
● *Contributed Paper*

VISUALISATION OF STRUCTURE AND FLOW IN PACKED BEDS

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Magnetic resonance imaging (MRI) volume- and velocity-measurement techniques are used to probe structure-flow correlations within the interparticle space of a packed bed of ballotini. Images of the three mutually orthogonal components of the velocity field are obtained in axial and radial image slices within a bed of 5-mm-diameter ballotini, packed within a glass column of internal diameter 4.6 cm. A three-dimensional volume image of the bed is also obtained and analysed to partition the interparticle space into individual pores and determine the location of pore necks. Significant heterogeneity in the flow is observed; in one slice approximately 8% of the pores carry 40% of the volume flow. The characteristics of pores carrying anomalously high values of fluid flow rate and velocity are investigated. © 1998 Elsevier Science Inc.

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INTRODUCTION

Characterising the structure of porous media and the transport processes occurring within the void space is of fundamental importance to many chemical engineering systems, such as oil recovery from rock formations, remediation of soil contaminated by non-aqueous phase liquids, and heat and mass transport in packed beds. Experimental and theoretical studies of flow through such systems often treat the porous medium as an effectively homogeneous system and concentrate on the bulk properties of the flow. Such an approach neglects completely the complexities of the flow within the void space of the porous medium, although the details of these local flow processes may be the most important factor influencing the behaviour of a given physical process occurring within the system. To understand fully the transport through a porous medium, we need to obtain a detailed description of the void space of the porous medium and also of the detailed flow through the pores and constrictions which constitute that void space.

In this work, flow through a packed bed of spheres is studied. This is a particularly interesting system for study because it not only represents a system of direct interest to chemical engineers but also serves as a model for other

porous systems. A packing of spheres has the advantage that the pore size can be chosen to match the resolution of the technique used to image the system, while at the same time, flow at Reynolds numbers characteristic of real porous structures, such as packed bed reactors, can be achieved.

EXPERIMENTS

The magnetic resonance imaging (MRI) flow experiments were performed using a Bruker Spectrospin DMX 200 nuclear magnetic resonance (NMR) spectrometer with a 4.7 T, 15-cm-bore vertical magnet, equipped with shielded gradient coils providing a maximum gradient strength of 13.9 G/cm. A birdcage radio-frequency coil of diameter 6.3 cm, length 6 cm, and tuned to 199.98 MHz for the ^1H resonance, was used to irradiate a glass flow column containing glass ballotini and water doped with copper (II) sulphate, which reduces the spin-lattice relaxation time of water from 3000 ms to 600 ms, hence decreasing data acquisition time. The internal diameter of the flow column was 4.6 cm, with a maximum height of 70 cm. The MRI probe allowed access to the imaging section from both top and bottom; the fluid was passed in a continuous loop through the magnet. The construction of the packed bed and operation of the flow loop have

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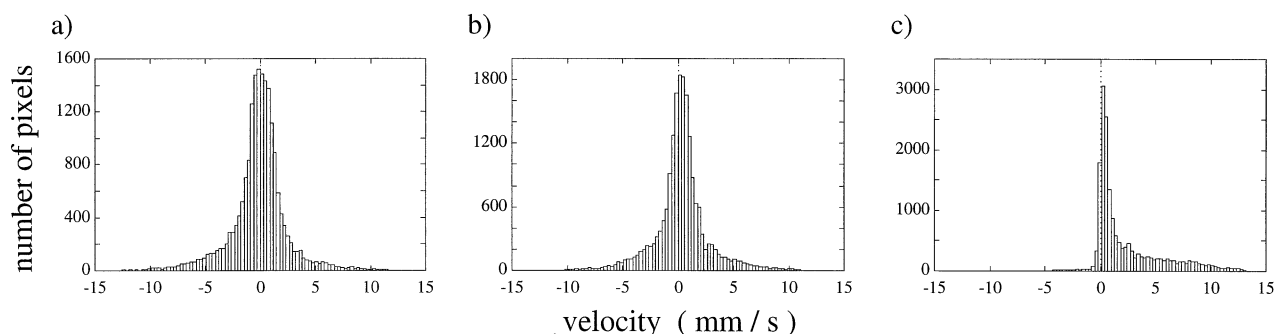


Fig. 1. Histograms showing the distribution of velocities in each coordinate direction within the packing of spheres in a zx-slice: (a) u_x , (b) u_y , (c) u_z .

been described elsewhere.¹ Flow visualisation was achieved using the pulse sequence reported earlier,¹ based on the velocity-imaging technique of dynamic NMR microscopy.^{2,3} The final data matrix consisted of 256×256 spatial points by 12 velocity points; given the selected field of view of 50 mm, the in-plane spatial resolution was therefore $195 \times 195 \mu\text{m}$, with a slice thickness of 1 mm. Macroscopic flow measurements yielded a value for the volume flow rate through the apparatus of $2 \text{ cm}^3/\text{s}$. The data-analysis procedure described earlier¹ was used to obtain visualisation of the x, y, and z components of the flow within xy and zx slices through the bed, where z is the direction of the superficial flow along the axis of the bed.

A three-dimensional (3D) volume image of the packed bed was also obtained using a 3D spin-warp imaging sequence. The image was taken in the absence of flow but with the void space filled with water. For this experiment the 3D matrix consisted of a $256 \times 128 \times 128$ array, giving a resolution of $195 \times 390 \times 390 \mu\text{m}$; zero filling was used prior to Fourier transformation to produce an image with cubic voxels. The volume images were analysed to produce a partitioning of the interparticle (void) space into pores as described in earlier work.^{4,5} In this analysis the definition of a pore as given by Dullien⁶ is used, in which a pore is considered as a portion of the void space bounded by a solid surface and planes erected where the hydraulic radius of the void space exhibit local minima; these planes are the pore necks and are particularly important in the present context because they represent the constrictions in the flow paths through the void space. The algorithm employed is based on a variant of morphological thinning and results in a partitioning of the void space which is unambiguous and which has a clear physical basis. The analysis produces an image in which each pore in the 3D volume is identified, along with the pore necks, and hence, the interconnectivity of the pore space is also determined.

RESULTS AND DISCUSSION

The Velocity Field within the Packed Bed

Fig. 1 shows histograms of the fluid velocity, u , within each image pixel in three orthogonal directions x, y, and z, derived from flow visualisations in a zx slice. For flow in the direction of the superficial flow (z-direction), the average velocity determined from the distribution function is 3.22 mm/s; the substantial number of voxels which contain nearly stagnant fluid is apparent from these distributions, as is the small number of voxels with extreme velocities. The distribution for u_z also shows some negative, counter-current flow in agreement with MRI data presented by Kutsovsky et al.⁷ The positive values of u_z are characterised by an exponential distribution. The distributions in u_x and u_y through the same image slices are, as expected, symmetric about and centred on zero velocity. Analogous histograms derived from flow visualisations in the radial slices yield similar observations.¹

Having partitioned the void space into individual pores using the algorithm referenced earlier, the z component of the mean flow velocity (v_z) and the z component of the volume flow rate (q_z) are calculated from:

$$q_z = \int_{\text{pore}} u_z dS_z, \quad v_z = q_z/A, \quad (1)$$

where S_z is the component of the vector area of a pore with normal parallel to the axis of the bed, and the cross-sectional surface area of the pore perpendicular to the axis of the bed, an xy slice, is given by $A = \int_{\text{pore}} dS_z$. For each pore identified in the partitioning of the void space, these quantities are calculated via a numerical integration over the velocity image (see Fig. 2). An immediate observation from the flow visualisation is the extent of heterogeneity in the flow. For a typical

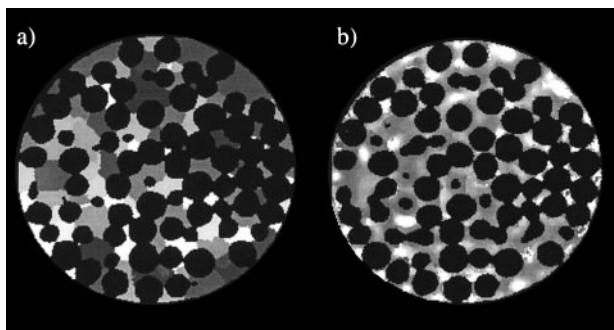


Fig. 2. Variation of structure and flow within the same xy-slice within the bed: (a) Individual pores within the void space are indicated by blocks of shading of area A ; (b) The z -component of velocity, u_z , is shown. Lighter shades indicate higher velocities.

image slice 40% of the flow is carried by just 8% of the pores, which constitute about 22% of the available cross-sectional area. Although a range of flow behaviours is observed, the flow through the majority of pores approximates laminar conditions.

The $q_z - v_z$ Plane

In Fig. 3 the position of each pore in the $q_z - v_z$ plane is shown. The data in this plot are taken from six xy image slices through the same bed. The individual pores are also identified in the diagram as a function of their radial position within the packed bed. From this plot a number of observations can be made. First, because there is not a simple correlation between q_z and v_z , there must be substantial variation in the mean flow velocities

through pores of similar cross-sectional areas. Second, there are no pores having large values of both q_z and v_z . Third, two groups of pores with extreme flow properties are identified: 1) pores with the largest volume flow rates ($q_z > 60 \text{ mm}^3/\text{s}$), which are also characterised by a flow velocity in the range $2.5 - 6.0 \text{ mm/s}$; and 2) pores that exhibit large mean velocities, above 7 mm/s , which are associated with volume flow rates in the range $7 - 40 \text{ mm}^3/\text{s}$. The reason two groups of pores occupy extreme regions of the $q_z - v_z$ plane is now considered in terms of the local geometry and topology characterising the pore space. The pores associated with a large-volume flow rate for a given mean velocity must be pores of large cross-sectional areas; such pores may be expected to occupy the region at the edge of the bed where the structure of the packing is significantly modified and ordered by the walls. Inspection of Fig. 3 indicates that for most of these pores this is indeed the case; it is also observed from the 3D volume image that the extent of these pores in the flow direction is typically only of the order of one or two ballotini diameters. Pores associated with the highest volume flow rates are also characterised by a large pore radius and a high interfacial surface area to adjoining pores. Pores with high mean-flow velocities tend to have low coordination to pores which they feed; the pore necks linking these pores also tend to be of relatively low interfacial area.

CONCLUSION

Visualisations of the x , y , and z components of the flow vector describing fluid flow within a packed bed of

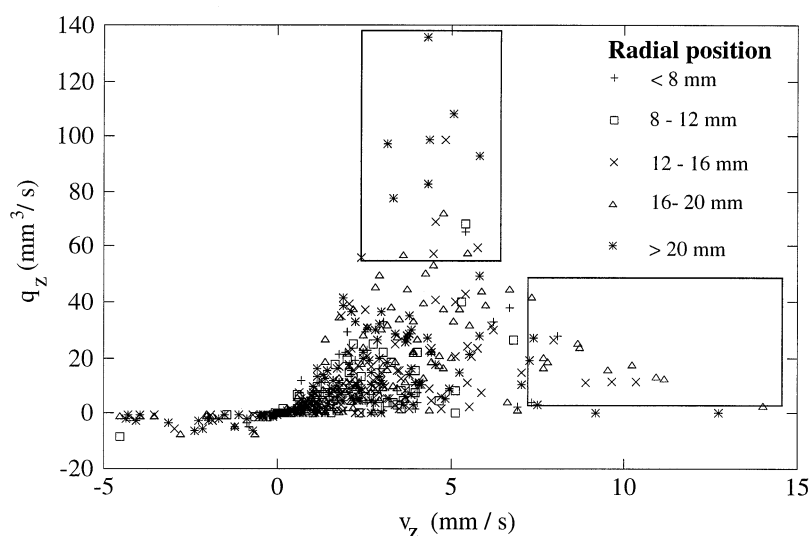


Fig. 3. Distribution of pores in the $q_z - v_z$ plane. The location of the pores within defined radial annuli within the bed is indicated. The boxed regions identify pores which exhibit the highest velocities and volume flow rates within the bed.

spheres allow us to characterise the extent of heterogeneity in the flow field and the characteristics of the void space within the bed which promote high fluid velocity and volume flow rates. In ongoing studies, we are using both pore-network analysis and lattice-Boltzmann simulation techniques in combination with these data to gain a greater understanding of structure-flow correlations within packed beds.

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