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# A lung-inspired approach to scalable and robust fuel cell design†

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A lung-inspired approach is employed to overcome reactant homogeneity issues in polymer electrolyte fuel cells. The fractal geometry of the lung is used as the model to design flow-fields of different branching generations, resulting in uniform reactant distribution across the electrodes and minimum entropy production of the whole system. 3D printed, lung-inspired flow field based PEFCs with  $N = 4$  generations outperform the conventional serpentine flow field designs at 50% and 75% RH, exhibiting a  $\sim 20\%$  and  $\sim 30\%$  increase in performance (at current densities higher than  $0.8 \text{ A cm}^{-2}$ ) and maximum power density, respectively. In terms of pressure drop, fractal flow-fields with  $N = 3$  and 4 generations demonstrate  $\sim 75\%$  and  $\sim 50\%$  lower values than conventional serpentine flow-field design for all RH tested, reducing the power requirements for pressurization and recirculation of the reactants. The positive effect of uniform reactant distribution is pronounced under extended current-hold measurements, where lung-inspired flow field based PEFCs with  $N = 4$  generations exhibit the lowest voltage decay ( $\sim 5 \text{ mV h}^{-1}$ ). The enhanced fuel cell performance and low pressure drop values of fractal flow field design are preserved at large scale ( $25 \text{ cm}^2$ ), in which the excessive pressure drop of a large-scale serpentine flow field renders its use prohibitive.

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## Broader context

Flow-field design is crucial to fuel cell performance, since non-uniform transport of species to and from the membrane-electrode assembly results in significant power losses. The long channels of conventional, serpentine flow fields cause large pressure drops between inlets and outlets, thus large parasitic energy losses and low fuel cell performance. This issue is exacerbated for small, portable fuel cells, where the power required for fluid transport should be minimal. To ensure uniform distribution of reactants across the electrode and a low pressure drop, we use a nature-inspired design that is rooted in thermodynamic and mechanical fundamentals, rather than biomimicry in a narrow sense. Inspiration is derived from the structure of the human lung, which ensures uniform gas distribution *via* an optimized fractal structure linking bronchi to alveoli, and realizing a remarkable combination of minimal entropy production, low pressure drop, and scale-invariant operation. Our 3D-printed, conducting flow-field plates maintain these unique characteristics of the lung, resulting in improved fuel cell performance over conventional serpentine flow-field based fuel cells. Uniformity in reactant distribution and minimal pressure drop are retained during scale-up, demonstrating the robustness of the proposed nature-inspired approach across length scales.

## 1. Introduction

Polymer electrolyte fuel cells (PEFCs) have tremendous potential as an energy technology with zero emissions at point of use.<sup>1</sup> The rapid start-up time, low weight and high efficiency make PEFCs particularly attractive for portable and automotive applications.<sup>2</sup> However, there remain challenges to broader commercialization of this technology, including high electro-catalyst cost, durability issues and performance limitations associated with unoptimized flow-field designs. For example, poor flow-field design can lead to channels becoming clogged with liquid water and non-uniform reactant distribution.<sup>3,4</sup> Such mass transport issues can lead to the accumulation of excess water in the pores of the gas diffusion layer (GDL)<sup>5</sup> and

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reactant starvation, which, in turn, can lead to corrosion of carbonaceous support material,<sup>6</sup> electrocatalyst sintering and facile membrane degradation,<sup>5</sup> all of which are detrimental to fuel cell longevity. Reactions of bulk and crossover gases at each electrode<sup>7</sup> result in the formation of harmful radicals,<sup>8</sup> which significantly hinder the oxygen reduction kinetics and oxygen/air transport through the polymer electrolyte.<sup>9</sup>

Thus far, there have been two prevalent strategies reported in the literature to overcome the uneven reactant distribution issue in PEFCs. The first approach is based on empirical alteration of the channel configurations (such as channel path length,<sup>10</sup> land width,<sup>11,12</sup> and land/channel ratio<sup>13,14</sup>), whereas the second approach imitates the apparent structure of biological organisms.<sup>15–19</sup> The consensus to the first strategy is that the utilization of flow-fields with wider rib spacing, narrower and shorter channels and path length improves reactant distribution.<sup>10,11,14</sup> However, these modifications tend to result in lower membrane hydration and membrane conductivity,<sup>13</sup> a higher pressure drop<sup>20</sup> as well as ineffective water and heat management.<sup>10</sup>

These drawbacks to the first strategy have led to the exploration of an alternative route, taking “inspiration” from biological systems. The term “inspiration” is purposely enclosed within parentheses, since all reports to date imitate the apparent structure of a natural fluid distribution system (such as leaves, lungs, veins, *etc.*) without being fundamentally grounded in the underlying physical phenomena.<sup>15–19</sup> Lack of a formal mathematical description and a methodology to inform the design of such flow-fields leads to difficulties in reproducing those designs, optimizing their channel geometries and scaling them up.

Here, a more systematic nature-inspired approach<sup>21–23</sup> is used to design (Fig. 1A) and evaluate against conventional serpentine flow-field based PEFCs, the performance of PEFCs with flow fields guided by the structure of a lung. This approach is based on the mechanistic understanding of the structure of the respiratory organ, applied in the context of fuel cell technology. In the following sections, the utilization of this approach for engineering lung-inspired flow fields is presented step-by-step, followed by experimental validation.



**Fig. 1** (A) Inspired by nature: the unique characteristics of the lung (fractal structure and minimum entropy production) are implemented into the design of lung-inspired flow fields for PEFCs; (B and D) prior to experimental validation, numerical simulations are conducted to determine the number of generations,  $N$ , required to achieve matching convection and diffusion driven flow through the outlets, and (C) uniform reactant distribution. A close-up view of the cathode side of the modeling domain is demonstrated in (B), where white and blue arrows represent the inlet and outlet flow of oxidants to, and oxidants plus formed  $\text{H}_2\text{O}$  from the catalyst layer, respectively, and  $x_{\text{O}_2}$  is the mass fraction of  $\text{O}_2$ .









Fig. 3 The final step involves the experimental validation of the lung-inspired flow-field based PEFCs, demonstrating improved performance at 50 and 75% RH ( $N = 4$ ) compared to conventional, serpentine flow-field based PEFCs (A and B); 10 cm<sup>2</sup> flow field area. When scaled (25 cm<sup>2</sup> flow field area), similar results are obtained for fractal flow fields at 50 and 75% RH (C and D), even though the performance of serpentine flow field based PEFCs is improved due to an order of magnitude higher pressure drop than fractal flow field based PEFCs. (E) Extended current hold measurements (24 h) are conducted to evaluate the effect of uniform reactant distribution on fuel cell performance; lung-inspired flow field based PEFCs with  $N = 4$  demonstrate the lowest voltage decay compared to conventional serpentine flow field based PEFCs.

~30% increase in maximum power density compared to conventional serpentine based PEFCs.

However, under all experimental conditions tested, fractal flow-field based PEFCs with  $N = 5$  demonstrate lower performance than expected. Although it is thermodynamically favorable to operate the PEFC at this state (minimum entropy production of the system),<sup>25</sup> the performance results indicate that operation at  $Pé > 1$  under high humidity conditions requires methods for the efficient removal of liquid water to avoid flooding.

The above statement is verified by fuel cell performance measurements at fully humidified conditions (Fig. S4, ESI<sup>†</sup>). At 100% RH, additional generation of water vapor (after complete membrane hydration) supersaturates the PEFC, resulting in water condensation in the electrode and flow-field channels,

increasing the mass transport resistance. This is evident by the lower performance (~10%) of the  $N = 4$  design compared to serpentine based PEFCs (Fig. S4, ESI<sup>†</sup>). Fractal flow-field based PEFCs with  $N = 5$  could not be tested due to excess flooding; the gas flow rate from individual fractal channels is insufficient to effectively remove liquid water.

Fractal and serpentine flow-field based PEFCs were also subjected to a 24 h current hold experiment to further evaluate the effect of reactant distribution across the electrode. The positive effect of uniform reactant distribution on fuel cell performance is evident (Fig. 3E). Fractal flow-fields with  $N = 4$  exhibit the lowest voltage decay (~5 mV h<sup>-1</sup>) compared to the serpentine flow-field design (~6.2 mV h<sup>-1</sup>). Assuming that the initial catalyst loading is uniform, the increased voltage decay



rate of the serpentine flow field based PEFCs shows that uneven reactant distribution leads to higher particle agglomeration and carbon support loss across the channel.<sup>38</sup> The highest voltage decay rate ( $\sim 11 \text{ mV h}^{-1}$ ) is observed for fractal flow-fields with  $N = 3$ , in which the insufficient reactant concentration may have caused local reactant deprivation and cell reversal.<sup>5</sup>

In terms of pressure drop (Fig. S6–S8, ESI<sup>†</sup>), fractal flow-fields with  $N = 3$  and 4 exhibit the lowest values (respectively  $\sim 75\%$  and  $\sim 50\%$  lower than conventional serpentine flow-field design for all RH tested) reducing the power requirements for pressurization and recirculation of the reactants.<sup>39</sup> On the contrary, fractal flow-fields with  $N = 5$  exhibit a similar pressure drop to serpentine flow-field designs due to the constricted air flow through smaller hydraulic diameters of the inlet and outlet channels.<sup>40,41</sup>

### 3. Unique characteristic of the proposed nature-inspired approach: scalability

To sum up, the obtained experimental results show that the proposed nature-inspired approach can be successfully used to resolve uneven reactant distribution issues in PEFCs. The defining characteristic of the fractal approach, though, is scalability, which is an important feature in nature. This characteristic makes the proposed nature-inspired approach stand out among other, bio-mimetic techniques reported in the literature, even though advancements in 3D printing technology *via* DMLS are required to mass produce large fractal flow fields with a high number of generations.

Fractal flow-fields can bridge multiple length scales by adding further generations, while preserving the building units and microscopic function of the system.<sup>21,42</sup> Larger, 3D printed fractal flow-fields ( $25 \text{ cm}^2$  surface area) with  $N = 4$  are compared

to conventional, serpentine flow-field based PEFCs. Performance results (Fig. 3C, D and Fig. S5, ESI<sup>†</sup>) show that fractal and serpentine flow-field based PEFCs have similar polarization curves, which is attributed to the significantly higher pressure drop ( $\sim 25 \text{ kPa}$ ) of large serpentine flow fields compared to fractal flow-fields (Fig. S9–S11, ESI<sup>†</sup>). The increased mass flow rate enhances the overall reaction rate and greatly reduces the resident water in the serpentine channels, resulting in a more uniform reactant distribution across the electrode and thus, improved performance.<sup>43</sup> On the contrary, large fractal flow-fields with  $N = 4$  have minimal pressure drop ( $< 2 \text{ kPa}$ ) under all RH conditions tested, revealing their difficulty to purge the produced liquid water from the fuel cell at the same pace as the serpentine flow-fields. Hence, to further improve the design of these fractal flow-fields, it is required to implement different outlet channel designs to remove the unreacted gas and product water, while operating the PEFC at a Péclet number close to unity. The combination of these two design parameters will achieve maximum fuel cell efficiency from uniform entropy production and minimal parasitic loss, leading to a maximum power density.

### 4. Conclusions

In conclusion, this article introduces a nature-inspired engineering methodology, which is utilized step-by-step to solve the uneven reactant distribution issue in PEFCs. 3D printed, lung-inspired fractal flow-fields with  $N = 4$  generations outperform the serpentine flow fields at high current densities (at 50% and 75% RH) due to more uniform reactant distribution across the catalyst layer. At higher humidity levels (100% RH), though, the performance of  $N = 5$  fractal flow fields significantly deteriorates; the reduced air flow rate within the fractal flow fields hampers effective gas diffusion within the porous medium, resulting in insufficient convective liquid water removal. Even though modeling results suggest that a  $N = 5$  design delivers

Table 1 Comparison of different cathode flow-field designs

Flow field design	Advantages	Disadvantages
Serpentine	<ul style="list-style-type: none"> <li>Efficient water removal</li> <li>Designed for small active area</li> </ul>	<ul style="list-style-type: none"> <li>High pressure drop</li> <li>Water build-up in bends</li> <li>Highly uneven reactant distribution due to reactant depletion along channels</li> </ul>
Multiple serpentine	<ul style="list-style-type: none"> <li>Moderate water removal</li> <li>Designed for large active area</li> </ul>	<ul style="list-style-type: none"> <li>Moderate pressure drop</li> <li>Uneven reactant distribution</li> <li>Elevated susceptibility to flooding with increased number of channels</li> </ul>
Interdigitated	<ul style="list-style-type: none"> <li>Efficient water removal</li> </ul>	<ul style="list-style-type: none"> <li>Highest pressure drop of all flow-field designs</li> <li>Possible damage to electrode from excess convective force</li> <li>Uneven reactant distribution</li> <li>Difficult to scale</li> </ul>
Lung-inspired	<ul style="list-style-type: none"> <li>Low pressure drop</li> <li>Uniform reactant distribution for low and high temperature fuel cells</li> <li>Higher electrocatalyst stability than serpentine</li> <li>Easily scalable</li> </ul>	<ul style="list-style-type: none"> <li>More susceptible to flooding than serpentine at high RH</li> </ul>



optimum PEFC performance, in practice, the utilization of a fractal flow-field above  $N = 4$  is not currently feasible. The identification of the shortcomings of fractal flow-fields pertaining to water management provides a rationale for design improvements, mainly on the land and outlet channels. The closely intertwined nature of these two factors emphasizes the need to implement alternative outlet channel geometry or engineered water removal strategies to alleviate flooding and parasitic loss, especially at higher generations. A critical comparison of different cathode flow-field designs is presented in Table 1.

The uniform gas distribution across the catalyst layer is preserved when these fractal flow fields are scaled-up (25 cm<sup>2</sup> surface area). The fuel cell performance of the large-scale fractal flow field remains almost unchanged on a per area basis, compared to its smaller active area counterpart. On the contrary, larger, conventional serpentine flow fields (25 cm<sup>2</sup> surface area) exhibit improved relative performance over 10 cm<sup>2</sup> ones due to an order-of-magnitude higher pressure drop than that of a fractal flow field, resulting in faster overall reaction rates and better liquid water removal. However, such excessive pressure drop renders the use of a large-scale serpentine flow field prohibitive, thus favoring the fractal flow field. Implementation of effective water removal mechanisms should circumvent remaining problems of high-generation fractal flow fields.

Current water management strategies<sup>44–46</sup> for commercial flow fields cannot be easily employed into these engineered fractal flow fields, since they require the installation of a porous carbon plate to wick out the generated liquid water. Hence, additional theoretical and experimental studies are needed to design new water removal mechanisms and integrate these with the fractal flow fields. To fully assess the effect of channel geometries on water removal, a 3D model should be developed. Despite its high computational demands, such a model will be able to fully simulate flooding at high RH conditions. These modeling results, in combination with experimental neutron radiography measurements, will provide valuable information towards the development of a water management strategy for fractal flow fields.

However, at present, typical operating conditions of PEFCs in practice are much lower than 100% RH.<sup>47</sup> Commercial PEFCs utilize air without humidification to pre-empt flooding in the cathode.<sup>47</sup> These operating conditions favor the utilization of the proposed fractal flow fields, due to their excellent performance at low and mid humidity levels, which is superior to commercial flow fields.

Finally, the proposed nature-inspired approach is not limited to PEFCs, but should lead to performance improvements in other electrochemical systems as well. Redox flow batteries, electrolyzers and different types of fuel cells (alkaline, high temperature, direct methanol, etc.) could thus benefit from the proposed nature-inspired approach, as flooding is mitigated in these systems.

## Conflicts of interest

There are no conflicts of interest to declare.

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## References

- 1 J. Larminie, *Fuel Cell Systems Explained*, Wiley & Sons, Chichester, West Sussex, 2nd edn, 2003.
- 2 R. T. White, F. P. Orfino, M. E. Hannach, O. Luo, M. Dutta, A. P. Young and E. Kjeang, *J. Electrochem. Soc.*, 2016, **163**, F1337–F1343.
- 3 S. Ge and C.-Y. Wang, *J. Electrochem. Soc.*, 2007, **154**, B998–B1005.
- 4 Z. Tayarani-Yoosefabadi, D. Harvey, J. Bellerive and E. Kjeang, *J. Power Sources*, 2016, **303**, 208–221.
- 5 A. Taniguchi, T. Akita, K. Yasuda and Y. Miyazaki, *J. Power Sources*, 2004, **130**, 42–49.
- 6 P. Trogadas, T. F. Fuller and P. Strasser, *Carbon*, 2014, **75**, 5–42.
- 7 V. O. Mittal, H. R. Kunz and J. M. Fenton, *J. Electrochem. Soc.*, 2007, **154**, B652–B656.
- 8 P. Trogadas, J. Parrondo and V. Ramani, *Chem. Commun.*, 2011, **47**, 11549–11551.
- 9 T. Okada, Y. Ayato, H. Satou, M. Yuasa and I. Sekine, *J. Phys. Chem. B*, 2001, **105**, 6980–6986.
- 10 S. Shimpalee, S. Greenway and J. W. Van Zee, *J. Power Sources*, 2006, **160**, 398–406.
- 11 A. P. Manso, F. F. Marzo, J. Barranco, X. Garikano and M. Garmendia Mujika, *Int. J. Hydrogen Energy*, 2012, **37**, 15256–15287.
- 12 P. Wawdee, S. Limtrakul, T. Vatanatham and M. W. Fowler, *Int. J. Hydrogen Energy*, 2015, **40**, 3739–3748.
- 13 D. H. Ahmed and H. J. Sung, *J. Power Sources*, 2006, **162**, 327–339.
- 14 S.-W. Cha, R. O’Hayre, S. J. Lee, Y. Saito and F. B. Prinz, *J. Electrochem. Soc.*, 2004, **151**, A1856–A1864.
- 15 N. Guo, M. C. Leu and U. O. Koylu, *Int. J. Hydrogen Energy*, 2014, **39**, 21185–21195.
- 16 J. P. Kloess, X. Wang, J. Liu, Z. Shi and L. Guessous, *J. Power Sources*, 2009, **188**, 132–140.
- 17 R. Roshandel, F. Arbabi and G. K. Moghaddam, *Renewable Energy*, 2012, **41**, 86–95.
- 18 B. Ramos-Alvarado, A. Hernandez-Guerrero, F. Elizalde-Blancas and M. W. Ellis, *Int. J. Hydrogen Energy*, 2011, **36**, 12965–12976.
- 19 K. Tüber, A. Oedegaard, M. Hermann and C. Hebling, *J. Power Sources*, 2004, **131**, 175–181.
- 20 S. Shimpalee and J. W. Van Zee, *Int. J. Hydrogen Energy*, 2007, **32**, 842–856.
- 21 P. Trogadas, M. M. Nigra and M.-O. Coppens, *New J. Chem.*, 2016, **40**, 4016–4026.



- 22 M. M. Lynch, J. Liu, M. Nigra and M.-O. Coppens, *Langmuir*, 2016, **32**, 9604–9610.
- 23 M.-O. Coppens, *Curr. Opin. Chem. Eng.*, 2012, **1**, 281–289.
- 24 C. D. Murray, *Proc. Natl. Acad. Sci. U. S. A.*, 1926, **12**, 207–214.
- 25 S. Gheorghiu, S. Kjelstrup, P. Pfeifer and M.-O. Coppens, in *Fractals in Biology and Medicine*, ed. G. A. Losa, D. Merlini, T. F. Nonnenmacher and E. R. Weibel, Birkhäuser Basel, Basel, 2005, pp. 31–42, DOI: 10.1007/3-7643-7412-8\_3.
- 26 B. Mauroy, M. Filoche, E. R. Weibel and B. Sapoval, *Nature*, 2004, **427**, 633–636.
- 27 B. Sapoval, M. Filoche and E. R. Weibel, *Proc. Natl. Acad. Sci. U. S. A.*, 2002, **99**, 10411–10416.
- 28 S. Kjelstrup, M.-O. Coppens, J. G. Pharoah and P. Pfeifer, *Energy Fuels*, 2010, **24**, 5097–5108.
- 29 P. Trogadas, V. Ramani, P. Strasser, T. F. Fuller and M.-O. Coppens, *Angew. Chem., Int. Ed.*, 2016, **55**, 122–148.
- 30 C. Hou, S. Gheorghiu, M.-O. Coppens, V. H. Huxley and P. Pfeifer, in *Fractals in Biology and Medicine*, ed. G. A. Losa, D. Merlini, T. F. Nonnenmacher and E. R. Weibel, Birkhäuser Basel, Basel, 2005, pp. 17–30, DOI: 10.1007/3-7643-7412-8\_2.
- 31 J. C. Ruiz-Morales, A. Tarancon, J. Canales-Vazquez, J. Mendez-Ramos, L. Hernandez-Afonso, P. Acosta-Mora, J. R. Marin Rueda and R. Fernandez-Gonzalez, *Energy Environ. Sci.*, 2017, **10**, 846–859.
- 32 R. L. Truby and J. A. Lewis, *Nature*, 2016, **540**, 371–378.
- 33 S. Seyed Farid Seyed, G. Samira, M. Mehdi, Y. Hooman, M. Hendrik Simon Cornelis, K. Nahrizul Adib and O. Noor Azuan Abu, *Sci. Technol. Adv. Mater.*, 2015, **16**, 033502.
- 34 J. R. Atkins, S. C. Savett and S. E. Creager, *J. Power Sources*, 2004, **128**, 201–207.
- 35 T. F. Fuller and J. Newman, *J. Electrochem. Soc.*, 1992, **139**, 1332–1337.
- 36 J. Marquis, *PhD thesis*, Rensselaer Polytechnic Institute, Troy, NY, 2013.
- 37 I. S. Hussaini and C.-Y. Wang, *J. Power Sources*, 2009, **187**, 444–451.
- 38 J. Chen, J. B. Siegel, T. Matsuura and A. G. Stefanopoulou, *J. Electrochem. Soc.*, 2011, **158**, B1164–B1174.
- 39 H. Kahraman and M. F. Orhan, *Energy Convers. Manage.*, 2017, **133**, 363–384.
- 40 D.-H. Chang and S.-Y. Wu, *Int. J. Hydrogen Energy*, 2015, **40**, 11659–11667.
- 41 M. Mortazavi and K. Tajiri, *Renewable Sustainable Energy Rev.*, 2015, **45**, 296–317.
- 42 M.-O. Coppens, *Ind. Eng. Chem. Res.*, 2005, **44**, 5011–5019.
- 43 A. B. LaConti, M. Hamdan and R. C. McDonald, in *Handbook of Fuel Cells: Fundamentals, Technology, and Applications*, ed. W. Vielstich, H. A. Gasteiger and A. Lamm, John Wiley & Sons, New York, 2003, vol. 3, pp. 647–662.
- 44 T. Fabian, R. O'Hayre, S. Litster, F. B. Prinz and J. G. Santiago, *J. Power Sources*, 2010, **195**, 3640–3644.
- 45 S. Litster, C. R. Buie, T. Fabian, J. K. Eaton and J. G. Santiago, *J. Electrochem. Soc.*, 2007, **154**, B1049–B1058.
- 46 J. S. Yi, J. D. Yang and C. King, *AIChE J.*, 2004, **50**, 2594–2603.
- 47 T. Yoshida and K. Kojima, *Electrochem. Soc. Interface*, 2015, **24**, 45–49.

