

● *Short Communication***MRI STUDY OF NON-AQUEOUS PHASE LIQUID EXTRACTION FROM POROUS MEDIA**

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Magnetic resonance imaging is used to investigate, at the pore scale, the dissolution and mobilisation of discrete non-aqueous phase liquid (octanol) ganglia trapped within porous media by capillary forces, by a mobile aqueous phase. Dissolution is observed to be described by a mass-transfer limited model. Mobilisation of entrapped ganglia commences at lower flowrates when a surfactant is introduced into the mobile aqueous phase. © 1998 Elsevier Science Inc.

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INTRODUCTION

The gradual dissolution by a mobile aqueous phase of a virtually immiscible non-aqueous phase liquid (NAPL) trapped by capillary forces in a porous medium in the form of blobs or ganglia is investigated at the pore scale using magnetic resonance imaging (MRI). An understanding of such dissolution phenomena is important in attempts to model soil remediation processes,¹ particularly when the dissolution process is limited by mass transfer between the aqueous and non-aqueous fluid phases, as is the case here. Octanol ganglia were formed in a porous medium, composed of randomly packed glass ballotini in a glass column, and their subsequent dissolution by a mobile aqueous phase was monitored. Three-dimensional MRI images, which selectively show the octanol ganglia, enable geometric changes in individual ganglia to be observed in situ as dissolution proceeds. In addition, two-dimensional velocity maps of the aqueous phase around the ganglia were produced using the technique of dynamic nuclear magnetic resonance (NMR) microscopy.² Thus additional pore scale information is available compared to previous experimental studies of such a dissolution process.¹ The mobilisation process is studied as a function of the flowrate of the aqueous phase, both with and without the presence of a surfactant.

MATERIALS AND METHODS

All imaging was performed using a Bruker Spectrospin DMX 200 nuclear magnetic resonance spectrometer (Bruker Spectrospin Ltd., Coventry, UK), tuned to 199.98 MHz for the proton resonance. The non-aqueous phase liquid used was octanol. The proton spin-lattice relaxation times (T_1) of octanol and water were 0.8 and 3 s, respectively. Discrimination between the two phases was therefore achieved, in the form of T_1 -weighted images, by reducing the recycle time. The porous medium studied consisted of a 46-mm internal diameter glass column containing a random packing of 5-mm diameter glass ballotini. The octanol was first imbibed into the column and subsequently replaced by the aqueous phase to establish residual octanol ganglia. Dissolution was then commenced by flushing with the aqueous phase at a constant flowrate. Three-dimensional NAPL-selective spin-echo images (during these acquisitions the aqueous flow was stopped) and two-dimensional velocity maps were acquired periodically during the dissolution process. This procedure was repeated for aqueous flushing rates of 18, 35, and 63 mL/min respectively, hereafter referred to as Experiments A–C.

For the investigation of ganglia mobilisation, ganglia were formed by allowing octanol to flow up through the same porous medium as that used in Experiments A–C.

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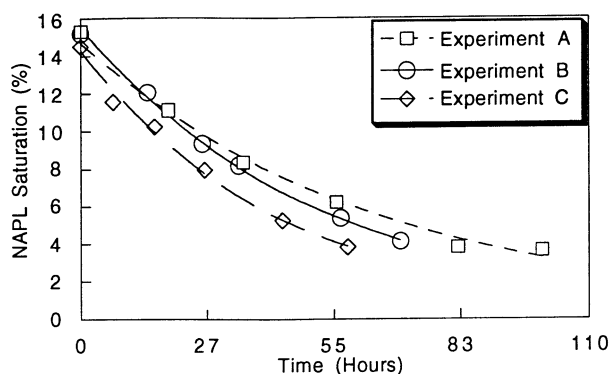


Fig. 1. NAPL saturation as a function of time for three water flushing rates.

Thus the octanol, which has a lower density than water, was propelled up by a buoyancy force while capillary forces acted to retain some of it in the form of ganglia. The ganglia were subsequently subjected to flushing by the aqueous phase, the flow rate of which was incremented in discrete steps. Before being introduced into the column, the aqueous phase was saturated with octanol, which prevented dissolution of the ganglia, allowing mobilisation alone to be studied. NAPL-selective three-dimensional images of the ganglia were acquired after each increment in flow rate; during image acquisition, the aqueous flow was stopped. This set of images is hereafter referred to as Experiment D. This procedure was subsequently repeated with the aqueous phase containing a non-ionic surfactant, Tween-80 (trademark of Atlas Chemical Industries, Poole, UK), which contains polyoxyethylene sorbitan monolaurates (Experiment E). The surfactant concentration used was 20 mg/L.

RESULTS AND DISCUSSION

Dissolution (Experiments A–C)

Figure 1 shows NAPL saturation S_n as a function of time for the three water flushing rates studied here. S_n is obtained by counting the number of octanol- and water-containing voxels in the various images. In all the experiments the rate of dissolution (i.e., rate of change in S_n) was found to decrease as S_n decreased. This is consistent with a mass transfer-limited model of dissolution. In addition, the overall rate of dissolution increased as the velocity of the aqueous phase increased. Preferential dissolution of the smaller ganglia was observed. The three-dimensional images allowed the changing geometric characteristics of ganglia to be investigated during the dissolution process. In particular, the interfacial area between the organic and aqueous phases, the ganglion volume, and the number of pores occupied by the individual ganglia were all monitored.

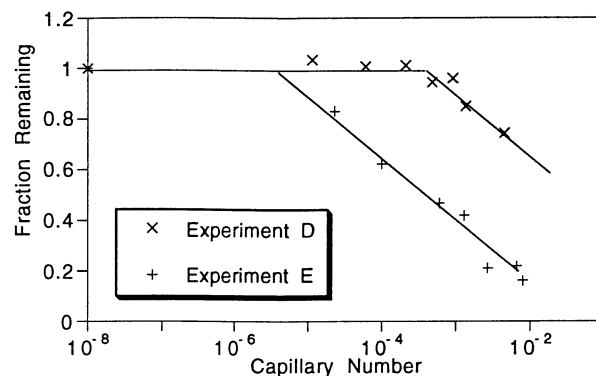


Fig. 2 The fraction, in terms of total volume occupied, of ganglia remaining as capillary number is increased.

Mobilisation (Experiments D and E)

Mobilisation of the ganglia started at considerably lower aqueous flow rates when an aqueous phase containing surfactant was employed. This is evident in Fig. 2, which shows the fraction of ganglia remaining, in terms of volume, as a function of capillary number, for Experiments D and E. Here capillary number is defined as:

$$\frac{\nu_w \mu_w}{\gamma_{ow}}, \quad (1)$$

where ν_w is the aqueous velocity, μ_w is the viscosity of the aqueous phase, and γ_{ow} is the interfacial tension between the organic and aqueous phases, which decreased from 8.5 to 5.2 mN/m on addition of the surfactant. In both Experiments D and E, a decrease in the average size of the ganglia occurs as the aqueous flow rate increased. A preferential mobilisation and breakup of larger ganglia during the mobilisation process have been shown both theoretically and experimentally³ and were observed in this work.

CONCLUSIONS

By application of magnetic resonance imaging, changing characteristics of dissolving octanol ganglia in the pore space of a porous medium have been successfully monitored. The interfacial area between the organic and aqueous phases, the ganglion volume, and the number of pores occupied by the individual ganglia were all investigated as a function of NAPL saturation. These data are now being used to aid in the development of numerical models of the dissolution process. Mobilisation of ganglia by a flowing aqueous phase was also investigated, both with and without the presence of a surfactant. Larger ganglia were found to be mobilised more easily.

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