NMR Imaging of Water Flow in Packed Beds

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Abstract

Measurements by magnetic resonance imaging (MRI) of water flow within granular porous media are presented in this study. Our goal was not only to obtain visualizations of velocity field in porous media but rather to make accurate measurements of interstitial and averaged velocities in bead packs. Two situations were examined: the first for a packed bed with a large beads diameter where it was possible to visualize the interstitial velocities and the second with a packed bed with a small beads diameter where only averaged interstitial velocities were measured.

Keywords

Magnetic Resonance – MRI – Porous Media – Velocity imaging – Flow

1. Introduction

Flows in porous media are everywhere in our environment (soils, oil reservoirs, biological tissues) and in industrial processes (filtration, drying, fixed-bed reactors). In order to explain further the transport mechanisms through a porous medium, we have to know the characteristics of the medium (e.g. porosity, pore size) and also the flow characteristics through its pores. Magnetic resonance imaging has been extensively used [1-8] to visualize directly fluid flows within porous media but few studies really focused on the accuracy of such measurements. Indeed, many difficulties due both to the acquisition of the NMR signal and image processing arise when accurate quantitative measurements are searched.

In this study we present measurements obtained by MRI in packed beds with beads of two sizes: large diameter (3.175 mm) and small diameter (0.5 mm). Packed beds with large beads allow to measure interstitial velocities inside the pores while packed beds with small beads can only give averaged interstitial velocities. In order to check the accuracy of the measurements, results were compared with those obtained by weighing.

2. Materials and Methods

The images were performed using an MRI equipment operating at 100 MHz (Bruker Biospec 24/40). A spin echo sequence was used to obtain the structure of the porous medium (signal intensity) and a PGSE sequence to measure the velocity field (signal phase) of the fluid. The experimental parameters were chosen as follows: duration of the flow encoding gradient pulses δ=2 ms, spacing between the gradient pulses Δ=12 ms, field of view FOV=4 cm, image matrix of 256 × 256 points, number of scan N=4.

We used polymer beads in order to avoid the influence of paramagnetic elements and to limit magnetic susceptibility effects. They were packed into a central tube (length of 23 cm, inner diameter of 1.65 cm). This tube was inserted into a second tube of larger diameter to define an annular spacing of 6 mm (Fig. 1). The porous medium and the annular spacing were then fully saturated with water. The device was placed between two constant-head reservoirs. Thus water flowed only by gravity effect through the device. As we can see in figure 1, the mean flow directions are opposite in the porous and annular regions [1]. The annular region was used to calibrate the NMR signal of water and to check the quality of MRI flow measurements (fluid was incompressible and volume flow rates of water in the porous section and in the outer annulus section should be the same).

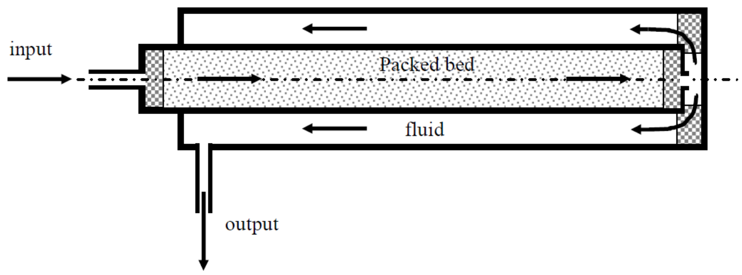

Fig. 1: Experimental cell constituted by a central porous tube (packed bed) and an annular gap. The mean flows in the two regions are in opposite direction.

3. Results

3.1. Velocity measurements through packed bed of large beads

MRI velocimetry measurements are performed on a packed bed of polyacetal beads of large diameter (3.175 mm) with a thin slice selection (1 mm). This allows observing the interstitial flows between the grains of the bed and minimizes the partial volume effects (voxels including both a liquid and solid phase).

Fig. 2 shows a cross-sectional velocity map for a mass flow rate of 0.914 g/s (Re_p = 36). The velocities are represented with components along the axis of the porous cylinder. The flow in the outer gap is an annular Poiseuille flow (Re = 25).

The velocity map in the porous tube shows the existence of preferential flow paths near the wall of the tube and also some regions with higher velocities towards the center of the packed bed between the grains. It is interesting to note that the local velocity can be 4 to 6 times higher than the mean velocity in the porous medium. This result will be useful to understand the results with small beads in the next section.

At Re_p = 36, the inertial effects may become important considering the viscous effects causing recirculations. Nevertheless by varying the Reynolds number between 14 and 36, we did not observe by MRI negative velocities that would have proved the existence of such an effect.

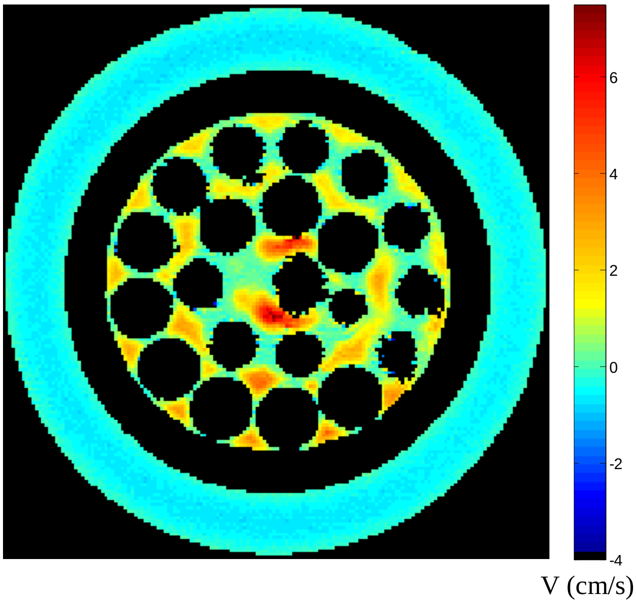

Fig. 2: Velocity map obtained by MRI velocimetry with a 1 mm thickness for slice selection. Areas in black correspond to the absence of signal (solid). The porous part contains a packed bed of polyacetal beads (3.175 mm in diameter). The mass flow rate is equal to 0.914 g/s.

Flow measurements by MRI in both the outer annulus and the inner porous tube deviate by less than 3% from the imposed values (Table 1). Measurement errors that we found are very low compared to literature results [1,2,7,10].

Table 1: Comparison between mass flow rates measured by MRI in annular and porous sections and that measured by weighing

	Mass flow rate (by weighing) (g/s)	Mass flow rate (by MRI) Outer annulus (g/s)	Mass flow rate (by MRI) porous tube (g/s)	Relative error MRI porous tube / weighing (%)
Polyacetal d = 3.175 mm	0.644	0.646	0.656	+ 1.9%
	0.813	0.809	0.808	– 0.6%
	0.914	0.903	0.936	+ 2.4%
Polystyrene d = 0.5 mm	0.254	0.259	0.248	– 2.4%
	0.276	0.277	0.268	– 2.9%
	0.333	0.334	0.320	– 3.9%

3.2. Velocity measurements through packed bed of small beads

MRI velocimetry measurements are then performed on a packed bed of polystyrene beads (diameter 0.5 mm) with a wide slice selection (20 mm) in order to reach average values (Fig. 3). This case is different from the previous one because each voxel contains a significant solid fraction (around 60%). There is a "*partial volume effect*" as mentioned in several articles [1,3,9,10]. The volume fraction of water can be different from one voxel to another, in particular near the tube wall. So it is necessary to correct the image by weighting the velocity in each voxel with the spin density. This has been performed using a classical spin echo imaging procedure. A change in the velocity distribution can be observed in the vicinity of the walls due to the ordering of the beads in this area (Fig. 3) as well observed on porosity maps.

Phase aliasing may exist in this case without clear appearance on the images. Indeed, the phase in each voxel is a mean phase shift of all the spins contained in the voxel. The range of velocity being relatively wide in a single voxel (from 0 to about 6 times the mean velocity, as mentioned above), a phase aliasing can be reached for some spins in a voxel. This effect is difficult to correct and it is preferable to adjust the strength of magnetic field gradient in the velocimetry sequence in a way to avoid any phase aliasing [4,8]. Fig. 4 shows that, below a 30° mean phase shift (consistent with over-velocities 6 times higher than the mean velocity), the phase aliasing is avoided.

In light of these precautions, measurements of mass flow rates have given errors between the fixed flow rates and those measured by MRI lower than 4 % (Table 1).
The result is a little worse than for packed beds of larger beads, but this is quite logical because the velocity measurements require a weighting by the spin densities. Also the magnetic susceptibility effects are greater with a bed of small beads. This becomes even more important for naturals materials (rocks, sand, wood…) Nevertheless those effects could be lowered by carefully choosing experimental parameters such as Δ [8].

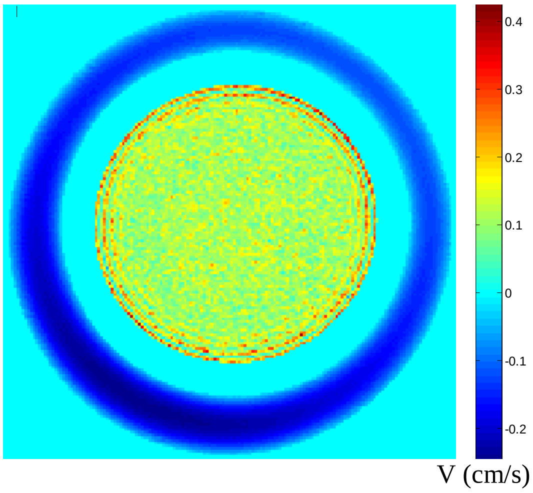

Fig. 3: Velocity map obtained by MRI velocimetry with a 20 mm slice selection. The porous part contains a packed bed of polystyrene beads (0.5 mm in diameter). The flow rate is equal to 0.254 g/s.

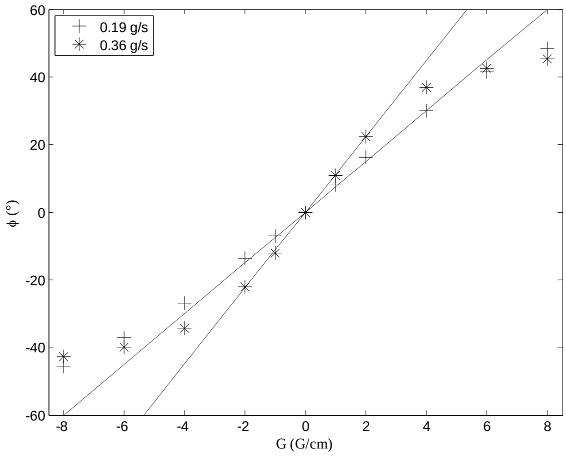

Fig. 4: Mean phase shift (°) according to the strength of gradient (G/cm) for velocity measurements in a packed bed of polystyrene beads (0.5 mm in diameter) and with a 20 mm slice selection. The dotted lines represent the linearization of the curves near the origin. The flow rates are respectively 0.19 g/s and 0.31 g/s.

4. Conclusions

We have shown in this article that velocity measurements can be carried out in packed beds by MRI with good precision (error inferior to 4%). To reach this accuracy we have used polymer beads in order to avoid magnetic susceptibility effects. Results would not be as good with other porous materials especially natural media. By using small beads we have shown the necessity to correlate the velocity and porosity maps to eliminate partial volume effects. These results also highlight the importance of adjusting the gradient strength to avoid any phase aliasing even if those aliasing not clearly appears on the velocity maps.

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