NMR MONITORING OF WATER SATURATION DURING GRAVITY DRAINAGE AND THE DETERMINATION OF WETTING PHASE RELATIVE PERMEABILITY

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ABSTRACT

Free fall gravity drainage experiments were conducted in 110-125 cm long columns of glass beads with 300 μm average particle size and absolute permeability of 100 Darcy. The wetting phase (water) saturation was monitored by proton NMR relaxation. NMR magnetization decay measurements using the CPMG (Carr-Purcell-Meiboom-Gill) pulse sequence were made at three fixed locations within the packed column during the free fall gravity drainage of water. As the bulk water drained with time at a selected location, the proton content decreased and the characteristic proton relaxation rate increased as water was gradually displaced from the larger pores. The NMR measurements thus permitted simultaneous determination of the water saturation $S_w(t, x)$ and the characteristic relaxation rate with time t at a fixed location x. NMR measurements at capillary equilibrium conditions were also made to determine the drainage capillary pressure curve for the glass bead packing. Numerical simulations of gravity drainage based on multiphase Darcy's law were used to test the predictive ability of two models of water relative permeability: an empirical model based on fitting of the capillary pressure data (Van Genuchten, 1980) and a model derived from percolation theory arguments and involving parameters measurable by NMR (Chen *et al*., 1994). Both models were able to reproduce the experimentally measured water saturation profiles at all three locations within the column, as well as the water production history. Two key conclusions emerge from this work. Firstly, the wetting phase relative permeability for gravity drainage in a homogeneous medium is independent of position. Secondly, the wetting phase relative permeability for gravity drainage in a homogeneous medium can be predicted from a model involving quantities measurable by NMR. The latter conclusion has potentially important implications for the estimation of wetting phase relative permeability.

INTRODUCTION

Gravity drainage in porous media is important to many industrial processes, including areas of soil physics, oil recovery and ground water hydrology. During gravity drainage it is important to know the distribution of wetting phase and the relative permeability functions of the wetting and non-wetting phase. It is not possible to observe directly and non-destructively the changes taking place in individual pores, however it is possible to make suitable measurements of wetting phase saturation by application of NMR techniques and mathematical modeling. NMR spectroscopy provides a number of exciting opportunities for determining the fluid states and properties within porous media. NMR signals from proton nuclei are related to properties of porous media such as water content and pore structure and in particular absolute permeability and relative permeability. Magnetization data obtained during the free-fall gravity drainage (FFGD) experiment at different locations in a column of glass beads using pulse NMR methodology can be used to determine the water saturation as a function of time at selected locations. The concept of saturation evolution with time at a known location enables the determination of relative permeability (Chen et al., 1994). A computer program applying two-phase flow theory was used to determine the relative permeability of water from relaxation measurements by way of history matching of production data.

The goals of this study were to explore the application of NMR technology for monitoring gravity drainage of water at different locations in a glass bead column when undergoing desaturation of water and to prove that relative permeability does not vary from location to location. Proton magnetization as a function of time and multi-exponential analysis of CPMG (Carr-Purcell-Meiboom-Gill) echo trains were carried out using a porous medium in the form of a glass bead column initially at 100% water saturation. The results obtained were used to obtain water saturation during dynamic and steady state drainage. The variation of dynamic water saturation at a specified location enabled the determination of wetting phase relative permeability during FFGD.

EXPERIMENTAL

Proton relaxation pulse NMR was used for monitoring gravity drainage of water from water saturated porous media to allow measurement of saturation profile at different locations. 110-125 cm long columns packed with 300μm particle size glass beads with an absolute permeability of 100 Darcy were used. We determined the relative permeability of the wetting phase from analysis of water saturation data as a function of position and time obtained using a Bruker DMX 500 ultrashield™ pulse NMR spectrometer.

a. Measurement of Steady-State Water Distribution with Height Using NMR

A column packed with 300 μm glass beads was drained using the free fall gravity drainage (FFGD) technique. During the course of FFGD, we measured the position of the gas front with time and the cumulative water production. At the end of the drainage experiment (after about 3 hours) the drainage of water ceased and the column is sealed at both ends to prevent evaporation. Right after, the column was transferred to the NMR facility to determine the water saturation distribution along the length of the column of glass beads. The glass column was placed in the Bruker DMX 500 ultrashield™ field of measurement for scanning. The exact location in the column coincided with the centre of the coil.. The column was scanned at different locations, namely 10cm, 25cm, 40cm 55cm, 70cm, 85cm, 87.5cm, 90cm, 92.5, 95cm and 97.5cm measured from the top of the column. The measured magnetization at each location was converted to saturation units. These data were used to obtain the capillary pressure curve. The coil was recalibrated every time the column was scanned at a new location.

b. Monitoring of the S_w (x, t) during free fall gravity drainage

A 114 cm long column of glass beads was placed inside the magnet of the NMR facility. The dynamic water saturation at designated locations was monitored. For each location there were 60 accumulations of data sets, the first 20 accumulations lasted for 3.26 minutes and the remaining 40 accumulations lasted for 2.47 hrs. For the last 40 accumulations each accumulation set has a time delay of 4 minutes (i.e., time delay of 3.15 min plus the time for 4 accumulations which is 45 sec in duration each). An empirical model is used to obtain the magnetization decay profiles. The values obtained after 40 accumulations are averaged for 4 accumulations to get one single magnetization value to evaluate the saturation of water. The temperature is controlled to within ± 1°C.

c. Modeling the Dynamic Water Saturation in Free Fall Gravity Drainage (FFGD)

The simulation of FFGD was carried out using the *CompFlow* simulator (Unger et al., 1996). The conservation equation for water is:

$$\frac{\partial}{\partial t}\left[\phi(\rho_w S_w)\right] = -\nabla(\rho_w v_w) \qquad (1)$$

where S_w is the water saturation, ρ_w and v_w are the density and velocity of water.
Darcy's law describes the flow of water during drainage from a saturated column by:

$$v_w = \frac{-kk_{rw}}{\mu_w}\frac{\partial}{\partial x}(\rho_w g x - P_c) \qquad (2)$$

where k = absolute permeability of the medium, k_{rw} = relative permeability of the wetting liquid at any specified saturation, x = direction of flow and P_c = capillary pressure.

The material balance for a constant density system is: $\frac{\partial v_w}{\partial x} = -\phi\frac{\partial S_w}{\partial t}$ (3)

Differentiating equation (2) and substituting the value of $\frac{\partial v_w}{\partial x}$ in equation (3) we obtain:

$$\frac{\partial S_w}{\partial t} = \frac{k}{\phi\mu_w}(\rho_w g - \frac{\partial P_c}{\partial x})\frac{\partial k_{rw}}{\partial x} - \frac{kk_{rw}}{\phi\mu_w}\frac{\partial^2 P_c}{\partial x^2} \qquad (4)$$

where S_w is the actual water saturation at a given location and time and S_{wr} is the residual water saturation for very large value of P_c. It is assumed S_{wr} is constant in our experiments (experimental value $S_{wr} = 0.12$).

We define a normalized saturation, S_e by: $S_e = \frac{S_w - S_{wr}}{1 - S_{wr}}$ (5)

The actual saturation of wetting phase in terms of S_e and S_{wr} is:

$$S_w = (1 - S_{wr})\, S_e + S_{wr} \qquad (6)$$

By differentiating equation (6) with respect to time we obtain:

$$\frac{\partial S_w}{\partial t} = (1 - S_{wr})\frac{\partial S_e}{\partial t} \qquad (7)$$

Substituting the value of $\frac{\partial S_w}{\partial t}$ from equation (7) into equation (4) gives:

$$\frac{k}{\phi\mu_w}(\rho_w g - \frac{\partial P_c}{\partial x})\frac{\partial k_{rw}}{\partial x} - \frac{kk_{rw}}{\phi\mu_w}\frac{\partial^2 P_c}{\partial x^2} = (1 - S_{wr})\frac{\partial S_e}{\partial t} \qquad (8)$$

The same assumptions as proposed by Pavone (1989) are used to obtain the solution of free-fall gravity drainage including capillary pressure. Equ. (8) was solved numerically using *ComFlow* subject to the initial condition: At $t = 0$, $S_e = 1 \quad 0 \le x \le 1$

The boundary conditions are: $t > 0 \quad x = L \quad P_{top} = P_{atm}$

$x = 0 \quad P_{bottom} = P_{top} - \Delta\rho g h_c$

The relative permeability was evaluated using i) the Chen et al (1994) model and ii) the Van Genuchten (1980) model. The Chen et al. relative permeability model is:

$$k_{rw} = (T_d / T_{d0})^2 S_w^{\ 2} \qquad (9)$$

where, T_d is the long time constant of diffusion and relaxation processes and T_{do} is the initial long time constant of diffusion and relaxation processes. The corresponding values of T_d, T_{do} and S_w are determined experimentally from NMR experiments. The Van Genuchten relative permeability model is: $k_r = S_e^{\frac{1}{2}}\left[1 - (1 - S_e^{\ 1/m})^m\right]^2$ (10)

where m is an empirical fitting parameter, S_{wr} is the residual water saturation and S_e is the normalized equilibrium saturation. Values of k_r obtained from these models are input to the *ComFlow* simulation program and the results of $S_w(x, t)$ were obtained (Purnakilli, 2003). The capillary pressure function P_c (S_w) is also input in the modeling.

RESULTS AND DISCUSSION

The porosity and permeability values for 3 different runs of experiments conducted in the laboratory using a 110 cm long column and subsequently used in the NMR tests were 38.3% and 100 Darcy respectively. FFGD results are shown in Fig.1 for three repeat experiments in a 110cm long glass bead column. It is evident that the same production history characteristics were obtained on repeat runs of the gravity drainage experiment.

Distribution of water saturation: Figure 2 shows very good repeatability of results for the saturation variation with capillary pressure in a 125 cm long column at the end of FFGD experiments. These data were used to obtain the capillary pressure as a function of water saturation that was used in the modeling of production history. Monitoring gravity drainage of water at different locations along the glass bead column using NMR proton relaxometry was carried out at three different locations in the packing, namely, at locations 25 cm, 40 cm and 55 cm measured from the top of the column along the fully water saturated glass bead column. The resulting magnetization data were fitted using the modified stretched exponential model (MSE). Fitting the magnetization data with the MSE model provided estimates of the initial magnetization value (M_0), initial spin relaxation time constant (T_0), the long time limit constant of diffusion and relaxation (T_d), and the MSE exponent β for each value of local saturation. The resulting magnetization decay with time, M(t) was scaled to determine saturation via the relationship: $S_{w_i}(t) = M_i(t) / M_0$, where i = 25, 40, 55cm designates the different location. Figure 3 shows the long time limit of diffusion (T_d) plotted versus drainage time for each of the three locations monitored. For a fully saturated column with water, an average T_d value at the three different locations was ~145ms. As the bulk water drains at each location, the proton magnetization decreases because the number of protons decreases. The observation that the decrease of M(t), $S_w(t)$ and T_d with time has a similar pattern indicates that T_d is a function of the bulk water saturation. Indeed, when the T_d data are plotted as shown in Figure 4, there is a very good correlation of $T_d(t)$ versus $S_w(t)$. It is inferred that $T_d(t)$ is a function of $S_w(t)$ and not a function of location in a homogeneous porous medium. The final water saturation at locations tested was observed to be between ~10% to ~12%, indicating that the selected locations were correctly chosen.

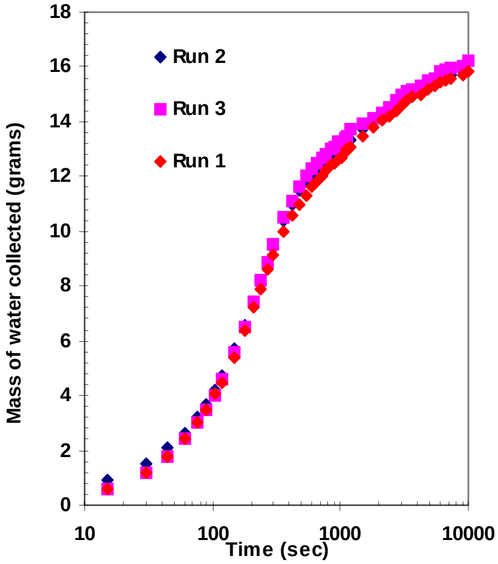

Fig. 1: Repeatability of FFGD production history in columns of 300 μm glass beads

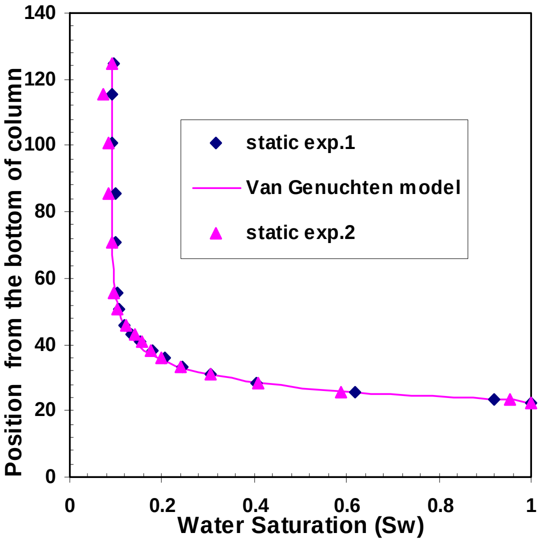

Fig. 2: Results of water saturation distribution after FFGD in a column of beads using NMR

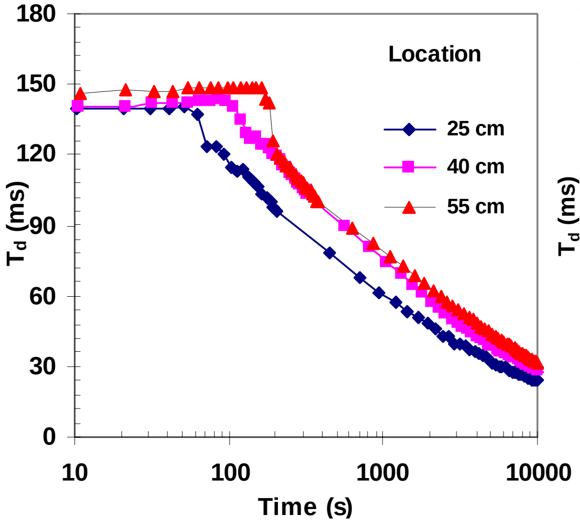

Figure 3: Variation of T_d (x, t) during FFGD

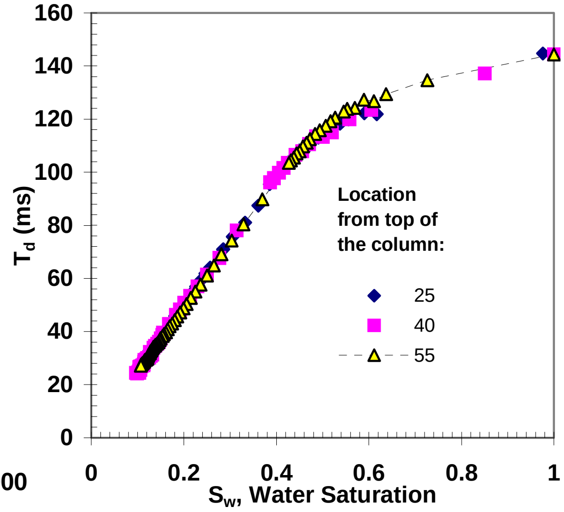

Fig. 4: Dependence of $T_d(t)$ on $S_w(t)$

Simulation of FFGD Tests: The commercial *CompFlow* simulator was used to obtain the production history characteristics and gas front position versus time. The production history obtained using the input relative permeability models of Chen et al. and the Van Genuchten model were compared with the experimental results. Figures 5 and 6 show that the water production history is predicted reasonably well using the Chen et al. relative model. A similar result was obtained with the Van Genuchten relative permeability model. Details can be found in Perunarkilli (2003). The gas front position (S_w = 90%) predicted using C*ompFlow* simulator with time was also in good agreement with experimentally measured front position versus time data during FFGD in a 3cm diameter column. The gas front position with time predicted using the Van Genuchten model trailed that predicted by the Chen et al. model and the experimental results.

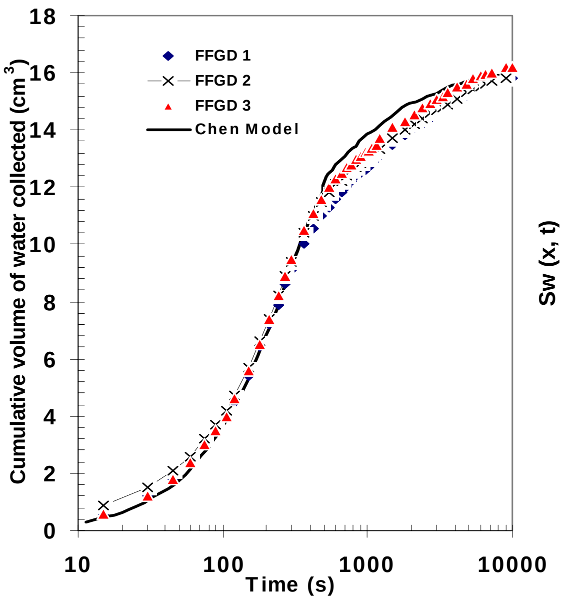

Fig. 5: Comparison of simulated production history with experimental data in FFGD

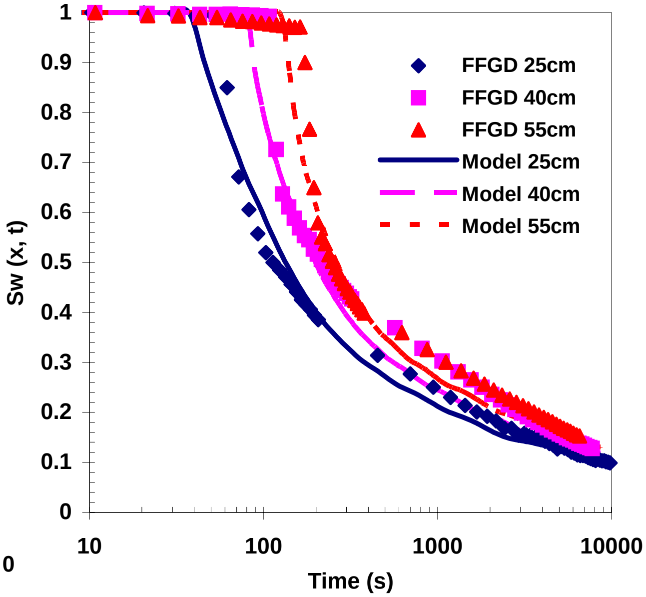

Fig. 6: Comparison of predicted dynamic saturations with experimental data in FFGD

CONCLUSIONS

1. NMR proton relaxometry can be used to monitor free fall gravity drainage of water in a porous medium and determine water saturation under dynamic and static conditions.
2. The relative permeability functions of Chen et al. (1994) and Van Genuchten (1980) led to good agreement between predicted production history and the experimental results. However, the predictions with the NMR-based Chen et al. relative permeability model were better than those from Van Genuchten's model, suggesting there is potential for NMR techniques for relative permeability determination in laboratory and field applications.

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