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Characterisation of the diffusion properties of metal foam hybrid flow-fields for fuel cells using optical flow visualisation and X-ray computed tomography

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HIGHLIGHTS

- Optical analysis of flow distribution in porous metal foam flow fields.
- Findings show Increasing manifold inlet area reduces residence time and pressure drop.
- New hybrid foam using pressed channels demonstrates controllable fluid distribution.
- Hybrid foam performance correlated to X-ray CT scans and porosity analysis.

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ABSTRACT

The flow distribution behaviour of open-cell metallic foam fuel cell flow-fields are evaluated using ex-situ optical analysis and X-ray computed tomography (X-ray CT). Five different manifold designs are evaluated and flow distribution and pressure drop quantitatively evaluated with reference to applications in polymer exchange membrane fuel cells (PEMFC) and heat exchangers.

A 'hybrid' foam flow-field is presented consisting of flow channels pressed into the foam to promote flow distribution and reduce pressure drop. Cross- and through-channel pressure drop measurements are conducted, along with X-ray CT analysis.

Results using dyed water show that metallic foams provide excellent fluid distribution across the fuel cell flow-field, closely following the theoretical filling rate. The time for dye to cover 80% of the flow-field area was 61% faster with a foam flow-field then with no flow-field present. Pressure drop was seen to reduce with increasing foam inlet area to levels comparable to multi-serpentine flow-fields. The introduction of flow channels in the foam can further reduce pressure drop and provide more even filling of the foam, at the expense of increased residence time.

1. Introduction

Porous metallic foams are a class of material that have seen increasing research interest in recent years, with broad applications ranging from acoustic absorption and vibration control to fuel cells and catalyst carriers [1]. Metallic foams possess a beneficial combination of properties, namely high porosities, low densities and large specific surface areas, whilst maintaining high electrical and thermal conductivities. Metallic foams are separated into two groups; closed-cell (where the internal surfaces are not accessible), and open-cell (where the internal surfaces can be accessed by a working fluid) [2]. The behaviour of the working fluid in contact with open-cell metallic foams is an area of research which has been explored for several different energy applications, most notably polymer exchange membrane fuel cells (PEMFCs).

Large surface area-to-volume ratios, high thermal conductivity and high permeability, make open-cell metallic foams ideal materials for effective heat transfer. One of the first to investigate this was Boomsma

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et al. [3], who demonstrated thermal resistances two to three times lower for compressed aluminium foam compared to conventional heat exchangers for the same pumping power when using a liquid coolant. Huisseune et al. [4] replaced the air side of a fin and tube heat exchanger with metallic foam in numerical simulations, showing improved heat transfer to fan power ratio compared to louvered fins, but over a larger frontal area. Other works have considered the influence of fouling [5], surface roughness [6] and use in improving the thermal conductivity of phase-change materials [7].

Open-cell metallic foams have been used as cooling plates in hydrogen fuel cell stacks as a replacement for conventional machined or pressed flow channels. Odabaee et al. [8] conducted experimental studies on replacing liquid cooling in parallel channels with air cooling in aluminium foam. Afshari et al. [9] conducted numerical simulations comparing different fuel cell cooling channels to metallic foams.

In addition to being used for coolant, open-cell metallic foams have seen successful deployment as a replacement for conventional land and channel reactant flow distributors in fuel cells [10] [11]. In this application, the metallic foam serves multiple purposes of distributing reactants, removing product water, conducting electricity, conducting heat and providing mechanical integrity. The use of metallic foam flow-fields in PEMFCs was first demonstrated by Murphy et al. [12] in an eight-cell stack with nickel foam flow-fields. Kumar and Reddy [13] [14] [15], then compared the performance of conventional multi-parallel land and channel flow channels to a Ni-Cr foam, showing improved performance of the foam, particularly at high current densities where mass transport phenomena dominate.

More recently, other studies have investigated the use of metallic foams on PEMFCs [16] [17] [18], direct methanol fuel cells (DMFC) [19] [20], alkaline fuel cells (AFC) [21] and high temperature polymer exchange membrane fuel cells (HTPEMFC) [22]. However, only a few studies have evaluated the fluid behaviour inside the flow-fields. Tsai et al. [23] conducted experimental comparisons of four different foam flow-fields in a PEMFC by putting physical separators into the flow-fields to control flow direction; showing that three parallel sections within the foam gave best pressure drop to electrochemical performance compromise. Kariya et al. [24] conducted a similar study using sintered metal powders with different flow-field partitions. Tabe et al. [25] conducted an in-situ optical study of a metallic foam flow-field in a PEMFC, correlating current density to liquid water accumulation and temperature distribution, demonstrating improved stability when using a hydrophilic foam treatment. Murphy et al. [12] used dyed water to visualise flow distribution in an expanded titanium porous flow-field by matching fluid Reynold's number to air, demonstrating good flow distribution across the cell surface after 7.0 s.

X-ray CT techniques have been used to great effect as a non-destructive means of capturing and analysing the internal three-dimensional (3D) structure of materials. In the fuel cell literature, X-ray CT scanning and 3D reconstruction techniques have been used for porosity-tortuosity analysis of membrane electrode assembly (MEA) structures [26] [27] and to generate fibre-level geometries of gas diffusion layers for two-phase Lattice-Boltzmann simulations [28] [29].

To date, there is yet to be an experimental evaluation of macroscopic flow distribution in metallic foam fuel cell flow-field designs. In this work, the flow distribution of five different metallic foam manifold designs are quantitatively evaluated through flow visualisation of dyed liquid water at Reynolds numbers representative of air flow rates in PEMFCs. A new hybrid foam flow-field is introduced, consisting of pressed channels in the metallic foam; porosity distribution of the new channel is assessed using X-ray computed tomography and experimental pressure drop measurements. The influence of three different hybrid flow channel geometries on flow distribution are then assessed. This work will help to inform future fuel cell flow-field designs.

Table 1
Metal foam parameters.

Parameter	Value	Source
Thickness	1.6 mm	Manufacturer
Cell size	110 ppi	Manufacturer
Density	262.5 kg/m^3	Manufacturer
Overall porosity	86.5%	X-ray CT
Flow porosity	84.0%	X-ray CT

2. Experimental

Three separate experimental procedures are used to characterise and understand the flow behaviour of the metallic foam; X-ray computed tomography (X-ray CT), pressure drop measurements and optical flow analysis. The same foam type is used in all tests, an open-cell nickel foam, supplied by Corun New Energy (China) in 1.6 mm thick sheets. Specification of the foam is shown in Table 1, where data is either sourced from the supplier or X-ray CT.

To promote the fluid distribution and reduce pressure drop, a hybrid porous flow channel has been developed which consists of semi-circular channels pressed into the foam to achieve regions of dense foam and regions of free space. The flow channels were manufactured by pressing 3 mm diameter stainless steel rods into the foam using a hydraulic press under a load of 3 kN. These values were chosen to give cross-sectional areas similar to flow channels in conventional PEMFCs.

2.1. X-ray CT

X-ray computed tomography images of the foam were captured using a Nikon XT 225 X-ray machine. The geometric configuration of the radiographic scans resulted in a pixel resolution of 10.8 μm, for a sample size of 1 cm × 1 cm. In all cases, an accelerating voltage of 95 kV and a current of 100 A was used to generate 3176 individual projections of the cells, with an exposure time of 1 s.

The single-phase material segmentation was reconstructed using Avizo software. The localised porosity in the z-direction (parallel-to-flow channel) was calculated from Equation (1) using ImageJ and Avizo software packages.

$$p(i,j) = 1 - \frac{1}{K}\sum_{k=1}^{K} x(i,j,k) \tag{1}$$

With p the localised porosity, (i, j) the location of a pixel over the x and y direction, k the location of the slice over the z axis, K the number of slices over the z axis ($K = 750$), and $x(i, j, k)$ the binarized value of the corresponding pixel (i, j, k). Despite the metal foam being open-cell, the foam ligaments are hollow, creating small gas voids which are inaccessible to flow. To assure the accuracy of the porosity calculations, these hollow void areas were manually filled-in before the 3D reconstruction and analysis was undertaken. In Table 1, overall porosity refers to the porosity calculated including ligament voids and flow porosity refers to the porosity calculated with the voids filled. Flow porosity is used for the remainder of this study. Scanning electron microscope (SEM) images were captured using a Hitachi TM3030 and a 15 kV accelerating voltage. The influence of the flow channel on fluid flow is discussed in Section 3.

2.2. Pressure drop testing

2.2.1. Manifold testing

A series of tests were performed to evaluate the pressure drop of different manifold and flow-field designs. Tests were conducted on a 100 × 100 × 1.6 mm foam sample pressed between 6 mm thick Perspex sheets, sealed using a 1.5 mm silicon gasket into which the flow manifolds were cut. The fixture was secured with 16 bolts tightened to