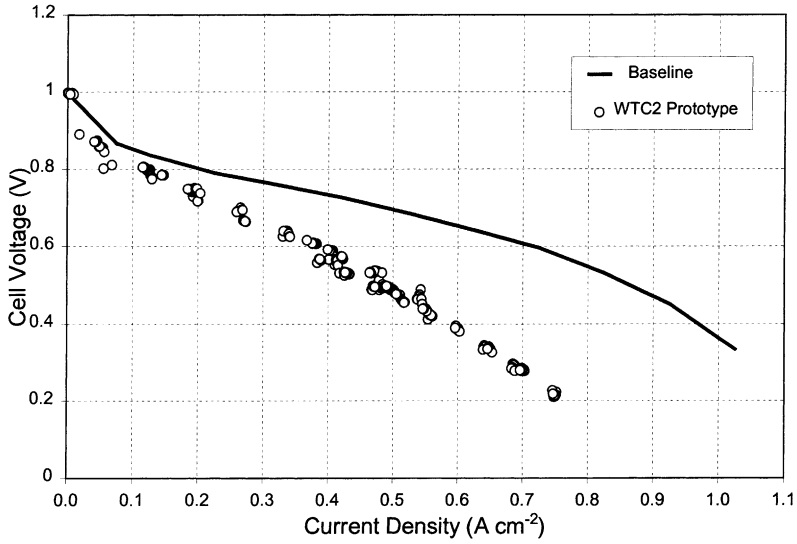

Fig. 9. Polarization curve for WTC2 and comparison with baseline plate and frame cell.

state of the art plate and frame design, but then WTC1 and WTC2 were not optimized either. Potential gains in cells using new membranes, thinner plates, and advanced electrodes can only be greater than those reported here.

The results with WTC1 demonstrate that the new topology can provide significant volumetric power density gains. WTC2, on the other hand, shows the significant challenges associated with metallic components.

3.1. Outstanding issues and future work

The use of metallic components in PEMFC stacks has received increased attention recently [15,16]. However, the use of ferrous and non-ferrous metallic materials has also been identified as a potential cause of cell degradation [17,18]. Most of the detrimental effects of these materials have been observed after relatively short periods (e.g. a few hundred hours). Extended lifetime testing was beyond the scope of this demonstration project. While aware of the potential lifetime reduction, the proposed WTC topologies consider three potential approaches.

1. Drive toward niche applications where the target lifetimes are compatible with the durability of WTC stacks (mission-critical military applications, life-support, emergency backup power, compact and portable power electronics, etc.).
2. Recognizing the potential for these applications, focus the efforts on promising new alloys (316L SS, Hastelloy™, Duplex™, etc.), or surface passivation methods (e.g. electrically conductive but chemically inert coatings).

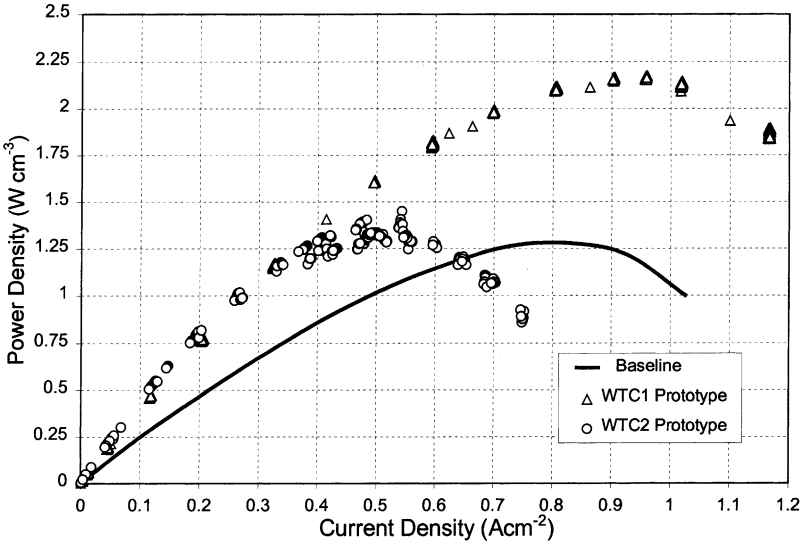

Fig. 10. Volumetric power density gains obtained with WTC1 and WTC2 prototypes in comparison with flat MEA cell (baseline).

3. Identify variations of the WTC architecture that can be manufactured using traditional (e.g. carbonaceous) fuel cell materials.

Both WTC1 and WTC2 were single-cell prototypes in which manifolding was relatively simple. WTC stacks will require more development, modified manifolding schemes, and improved manufacturing techniques. The welding technique, for example, could be problematic because, to maintain the required reactant configuration, the sinusoidal profiles on one side of the separator plates must be in-phase with the profile immediately underneath. Staggering configurations, folding, and other approaches based on published designs are currently being investigated [6,7].

One of the basic premises of the WTC architecture is the notion of straight flow channels and flow configurations defined by the pressure drop in both prototypes was a function of manifolding gasket design, total flow-path length, and channel cross-section. The first two factors can be modified by improved gaskets and flow re-direction design. The minimum channel cross-section, on the other hand, is determined by the minimum radii of curvature allowed by standard MEA materials and, in particular, by the brittleness of electrode substrates based on carbon fibre paper. Thinner polymers and new electrode substrates capable of withstanding deformation are necessary to reduce the total MEA thickness and, consequently, reduce total channel cross-section. Optimization of the sinusoidal pattern (amplitude and wavelength) and its relationship to performance (water management, current collection, etc.) are also the subject of ongoing development.

4. Conclusions

A new PEMFC stack architecture has been designed and demonstrated with two proof-of-concept, single-cell prototypes. The proposed new topology can produce stacks with higher volumetric power densities, and has the potential to be implemented in unidirectional and continuous mass-production schemes. Significant challenges in materials, manifolding, and membrane manufacture remain the focus of ongoing efforts at IESVic.

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