MEASUREMENT OF SALTWATER-FRESHWATER FLOW VIA NUCLEAR MAGNETIC RESONANCE IMAGING

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ABSTRACT:

In this laboratory study a Nuclear Magnetic Resonance Imaging method was used to visualise the salt concentration distribution for a transient saltwater-freshwater flow problem in a three-dimensional bench scale experiment. Several measurements of this type were performed with well-known boundary conditions for a situation of upconing of a saltwater layer influenced by an abstraction. Different salt concentration and thus density differences were applied. The results could also used as test possibility for density-driven flow codes. Here the NMR method itself is illustrated using actual measurement results. Capabilities as well as the limitations are demonstrated.

INTRODUCTION

Seawater intrusion is inherently a density-driven flow phenomenon. The basic behaviour of this physical process still has to be studied in detail and also there are on-going discussions for example about the nature of dispersion for high concentration salt concentrations. For modelling purposes there is additionally the difficulty of numerical dispersion and limited accuracy of simulated results. Therefore there is the need to have the possibility to study saltwater-freshwater flow by direct measurement, which is aggravated by its limited access inside a porous medium.

At the Swim'16 conference we proposed an experimental set-up of a benchmark test for saltwater-freshwater flow in a porous media, based on former experimental experience with NMR measurements and a numerical scoping study (Oswald et al., 1996). In the meantime this type of experiments were performed and some aspects of the NMR imaging method and its application will be discussed here. A number of methods are available to observe flow and transport in two-dimensional porous media, but for three-dimensional problems there are only a few non-invasive and non-destructive methods, and Nuclear Magnetic Resonance Imaging (NMRI) is one of them.

METHOD

There are contrast agents like paramagnetic ions, which are known to influence the signal amplitude of NMRI measurements of fluids in porous media (Callaghan, 1991). The signal amplitude is then a function of the ion concentration in solution. Thus, the signal amplitude represents a measurable quantity that may provide the actual concentration of the paramagnetic ions like Cu^{2+}. The relationship between the Cu^{2+} concentration and the signal amplitude can be linear if the pulse sequence is designed accordingly (Greiner et al., 1997; Oswald et al., 2002). Thus, the NMR properties primarily depend on the concentration of Cu^{2+} as NMR-tracer and the pore size of the porous medium.

The measurements were performed using a commercially available 1.5 Tesla Magnetic Resonance whole body system (Philips Gyroscan ACS/NT, Best, The Netherlands) using the proton spin frequency. The three-dimensional volume was scanned as a series of adjacent two-dimensional (2D) slices within a short period of time using a 2D spin-echo technique. An overview about NMR applications in porous media is given in van As and van Dusschoten (1997).

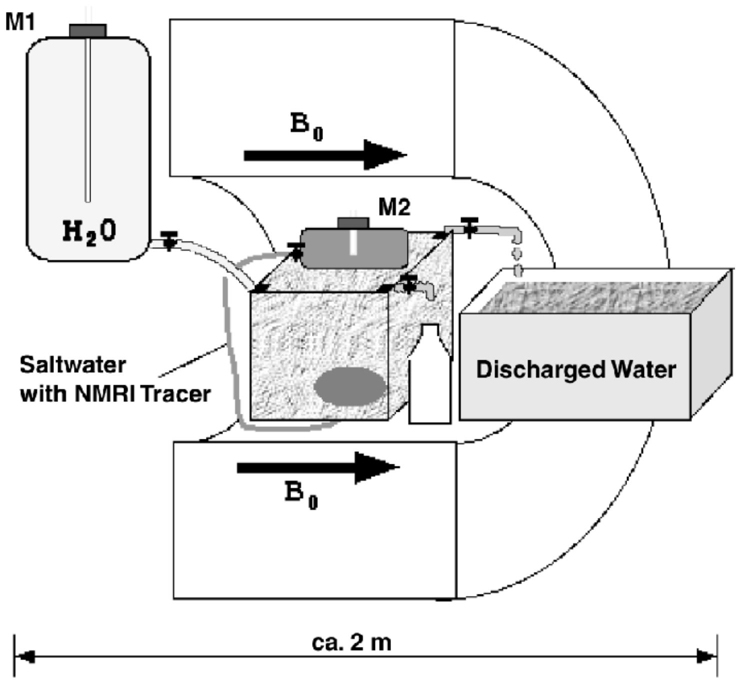

Figure 1 *Set-up for the NMRI measurements in the medical NMR apparatus. Saltwater and freshwater is recharged via the reservoirs M_1 and M_2, effluent water collected in flasks or a container.*

A cubic container with side length a=200 mm was filled with a porous medium consisting of glass beads with mean diameter d=1.2 mm. Openings at the top and the bottom enabled recharge and discharge of water. At the beginning of the experiments a salt solution was recharged from the centre of the container bottom into the porous medium, which had been saturated with freshwater beforehand. Two initial salt concentrations of about 1% and 10% (per weight) were used. In a second phase no recharge or discharge took place. Afterwards, in the third and main phase, water was abstracted in one top corner while freshwater was recharged at the diagonally opposite top corner. Below the discharge opening there developed an upconing (Figure 2) or a plume of low salt concentrations, depending on the saltwater density. Additionally, breakthrough curves at outlet were measured via the electrical conductivity of the discharged water.

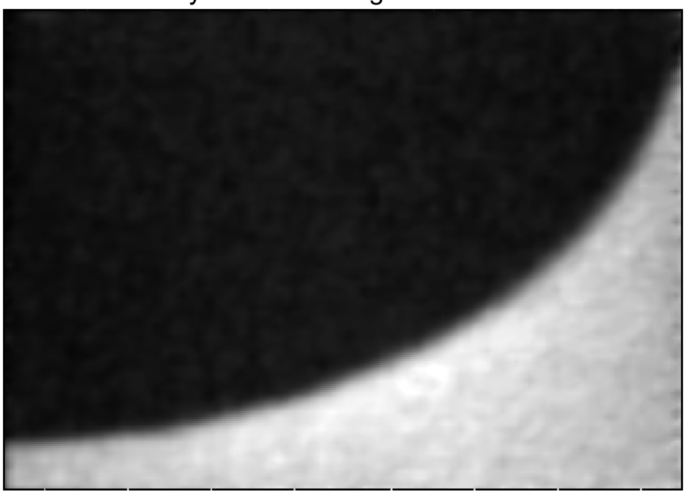

Figure 2 *Measured salt concentration distribution in the third phase showing an upconing of saltwater (bright) below the discharge (at top right) in a vertical cross-section; C = 1% by weight.*

NMRI EFFECTS

The signal to noise ratio is an important factor for the quality of the images. A high spatial resolution was achieved in the experiments, but on the other hand this increased the image noise. Additionally, the short measurement times increased the image noise for similar reasons. One of the effects of the signal noise is that the calibrated values exceed the physical concentration limits. Furthermore, the signal noise makes the use of a background image for field correction more difficult. The negative effect of signal noise can be compensated partly by smoothing, preferably via intelligent smoothing techniques (Figure 3).

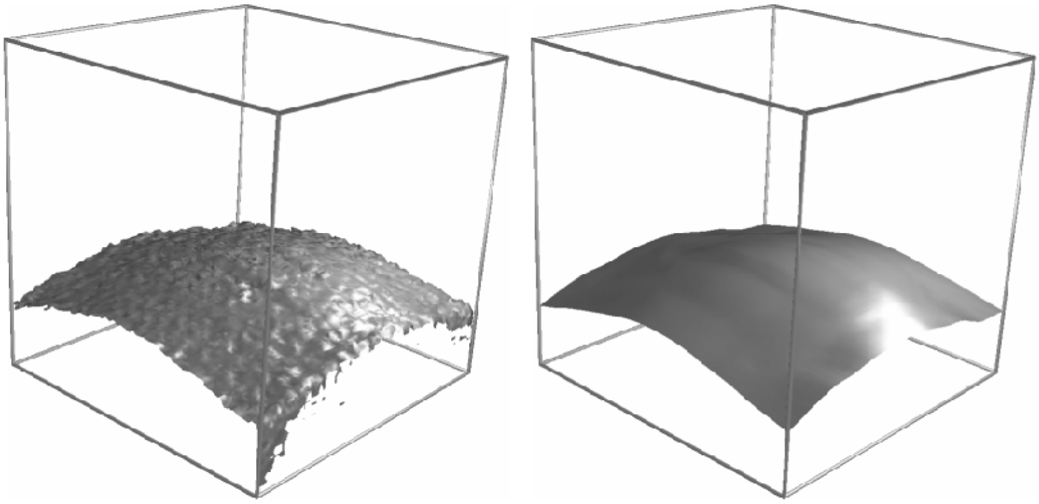

Figure 3 *Measured concentration isosurface in the second phase (left) and the same isosurface after smoothing (right) based on the theory of geometric evolution problems and non-linear diffusion equations (as presented in Preußer and Rumpf, 2000); C = 1% by weight.*

For high salt concentrations there may occur a signal loss by shielding effects caused by the electrical conductivity of the salt solution. This signal loss takes place predominantly in the inner part of the saltwater body. This was the case here for the experiments with C = 10% by weight. The shielding effect can to some extent be corrected by applying a correction matrix (Oswald et al., 2002), but this strongly depends on the specific experimental set-up and the flow behaviour.

The flow velocities are not detectable directly by the NMRI imaging. Therefore we used a marking technique to get path lines. At beginning of the third phase small quantities of fluid containing the NMR-tracer were injected at different locations with a syringe, via injection ports especially built into the container wall. Then the movement of the marked fluid volumes was visualised by NMR imaging. The tracking of particular marked volumes allows gaining insight into the flow field at that starting location (Oswald et al., 2002).

The 3D images were constituted from bunches of two-dimensional slices. During a single scan thus not all slices are recorded at exactly the same time. The saltwater movement may interfere with the measurement in slices, if flow velocities are high. This effect seems to cause concentration jumps in the images, because the saltwater effectively has moved in the time between recording the particular two adjacent slices (Figure 4).

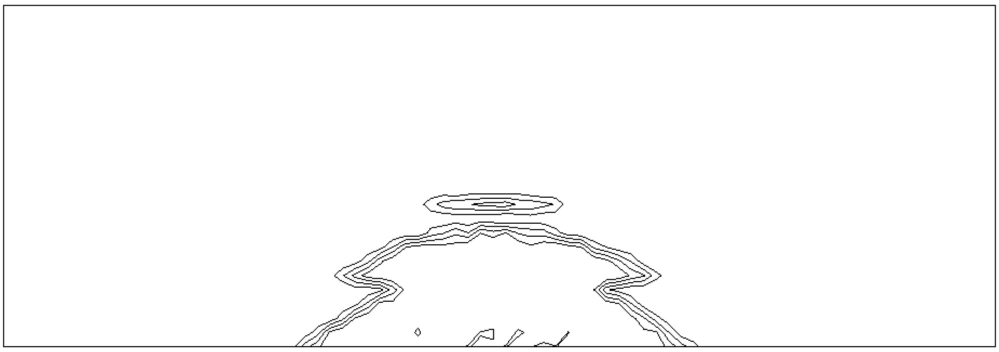

***Figure 4** Concentration isolines in a vertical cross-section at the very beginning of the experiment, when saltwater was entering the porous medium from the bottom. The NMRI data were recorded in horizontal slices, which causes artificial concentration jumps in the images because of the relatively fast vertical flow of saltwater; C = 1% by weight.*

Furthermore, signal mismatch was avoided as far as possible. For example ”local field deviations” were reduced by avoiding ferromagnetic partitions in the glass beads and by avoiding air bubbles during preparation. Image distortions along the edges were avoided by choosing a Field of View greater than the extension of the porous medium, and signal fold over was avoided by adjusting the orientations of phase encoding. Signal changes as result of local flow velocity were not observed except at the corners, very close to the recharge and discharge. At the boundary of the porous medium the signal could be reduced, either by imperfect positioning of the scanned area relative to the container walls, or by magnetic field deviations, especially at the edges of the porous medium.

Finally, NMR imaging can provide insight in to the behaviour of saltwater movement in 3D. It is well-suited for measurement of dispersive saltwater-freshwater interfaces in homogeneous media. The results can be used for comparison with numerical simulations provided the imaging effects are corrected or at least appropriately taken into consideration.

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