

Measurement and simulation of pressure drop across replicated microcellular aluminium in the Darcy-Forchheimer regime

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Abstract

Experimental measurements of the pressure drop across porous metal structures, typified by large pores with small interconnecting “windows”, have been compared, for the first time, with simulations using computational fluid dynamics modelling. Structural information for the porous structures was obtained from X-ray computed tomography and a robust methodology for developing a representative volume element is described. The modelling approach used was able to predict reliably the pressure drop behaviour within the Forchheimer regime. The methodology was extended to simulate flow through geometrically-adapted, “semi-virtual” pore structures and this approach could prove to be an invaluable tool in the design of porous metal components for applications involving fluid flow.

Keywords

Porous material; modelling; permeability

Background

Open cell porous metals are commonly used as structures that interact with a fluid in processes such as heat exchange and storage, filtration and catalysis. Pivotal to the performance of these structures is the resistance to fluid flow that is provided by the porous body, usually described by the pressure drop per unit length developed across the structure as a function of the flow rate (or velocity) of the fluid through it.

Knowing or predicting and then controlling the pressure-drop is key to optimising the performance of these structures and to designing new structures with enhanced or novel attributes.

Fluid flow through porous materials is normally associated with energy being dissipated as a result of the interaction between the two phases. For a very slow fluid flow, a viscous-drag energy dissipation mechanism dominates and the pressure-drop-airflow velocity relationship is described by the Hazen-Darcy equation [1,2];

$$\frac{\Delta P}{L} = \frac{\mu}{K} v \quad \text{Eq-1}$$

where ΔP is the pressure difference across the length of the porous material in the flow direction (Pa), L is the sample thickness in the same direction (m), K is the permeability (m^2), μ is the fluid viscosity (Pa s) and v is the Darcian velocity, the volumetric flow rate divided by the cross sectional flow area (m s^{-1}). For flow behaviour obeying this case, the fluid is said to be flowing in the Darcy regime [2, 3].

As the fluid velocity increases, the Hazen-Darcy equation fails to describe the pressure-drop behaviour [2]. A quadratic term, referred to as the Forchheimer or the form drag term, is added to equation 1 in order to capture the effect of the force exerted by any

solid surface on the flowing fluid and its resultant effect on the pressure drop. This yields equation 2 which is known as the Hazen-Dupuit-Darcy or Forchheimer equation:

$$\frac{\Delta P}{L} = \frac{\mu}{K} v + C\rho v^2 \quad \text{Eq-2}$$

where ρ is the fluid density (kg m^{-3}) and C is the form drag coefficient (m^{-1}) which is related to the structure of the permeable medium [3]. For typical fluid velocities and pore-size ranges used in engineering flow systems, the Forchheimer equation most accurately describes such unidirectional fluid flow [4].

Since the K and C terms in the Forchheimer equation are affected by facets of the structure of the porous metal, for example porosity, cell size and the morphology of the pores and the pore-network, altering the porous metal structure has the potential to greatly influence the pressure drop across it. It is vital to adopt a processing route that can manufacture high quality porous metal structures with reproducible structures, but additionally, these processes must enable some adaptability to tailor the geometrical features to enable the flow behaviour through the porous material to be altered to suit the service requirements.

The infiltration of liquid metal into a bed of sacrificial particles (often termed porogens or space fillers) offers a convenient and reproducible method for the manufacture of porous metals [5-8] with the potential to vary the porosity and pore size independently, thereby giving a good level of control over the structure and hence the fluid flow behaviour [5, 6, 9]. Using this method a “preform” is made from the porogen either from loose or tapped beads, or using subsequent compaction with or without sintering steps. Infiltration with a molten metal is affected by either applying a positive pressure to the metal or a vacuum to the porogen bed. The pore structure in

the porous metal is thus a negative of the morphology and spatial arrangement of the porogen.

Figure 1 shows the typical structure of porous metals made by replication of packed beds of near-spherical NaCl beads [10]. The most important structural feature of porous metals made in this way is the small windows that connect the pores. The number of particle-particle contacts (the coordination number for packing) primarily dictates the number of windows connecting the pores. The highlighted pore in figure 1 has at least 7 windows to neighbouring pores. The size of these windows is governed by the extent to which infiltrating liquid can penetrate within the region between contacting (or very close) particles. This is a function of the infiltration pressure (the capillary radius) the bead geometry and the packing behaviour.

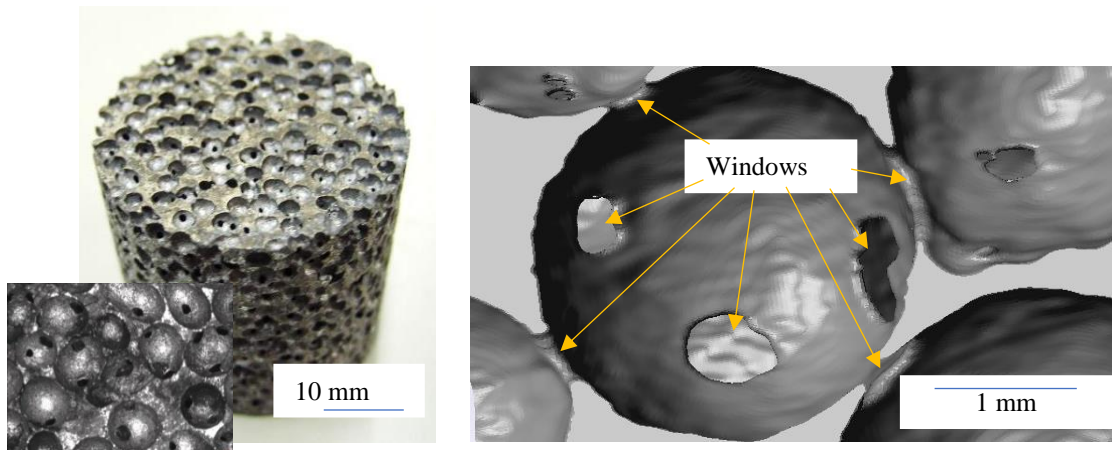


Fig. 1: Optical micrographs, left for a porous sample made by vacuum casting using near-spherical NaCl beads [10] and right, an X-ray CT image showing the typical pore connectivity [11].

Studies combining computational fluid dynamics (CFD) simulations and experimental measurements of flow through very open porous metals, often made by

replication of reticulated polymer foams, are reasonably common (an excellent overview is given in [2]). Approaches that use X-ray computed tomography to capture the solid and fluid domains have been successful in predicting the pressure drop to within 5% of the experimentally observed behaviour [12, 13]. Such simulations have not been extended to porous metals made by replication of packed beds of beads. Simple analytical permeability models for laminar (Darcy) flow have been developed [4, 14] and, supported by modelling [11], they show the flow behaviour to be dominated by the small windows between the pores (as marked in Figure 1) which create a “bottleneck” to flow through the structure. The model in [4] was extended to flow in the Forchheimer regime in [15] where it was shown that both the K and C terms are more strongly influenced by the size of the windows that connect the pores than the pore diameter. Although experimental measurements followed the theory quite well, K is over predicted by nearly a factor of 2, as result of the over-simplification of the model which neglects tortuous flow within the porous structure.

This paper aims to develop a robust simulation methodology for predicting the pressure drop response through porous metals with bottleneck-type structures and to test it against experimental measurements. It is hoped that the findings will contribute to the development of methodologies for structural optimisation of these porous structures to suit a range of applications.

Experimental procedure

Specimen manufacture

Porous Al samples were made by a replication process (similar to that described in [10]) using salt beads (Hydrosoft) as a sacrificial porogen and a vacuum casting method.

Castings were made by pouring 2-2.5 mm salt beads into a 35 mm diameter flanged stainless steel mould with a porous base. The flanged mould was pre-heated to 600°C and part-inserted into a vacuum chamber and when molten 99.5% purity Al was poured onto the top of the bed of beads, a pressure differential was applied to drive infiltration of the molten metal therein. The pressure differential was measured, and varied by controlling an outlet valve fixed to the vacuum chamber, such that the pressure differential varied between approximately 0.9 - 0.25 bar in four increments. Cast samples were machined into 25 mm diameter cylinders, 34.5 mm long, where after the salt beads were removed by dissolution in warm water.

Specimen characterisation

X – ray CT imaging was performed on each of the different porous Al samples using an Xradia 500 instrument, with a voxel dimension of 26 μm . The Scan IP module within SimplewareTM, a 3D image processing, analysis and model generation software package, was used to create a 3D representation from the 2D CT slices. Image processing methods, such as thresholding and creating masks or outlines to follow the boundaries between the 2 phases were found to have a significant effect on the accuracy of the representation of the porous structure and were thus optimised to ensure that characteristic pore features were as accurately reproduced as was possible and that there was less than a $\pm 0.25\%$ deviation between the nominal porosity of the thresholded image and that for the real foam structure. In addition to the porosity, the mean pore and window size were also determined from the 3D CT volume using a watershed segmentation method and by computing a mean minimum area of circles along the

centrelines adjoining two pores respectively. Comparisons were made with measurements from optical microscope images using image analysis software, Image J.

Experimental measurement of pressure drop

The experimental setup used to measure the pressure drop across porous samples at a defined air flow rate, is shown in Figure 2. The experimental arrangement and measurement methods are similar to those reported in [13, 16, 17]. In brief, the apparatus consists of a compressed air supply with filter and pressure regulator, a flow control valve and flow rate meter, a flow straightener and a sample holder for the porous Al samples. Samples with a diameter of 25 mm, 34.5 mm long, were placed in the tube and were wrapped with polytetrafluoroethylene (PTFE) tape to prevent bypass of the air.

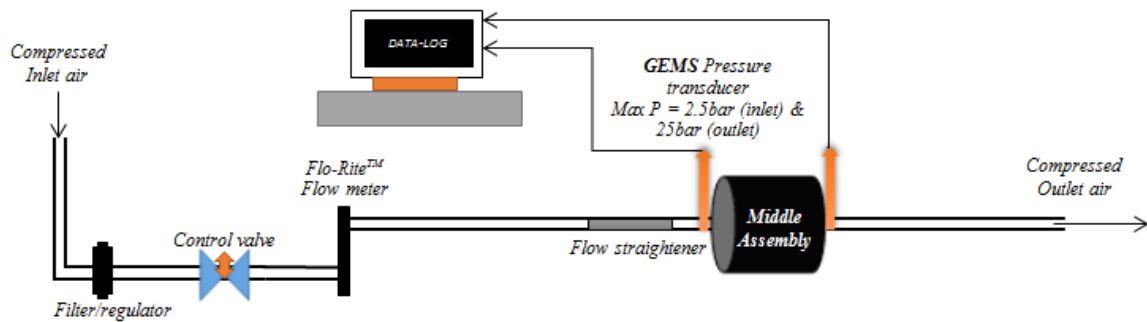


Fig 2: Schematic representation of the apparatus for pressure drop measurement.

The pressure either side of the sample was measured using GEMS pressure transducers (0 – 2.5 bar range for the inlet), the data from which were logged by a PC for 3 minutes at each flow rate, ensuring a steady state had been achieved before the flow rate was increased. The flow rate was varied to achieve superficial velocities in the range of approximately 0.6 to 2.4 m s⁻¹. The pressure drop (ΔP) across the foam length was calculated ensuring that compressibility effects were considered [2] using equation 3, where P_i and P_o are the inlet and outlet absolute pressures respectively (P_o was always

ambient pressure) and P_R is a reference pressure (ambient). The accuracy, reproducibility and mean standard deviation (typically < 1.5%) for the measurements are discussed in [16].

$$\Delta P = \frac{P_i^2 - P_o^2}{2P_R} \quad \text{Eq 3}$$

CFD simulation of permeability

Computational fluid dynamics (CFD) simulation of air flow through these porous structures was performed by solving the steady – state compressible Navier – Stokes equation (suitable only for laminar flow) on a meshed fluid domain within a representative volume element (RVE), using the Single-Phase flow module in COMSOL Multiphysics 5.0™. The size of the RVE, which was extracted from the centre of the scanned samples, was determined by shrinking a much larger volume until the porosity differed by no more than 0.5% from the initial (bulk) value, typically giving an x, y, z RVE dimension between 8x8x8 and 8x8x10 mm.

The boundary conditions and methodologies used to extract pressure data are similar to those reported in [13]. In brief, a zero outlet pressure was applied to suppress backflow and no slip boundary conditions were applied to the walls. The unidirectional pressure drop across the porous structure was measured by taking the difference between the surface average values of the computed inlet and the outlet (zero) pressures for a series of simulations at different fixed values of flow velocity, between 0.6 - 2.36 m s⁻¹.

Preliminary simulations were performed to determine a workable balance between mesh scale, convergence time and accuracy. A linear tetrahedral mesh was used, varying the minimum cell size seeded at the fluid-solid interface (from 1.5x to 5x the resolution of the image), keeping the mesh growth rate constant (at 1.3x) and setting the maximum

cell size, occurring in the centres of the pores, to 6.75x the minimum value. Figure 3 plots the effect of increasing the mesh density on the ratio of the pressure drop compared to that for the solution for the finest mesh, which was set by the maximum number of cells (circa 6M) that the computational power available could solve. The “optimum” was selected as having a minimum cell size of 2.7x the image resolution (26 μm), creating a mesh with 2.7M cells. A less than a 0.2% difference (increase) in pressure drop was observed compared with the maximum mesh density, with less than 1/10th of the runtime. Two-dimensional images for the mesh structures, for the same connected pores, are also shown in Figure 3 for the coarsest, finest and “optimum” cases.

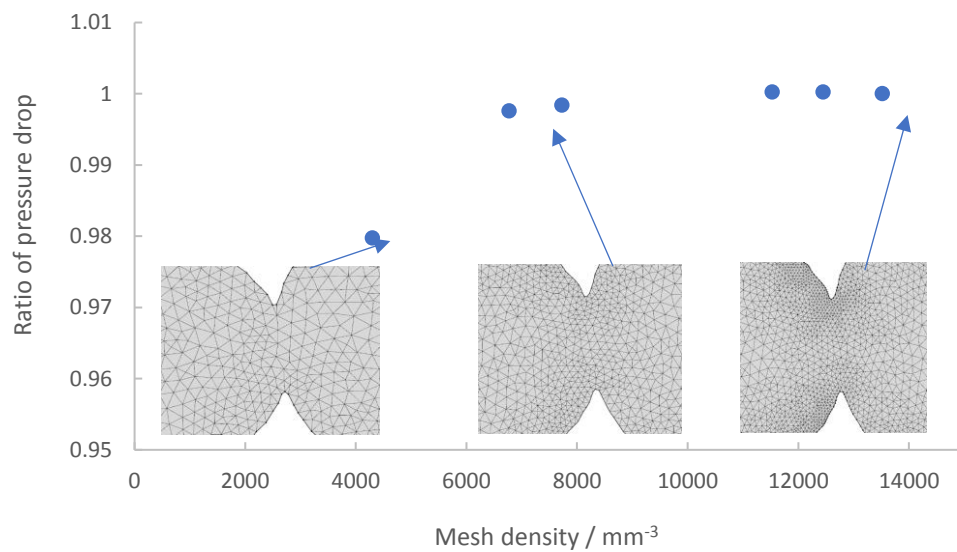


Figure 3 The effect of increasing mesh density on the ratio of the pressure drop compared to that for the solution for the finest mesh. Mesh structures for the coarsest, finest and “optimum” cases are shown.

Results and discussion

Structural characterisation

Figure 4 shows typical porous Al structures, with examples shown for the highest and lowest pressure differentials. They show near-spherical pores and multiple connections between these pores in the form of smaller, rounded “windows”. It was apparent that not only does the size of these windows increase as the pressure differential decreases, but the number per pore also increases. Previous studies by these authors [10,11] have shown that although the number of windows per cell is broadly dependent upon the coordination number for packing of the bead structure, typically 6-7 for monosized spheres, higher for irregularly-shaped beads such as those used in this study, this can increase significantly as the pressure differential is decreased, as liquid is less able to fill small spaces at the contact points between beads.

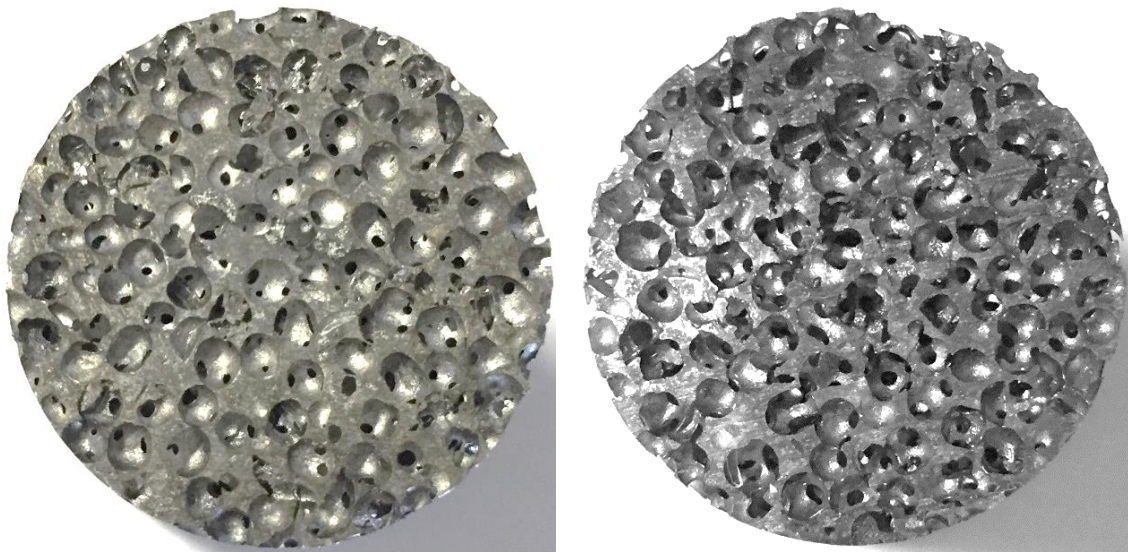


Fig 4: Optical microscope images of porous Al foam structures made at (left) the highest and (right) the lowest pressure differential

Figure 5 shows an optical microscope image for a porous Al sample and a typical 2D CT slice extracted from it. Figure 6 shows how the image processing methodology was optimised to ensure the outline of the porosity was accurately followed, in particular

making sure that the contact regions between the particles, which have a smaller radius of curvature for higher pressure differentials, were accurately represented. This figure also shows the corresponding 3D structures, highlighting the different morphologies at the extremes of the pressure differentials investigated.

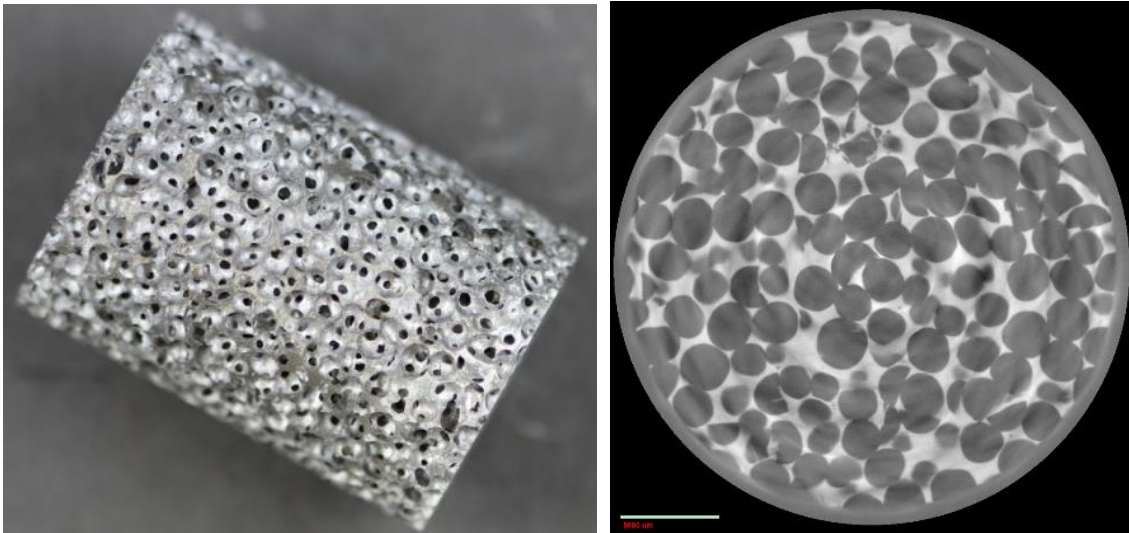
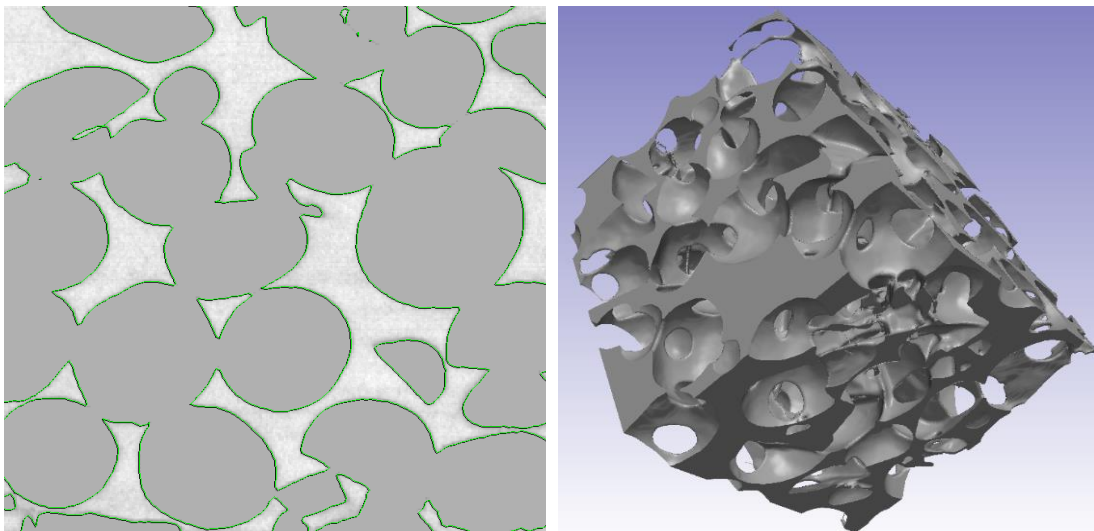


Fig 5: 3D optical and corresponding 2D X-ray CT images of a porous Al structure



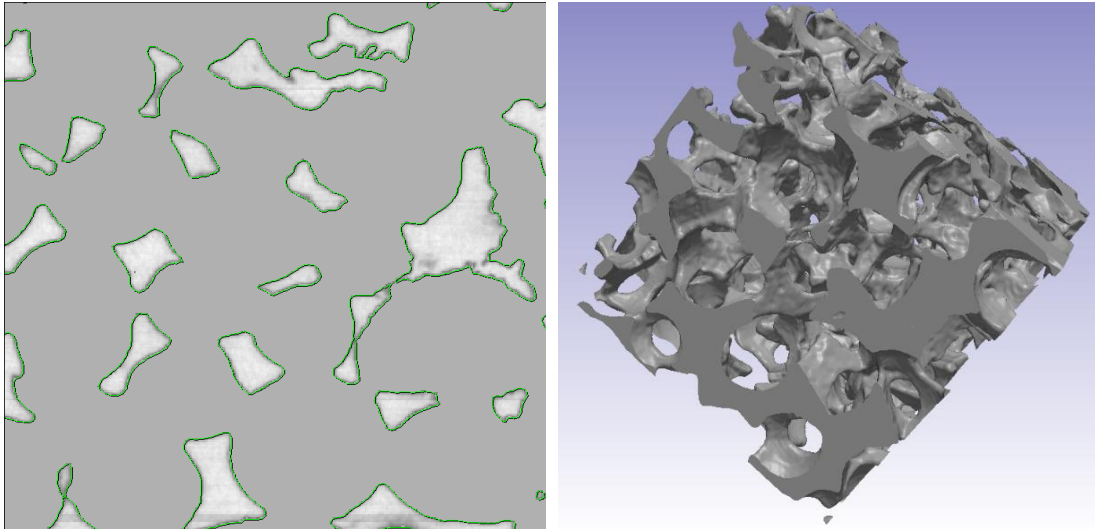


Fig 6: Left, 2D model contours and right, metal domains for porous Al made at the highest (top) and lowest (bottom) pressure differentials

Table 1 presents structural data for the porous metals produced, showing the key parameters of porosity, mean pore size and mean connectivity (window) size measured from 3D CT volumes (CFD). The measurements of pore diameter and connectivity taken from micrographs (EXP), also shown in this table, confirm the veracity of those measured from the CT images. The porosities determined experimentally from the dimensions and mass, also agree closely with those determined from the CT images.

Structural measurements bear out the trends expected. The bead size dictates the pore size, smaller connections between pores are observed as the casting pressure differential increases and although the porosity is primarily dictated by the packing behaviour of the beads, it also influenced by the infiltration pressure, with higher pressure differentials leading to more complete filling of the pore network and to lower levels of porosity.

Figure 7 shows the relationship between the pressure differential and the ratio of window size to pore size

Table 1: Structural parameters for porous Al structures measured from CT images (CFD) and directly from the samples (EXP)

	Pressure difference (bar)	Porosity (%)	Mean pore size, (mm)	Mean connectivity (mm)
P1 CFD	-	70.5	2.23	0.65
P1 EXP	0.90	70.6	2.21	0.64
P2 CFD	-	72.6	2.22	0.72
P2 EXP	0.60	72.6	2.23	0.73
P3 CFD	-	75.2	2.27	0.74
P3 EXP	0.45	75.1	2.22	0.75
P4 CFD	-	78.4	2.23	0.90
P4 EXP	0.25	78.2	2.24	0.92

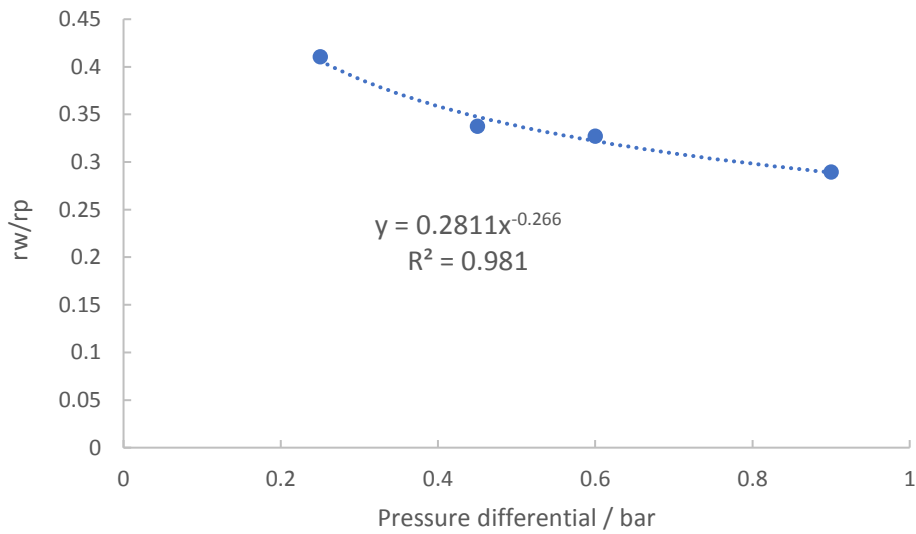


Fig 7: Relationship between pressure differential and ratio of window to pore size for the cast samples.

Experimental measurement of flow

Figure 8 shows the pressure drop characteristics for the range of different porous structures produced, where an order of magnitude difference in the pressure drop per unit length is observed between structures with the highest and lowest porosity, at the

maximum flow rate. The pressure drop behaviour is split into three groups; the highest pressure drop is observed for the sample with the lowest porosity and smallest windows, similar intermediate behaviour is observed for samples with similar, intermediate window sizes and the lowest pressure drops are observed for the sample with highest porosity and largest windows. The similarity in pressure drop behaviour for P3 and P2 (which have similar window sizes) indicates the relatively small effect of changes in porosity.

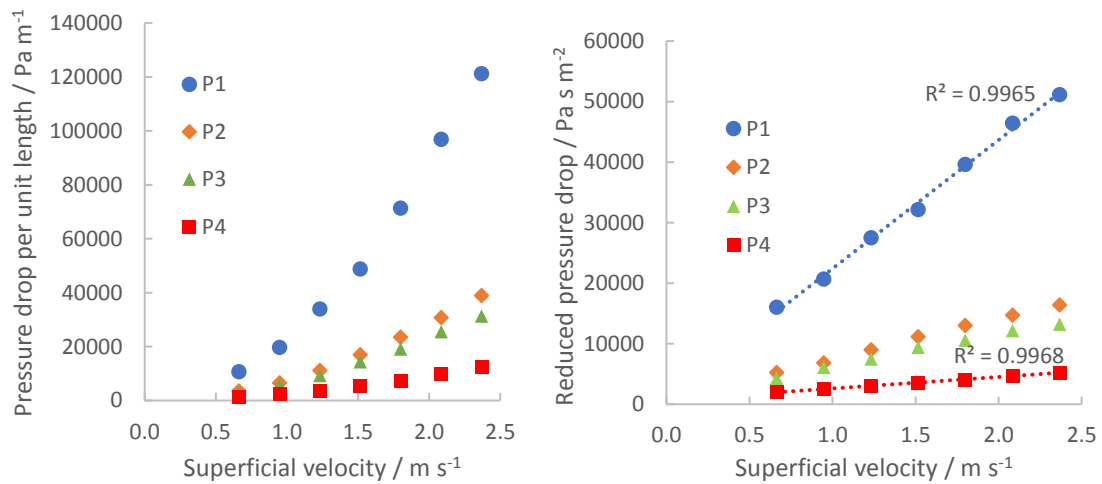


Fig 8: Plots of (left) pressure drop per unit length and (right) reduced pressure drop against superficial flow velocity

By plotting the reduced pressure drop, the pressure drop per unit length divided by the superficial velocity, against the superficial velocity, the relevant flow regimes can be identified to ensure that the modelling approach is apt [18]. Figure 8 presents such a plot and shows that for all the samples, the dependence is linear, with very close fit, indicating that the flow is within the Forchheimer regime across the entire range of velocities explored.

The Reynolds number for flow (calculated using the pore diameter as the length scale) ranges from roughly 90 to 350 over the interval of flow velocities explored. This would suggest a transition in the flow behaviour should be observed at close to 1 m s^{-1} ($\text{Re} = 150$), from the Forchheimer to the post Forchheimer regime, and a further transition to turbulent flow for velocities above 2 m s^{-1} ($\text{Re} = 300$) [19]. The clear absence of these transitions highlights the inadequacy of using the pore diameter to define the length scale when determining the Reynolds number for these types of porous structure.

Simulation of Flow

Figure 9 shows the simulated flow behaviour (flow is from top to bottom) through samples with the highest and lowest porosity (P1 and P4) at a superficial inlet velocity of 1 m s^{-1} . Bottleneck flow is apparent through preferential “channels” controlled by the availability and alignment of the windows in each pore. The intensity of this constrictive effect is shown by the regions of stagnant flow and of high velocity that correspond to the scale, and which are also indicated by the velocity vectors. It can be seen that fluid exiting the bottleneck regions in the P1 structure (with the smallest windows) does so with a velocity that is approaching 15x that for the superficial velocity and which is more than 3x times higher than that for corresponding flow in the P4 structure (with the largest windows).

For the P1 sample, made at the highest pressure difference, the number of windows in each pore is the smallest [10,11] and this reduces the likelihood of more than one “exit” window being aligned in the flow direction, encouraging the flow to become more tortuous. In contrast, the P4 sample, with the highest porosity and most numerous and largest windows, creates the least “diversion” to the incoming airflow and exhibits the fewest regions where flow stagnates.

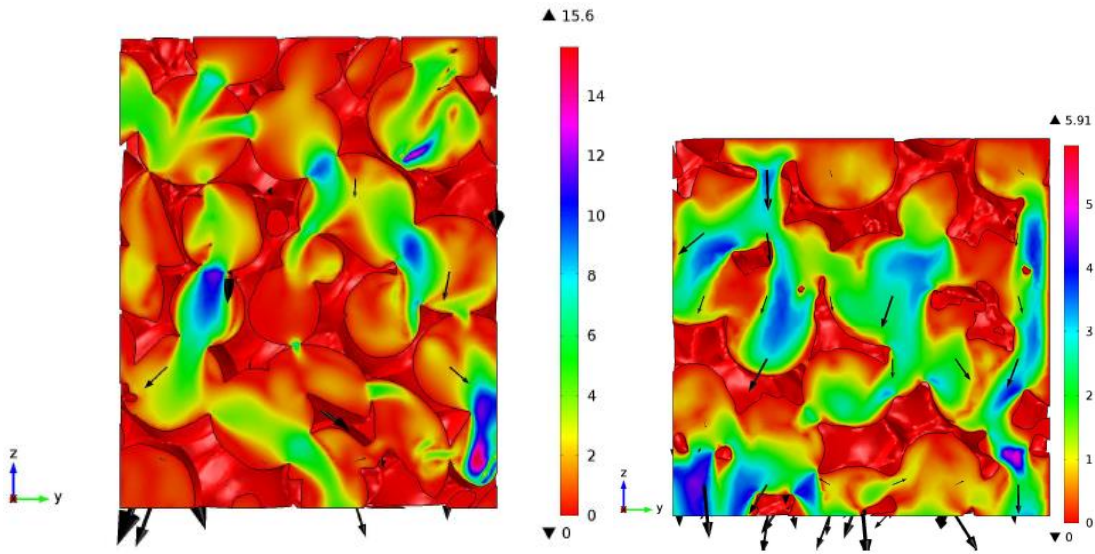


Fig 9: 2D sections of the velocity distribution for flow through porous samples P1 (left) and P4 (right) for a superficial velocity of 1 m s^{-1} .

Comparing simulations and experimental measurements

Figure 10 compares the pressure drop per unit length vs velocity curves for experimental measurements and modelling. Good agreement is observed for all samples, with average RMS fits to the experimental data of 99, 105, 95 and 102%, as the porosity increases respectively, without consistent over or under prediction of the pressure drop. These deviations are within established limits for “accurate” modelling of more open porous metal structures [12].

The permeability and form drag coefficients, as defined in the Forchheimer equation, were obtained by fitting a second order polynomial to experimental data and data from simulations, and are given in Table 2, where good agreement between the two sets is observed. From this, the individual contributions to the pressure drop per unit length from the two terms in the Forchheimer equation can be determined, and it is observed (as in [21]) that the contribution from the form drag term increases with velocity, in this

instance over the range of 64-99%. Thus for these bottleneck-type structures and the range of flow velocities investigated, form drag dominates the pressure drop behaviour.

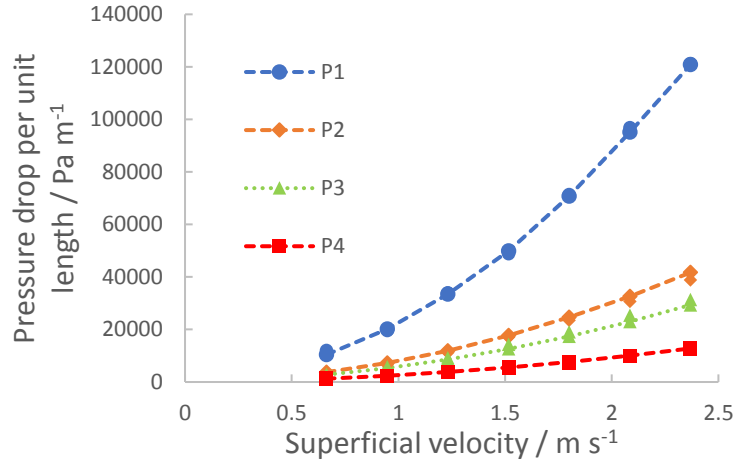


Fig 10: Graph of measured and modelled (dashed line) pressure drops per unit length against superficial velocity

Table 2: Forchheimer equation terms for flow simulations (CFD) and experimental measurements (EXP)

	Permeability (K) /10 ⁻⁰⁹ m ²	Form drag (C) m ⁻¹
P1 CFD	13.5	17466
P1 EXP	13.2	17283
P2 CFD	17.1	5802
P2 EXP	17.0	5417
P3 CFD	18.0	3986
P3 EXP	19.3	4491
P4 CFD	33.4	1700
P4 EXP	31.2	1636

When compared with the analytical model in [15], data fit more closely to predictions for C than for K (as was observed in [15]). The inertial term, C (and the form factor, C

\sqrt{K}) tend to be more closely predicted for samples with numerous and large openings between pores, that create less disrupted flow, more like the simplified case in the model in [15]. The model isn't however able to reliably predict the pressure drop behaviour in the same way that the more time-consuming simulations can, especially for sample P1 which experiences tortuous flow, with K and C only typically predicted to be 40-50% of the experimentally determined or simulated values.

Modelling considerations

It is rarely possible to have similar RVE and experimental test sample sizes owing to the extremely high mesh count and computational power that would be required. Whilst the process for determining an RVE will minimise variations in porosity between the modelled volume and the sample, pore morphological differences may arise for non-homogeneous structures, such as those examined in this study. Accurate modelling is dependent upon accurate representation of the porous structure by both sampling a "typical" volume and ensuring both the CT data capture and the image processing stages preserve the accuracy of the pore and window geometry. Despite the local inhomogeneities within these structures, it was found that pressure drop measurements for simulations on RVE's taken from different regions within the same sample differed by less than 2% if the porosities differed by no more than 0.5%.

Discrepancies between simulations and experimental measurements may arise from using an RVE size based on the structure, rather than the flow geometry [13].

Structure-derived RVE's are generally smaller in length than the "critical" sample length required for developing flow behaviour that is length independent (found by both experimentation and simulation for more open and more porous metal structures to be some 20-50 pore diameters in thickness [13, 16, 17, 20]). One study [17] reported

pressure drop increases of up to 25% for samples that were smaller than the critical length.

In this study, changes in the RVE length (in the flow direction) from 6 mm to 15mm produced very little variation in the pressure drop determined from simulations. Despite small differences in porosity ($\pm 0.3\%$) produced by “sectioning” the non-uniform structure, the pressure drop at the highest flow velocity remained within 97% of that for the largest RVE. The lack of observable length effect is worth remarking. It is thought that in the materials studied here, channelling of the flow through the much more restricted passages in the structure encourages a more rapid transition from flow in the pipe to distorted flow within the porous structure than occurs in more open structures such as those reported in [2, 13, 16, 17, 20].

Simulation of semi-virtual structures

CT images from real structures were modified to create semi-virtual 3D volumes. Adding or subtracting pixels (dilation or erosion) to the solid field is similar in principle to applying higher or lower pressure differences during casting. This approach could, therefore, aid the understanding of the effects of changes in structure on the pressure drop behaviour, without the need to produce samples. Figure 11 presents 2D views from the same CT section for images for the P3 structure and for semi-virtual samples with 1 (P31) and 2 (P32) pixels removed from the metal field; equivalent to creating a sample at 2 successively lower pressure differentials. From the 3D images, the opening of the windows connecting the pores and the increase in porosity are clear. It should be noted that over-erosion can lead to isolated struts and this should be avoided. Table 3 quantifies the structural changes corresponding to the images and presents the K and C values for the pressure drop per unit length-superficial velocity dependence. A

substantial increase in K and decrease in C is apparent, consistent with those affected by structural changes as a result of reductions in pressure difference, as reported in Table 2. It should be noted that by increasing the resolution of the CT images, a finer level of adjustment could be made.

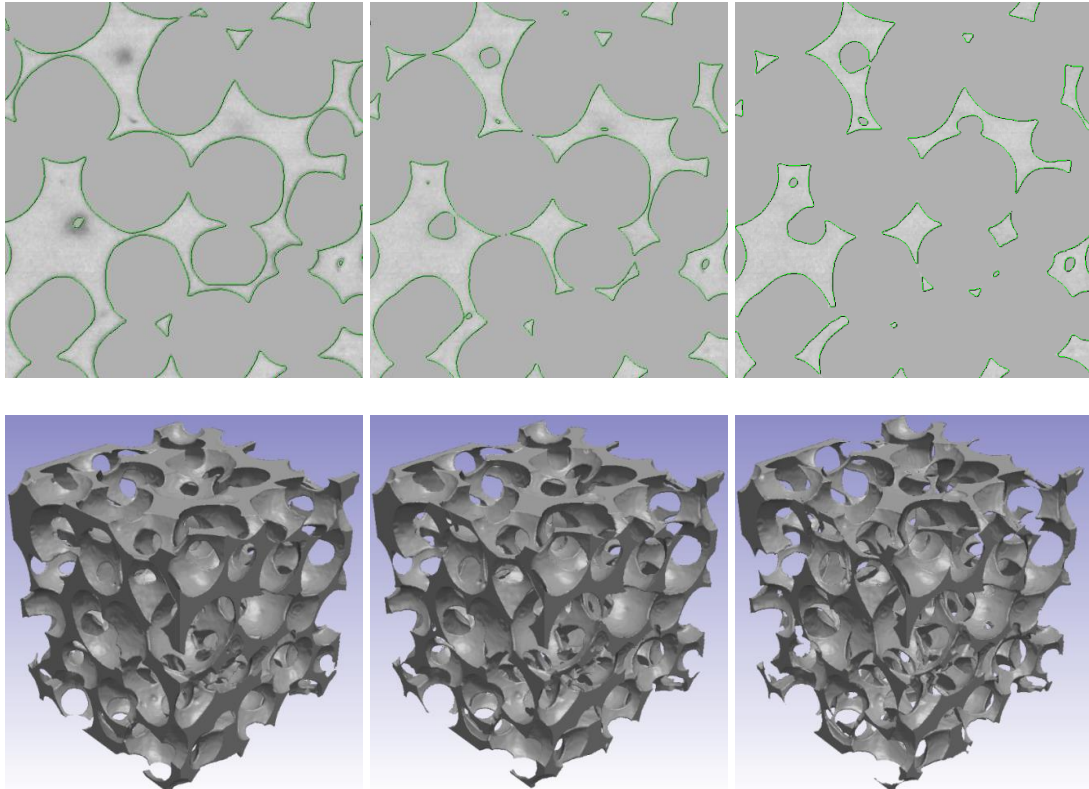


Fig 11: 2D CT images (top) and 3D volumes (bottom) for sample P3 (left) and after erosion of 1 (centre, P31) and 2 (right, P32) pixels from the solid field

Table 3: Comparison of structural parameters for “real” and semi-virtual structures derived from sample P3 (shown in figure 11) after erosion of the solid field.

	Porosity / %	Dw (mm)	Dp (mm)	Permeability (K) /10 ⁻⁰⁹ m ²	Form drag (C) m ⁻¹
CFD P3	75.2	2.27	0.74	18.0	3986
V31	80.9	2.36	0.92	35.4	2668
V32	85.9	2.48	1.16	58.9	1085

Dimensionless analysis enables the effect of multiple changes in porosity, pore size and window size that are affected by the erosion process to be rationalised. Figure 12 plots the permeability and form drag in dimensionless form (shown in equations 4 and 5) against the ratio of window to pore size for real and virtual structures made by multiple erosions of samples P1-P4.

$$K^* = \frac{K}{\phi r_p^2} \quad \text{Eq 4}$$

$$C^* = C r_p \phi^2 \quad \text{Eq 5}$$

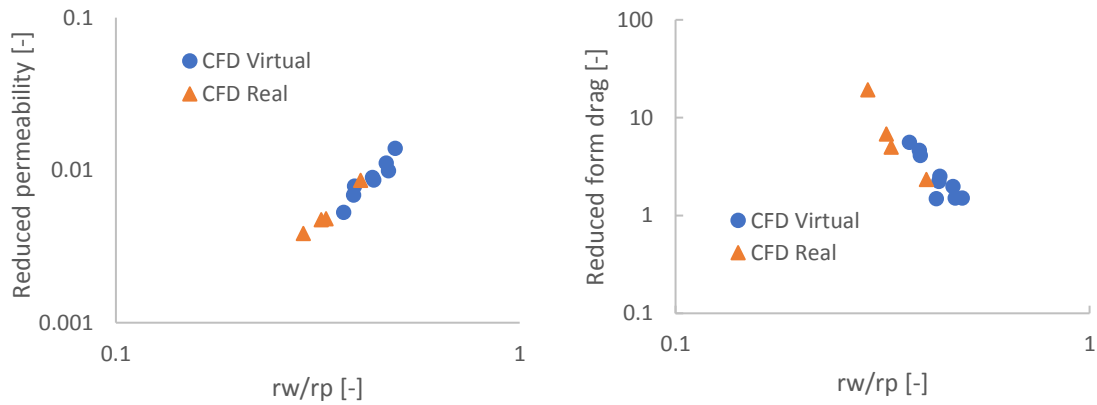


Fig 12: Plots of the reduced permeability and form drag against the ratio of window to pore diameter for real and semi-virtual structures.

The figures show that data for real and semi-virtual structures fall on broadly the same curves and follow the same form and are of similar magnitude to those from experimental data in [15]. Thus, the adaptation of real porous structures in this way appears to be a valid method to determine the effect of changes in structural morphology on the flow behaviour through these types of porous structures.

Such a limited number of simulations could then be wide-reaching in their ability to aid the design of porous structures of this type. For example, a porogen size and porosity

(packing fraction) are chosen, as are target values for the pressure drop. Using equation 2 and a representative flow velocity, K and C can be determined (although for higher velocities C dominates and K could be neglected in a first iteration). With a value for C^* determined, plots in figure 12 give the ratios of window to pore size (and K could be determined if needed). Plots of the form presented in figure 7 can then be used to define the pressure differential to achieve the window size required.

Summary

The modelling approach used here has been shown to reliably predict the pressure drop behaviour within the Forchheimer regime in replicated foam structures with bottleneck-type pore structures. Achieving accurate predictions (correlations between experiment and simulation within <5%) requires accurate representation of the porous structure. Geometrical adaptations of real porous structure can be used to create structures that bear resemblance to real ones. This enables an appreciation of the effect of changes in porosity and window size on the pressure drop, without the need for sample production. Such an approach could be invaluable in the design of porous components with bottleneck-type structures.

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