EXPERIMENTAL STUDY OF DYNAMIC CAPILLARY PRESSURE EFFECT IN TWO-PHASE FLOW IN POROUS MEDIA

S. BOTTERO [1], S. M. HASSANIZADEH[1], P.J. KLEINGELD[1], A. BEZUIJEN[2]

[1] *Department of Earth Sciences, Utrecht University, P.O.Box 80021, 3508 TA Utrecht, The Netherlands*

[2]*GeoDelft, Stieltjesweg 2, 2628 CK Delft, the Netherlands*

ABSTRACT

There is strong evidence in the literature that traditional equations describing two-phase flow processes in porous media may be inadequate under non-equilibrium or dynamic conditions. There exist theories that propose that the capillary pressure depends not only on saturation but also on the time rate of change of saturation. In this work, the significance of dynamic effects in the capillary pressure-saturation relationship is investigated through experiments in a homogeneous porous medium. A series of laboratory experiments were performed involving flow of two immiscible fluids, water and Tetrachloroethylene (PCE), in a homogeneous column. The experiments consist of a continuous cycle of drainage, imbibition, and drainage, where a large pressure of 20 kPa is applied to the displacing fluid. Contrary to traditional procedure, no hydrophobic or hydrophilic membranes were used in this experimental set-up. In this paper, the experimental set-up is described and preliminary results are presented. Capillary pressure and saturation curves measured under dynamic and static conditions are shown. The data are analyzed and the value of the dynamic coefficient τ is calculated.

1. INTRODUCTION

Two-phase flow processes in porous media are traditionally described by Darcy's law and mass conservation equations for both phases and by equations which relate to the properties of the medium. The capillary pressure (P^c) and saturation (S) is one of these material-dependent relationships. This is determined empirically under static conditions (Brooks and Corey (1964), van Genuchten (1980)). However, it is then employed in modeling dynamic flow processes. Evidences from the literature regarding unsaturated and saturated flow experiments (review Hassanizadeh (2002), Manthay (2006)) show that this relationship may be inadequate in case of flow condition. Both Hassanizadeh and Gray (1990) and Kalaydjian [1992] show, through thermodynamic approach, that under non-equilibrium conditions, capillary pressure may depend not only on saturation but also on the time rate of change of saturation. They defined the dynamic capillary pressure by the difference between the pressure of the non-wetting and the wetting fluids that flow inside the porous medium. According to this theory, the dynamic capillary pressure can be approximated as a linear function of the rate of change of water saturation.

$$P^c{}_{dynamic} = P^c{}_{static}(S) - \tau \frac{\partial S}{\partial t} \qquad [1]$$

where $P^c{}_{dynamic}$ is the dynamic capillary pressure, $P^c{}_{static}$ is the static capillary pressure, $\partial S/\partial t$ is the rate of change of saturation and τ is a damping coefficient. In this paper, the capillary pressure-saturation relationship under dynamic flow condition is investigated through laboratory experiments.

Traditionally, in laboratory experiments regarding saturated or unsaturated flow in porous medium the capillary pressure-saturation curves in both static and dynamic flow condition are determined in column in which the soil sample is placed between hydrophobic and hydrophilic membranes (Topp et al., (1967), Kalaydjian, (1992)). These membranes are used to obtain relatively rapidly the capillary pressure-saturation curves (or suction-water content). For example in a drainage experiment, involving two immiscible phases like DNAPL (dense non-aqueous phase liquid) and water, the hydrophilic membrane does not allow the non-wetting phase to leave the sample. So after it reaches the hydrophilic membranes it will start to accumulate on it and inside the soil. Thus, the pressure in the sample will increase, and the saturation of the non-wetting phase will approach the residual saturation. At that stage, the non-wetting phase breaks the hydraulic connection between water inside and outside the sample. It is obvious that the hydrophilic and hydrophobic membranes may significantly affect the distribution of fluids inside the soil sample. Given the fact that capillary pressure-saturation curve is supposed to be a soil property, the question arises: how far are the traditionally-measured capillary-pressure and saturation relationship affected by the presence of these membranes? Are the measured curves representative of field conditions where no such membranes exist? In this new set of experiments no membranes were used.

In the following sections, the experimental set-up and the measurement results are presented. The dumping coefficient τ is estimated.

2. MATERIAL AND METHOD

2.1 Experimental set-up.

A schematic representation of the experimental set-up is shown in Fig. 1. The set-up consists of a column of 9.8 cm in diameter and 19 cm in length which contains the sand sample. Two brass filters were placed at the top and at the bottom of the sample in order to hold the sand in place. The column was connected to a burette of 4 cm diameter and 100 cm length. At three different locations along the column, a set of two pore pressure transducers (PPTN-W1, PPTN-W2, PPTN-W3) were placed in the sand column in order to measure the water and PCE pressures. At the same elevations, three time domain reflectometry sensors (TDR) were installed in order to measure water saturation. Differential pressure gauge sensors were placed in the burette to determine the average saturation of water (or PCE) throughout all experiments. The pressure of the invading fluid was regulated imposing a high pressure on the air chamber in the burette. In order to impose a desired constant inflow pressure a pressure transducer was installed in the lower part of the column and connected to a pressure regulator at the top of the burette. In this way any change of pressure in the bottom part of column is rapidly and automatically compensated by changing the pressure in the air chamber in the burette. A system of two valves allows the flow of PCE during drainage and flow of water during imbibition, into the column. All measuring instruments were connected to a data acquisition system. All experiments were performed at 20 °C in a temperature-controlled room.

2.2 Experimental procedure.

A fine sand called Zeijen sand was used in these experiments. Prior to use, the sand was washed, dried and sieved to remove impurities. The size of the grain is quite uniform, with

D_{15}=0.06 mm and D_{60}=0.09 mm. The pore pressure transducers (PPT) were prepared for reading the pressures of the water and PCE phases. For more detailed description of the procedure see Oung O. and Bezuijen A. (2003). The sensors were first tested and calibrated. Time domain reflectrometry (TDR) sensors were used to determine water saturation. The TDR consists of four rod shaped electrodes; one central surrounded by three other, each 3 mm diameter and 60 mm in length. These sensors were calibrated (Gunzel, 2003) for this specific sand. It was found that for an output varying between 100 and 800 mV, there is a linear relationship with water content. The set-up was de-aired under the vacuum to get rid of any trapped air. Pore pressure transducer sensors (PPT) and time domain reflectrometry (TDR) were installed. The column was filled with de-air de -mineralized water. Then dry sand was placed in the column by continuously pouring and tapping. In the top part of the sand a brass filter was placed. The column was closed with a steel cap where one opening ensured a constant atmospheric pressure at the top of the sand column. The diameter of the opening was small such that evaporation of air and volatilization of PCE was negligible. To visualize the movement of PCE front inside the column sand, it was colored with a Red Sudan dye (1.3 mg/l).

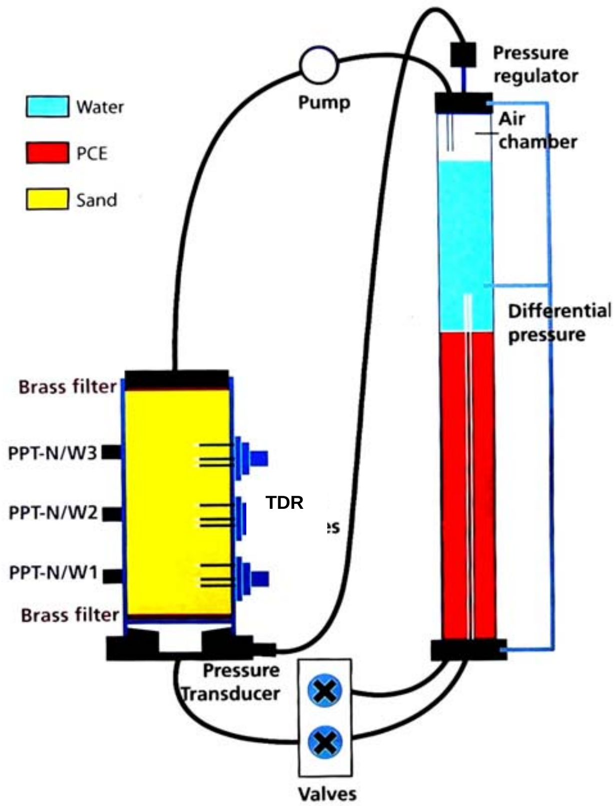

FIGURE 1. Schematic representation of the experimental set-up.

2.3 Drainage experiment

Initially the sand was fully water saturated. The burette was filled with one liter and half of PCE. Then, the pressure of the air chamber above PCE was increased in order to establish a large pressure of 20 kPa at the bottom of the column. As the pressure of PCE was much higher than its entry pressure, PCE flowed vertically upward in the sand displacing the water. The PCE was injected from the bottom in order to avoid any gravity-driven flow instability. The water and the PCE that flowed freely out of the column were pumped back into the burette where water and PCE were separated due to density difference and PCE was re-circulated in the sand column. The drainage experiment ran for 15 hours. After primary drainage experiment, imbibition and main drainage experiments are performed applying the same constant pressure of 20 kPa. The total duration of these series of experiment were three days.

3. RESULT AND DISCUSSION

Saturations at three different locations in the column are plotted as a function of time in Fig.2. These results are used to calculate $\partial S/\partial t$ as a function of time (shown in Fig. 3). As previously mentioned, throughout drainage processes, PCE is injected from the bottom of the column upward displacing water. Therefore, a higher PCE saturation and lower water saturation is expected. Contrary to this expectation, the measured saturations in Fig. 2 show that five minutes after the beginning of the primary drainage experiments the saturation of water in the first measurement point (Sw1) is larger than the water saturation at the other two elevations (Sw2, Sw3). The reason for this trend is not well understood. The cause can be attributed to various issues, for example micro-scale heterogeneity in sand packing, or presence of air in the sand voids. In case of no homogeneity of the sand, when a large pressure is applied the DNAPL will briefly occupy the largest voids trapping water in the smallest one. This effect may be more pronounced for a larger applied pressure and thus for quick rate of change of saturation. Fig. 3 shows that the change of water saturation is larger at location 1 compared to the other two at higher elevations. A certain amount of gas was noticed in the sample after circa six hours from the beginning of the experiment. However, the presence of small amount of air from the beginning of the experiment is not excluded. Presence of air will result in a three phase flow situation and unexpected results.

The capillary pressure is determined by subtracting water pressure from the PCE pressure. Due to malfunctioning of the DNAPL transducer at location 3 the capillary pressure at that elevation is not considered. Fig. 4 shows the dynamic capillary pressure-saturation curves throughout primary drainage, imbibition and main drainage at two elevations. In primary drainage, for a decrease in water saturation the capillary pressure increases monotonously. For large value of water saturation the capillary pressure determined in position two is larger than the one at the first location. From Sw= 0.55 approaching the residual saturation the two curves cross each other. The same trend is noticed in the main drainage and in the imbibition curves when they approach the DNAPL residual saturation.

The static capillary pressure-saturation curves are measured for the same fine sand separately in a previous experiment (Oung O. and Bezuijen A., 2003). We must point on that in those experiments they used hydrophobic and hydrophilic membranes. As said earlier, the effect of the membranes on measurements results should yet be investigated. The Pc-S curve determined under static and dynamic conditions are then compared (Fig. 4). The static and dynamic curves show significantly different residual saturations. This can be due to the presence of the membranes in the static experiments. Obviously, this needs to be verified and the static curves for the same type of sand need to be re-measured without use of membranes in the set-up. In both drainage curves, the dynamic capillary pressure is larger than the static one. In imbibition curve, the dynamic capillary pressure is generally smaller than static one. These are in agreement with the non-equilibrium equation [1].

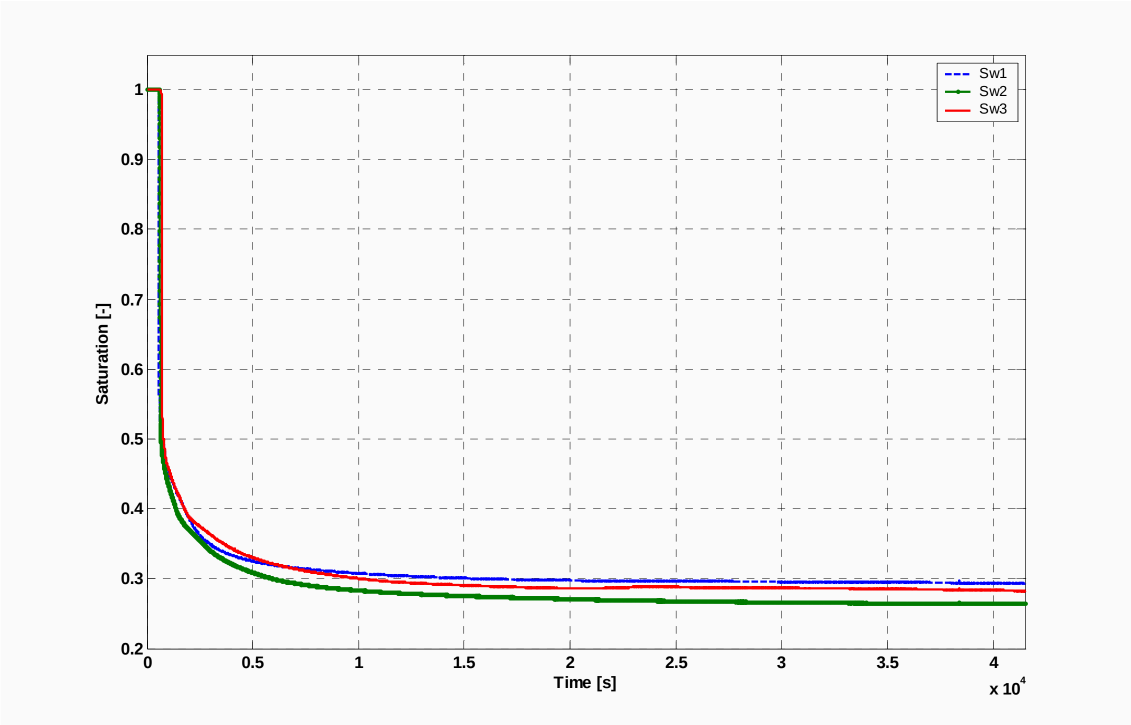

FIGURE 2 . Water saturation versus time at three locations along the sand column.

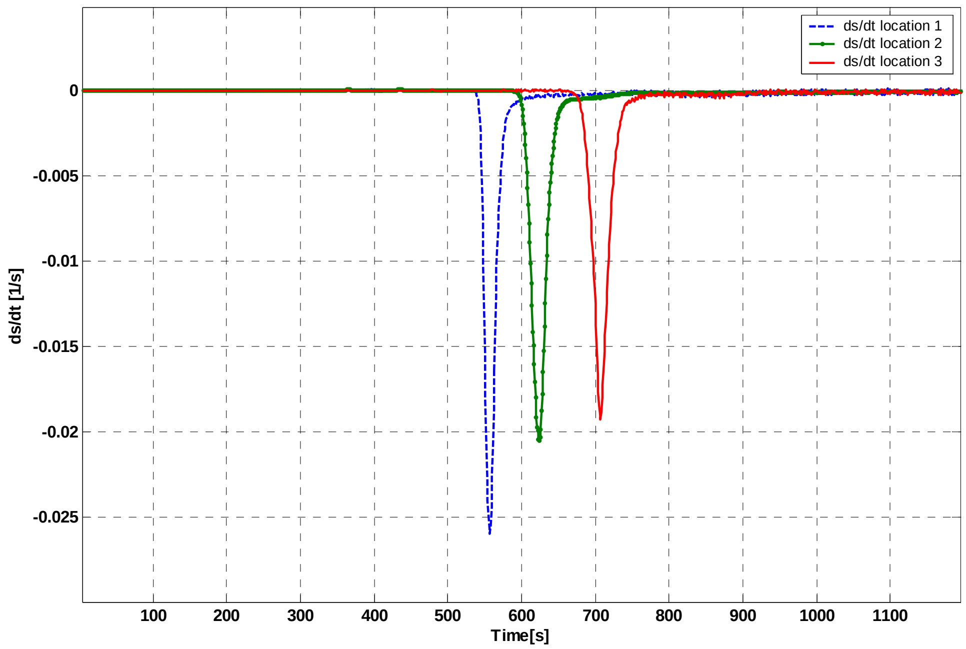

FIGURE 3. Rate of change of water saturation versus time.

The value of the damping coefficient τ was determined from the differences in dynamic and static primary drainage and the rate of change of saturation ($\partial S/\partial t$). This computation was performed for results from location 1 for the water saturation range 0.8 to 0.4. The results are plotted in Fig. 5. The general trend is that τ increases with the decrease of saturation.

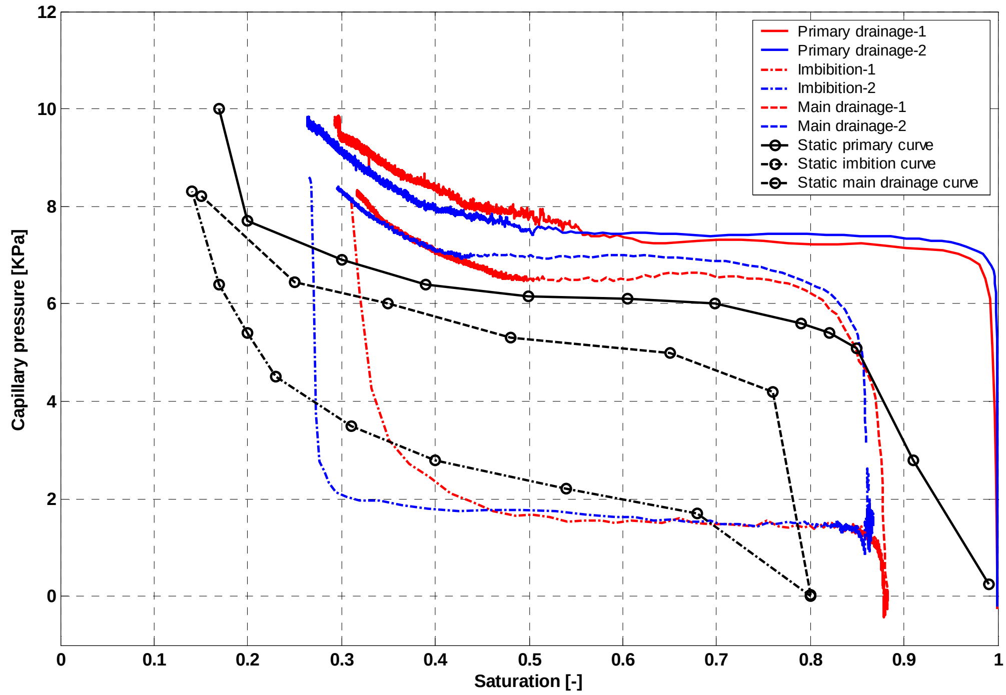

FIGURE 4. Dynamic capillary pressure-saturation curves versus water saturation throughout primary, main drainage and imbibiton experiments at applied pressure of 20 kPa.

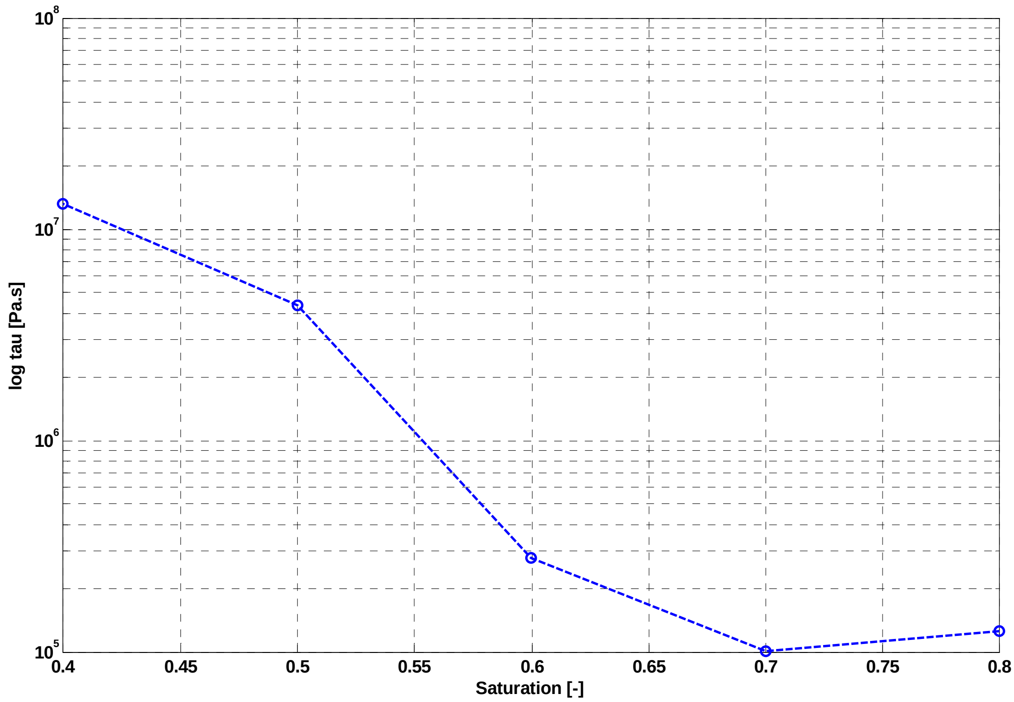

FIGURE 5. Dynamic coefficient τ as a function of water saturation.

4. SUMMARY AND CONCLUSIONS

A series of laboratory experiments was performed in order to study the non-equilibrium effect in the capillary pressure-saturation curve. The pressures and saturations of the two immiscible phases were measured inside the sand column at three elevations. Contrary to traditional experimental procedure, in this new set-up no hydrophobic and hydrophilic membranes were employed. The presence of such membranes may influence the Pc-S curve when it approaches the residual saturation. More experiments are needed to verify any eventual effect. The dynamic coefficient τ was estimated at different water saturations. A dependence of this coefficient on water saturation was found.

REFERENCES

Brooks, R.H. and Corey A.T. (1964) Hydraulic properties of porous media. *Hydrol.*Pap. 3, Colo. State Univ., Fort Collins.

Gunzel F.K., Craig W.H., Crancon P., Cottineau L.M., Kechavarzi C., Lynch R.J. Merrifield C.M., Oung O., Schenkeveld F.M., Soga K., Thorel L., and Weststrate F.A.(2003) Evaluation of probes and techniques for water content monitoring in geotechnical centrifuge models. *International Journal of Physical Modeling in Geotechnics,* 1, 31-43.

Hazanissadeh S.M., Celia M.A., Dahle H.K. (2002) Dynamic effect in capillary pressure-saturation relationship and its impact on unsaturated flow, *Vadose Zone J.*, 38-57.

Hazanissadeh S. M. and Gray W.G. (1993). Thermodynamic basis of capillary pressure in porous media. *Water Resources Research*, 29(19): 3389-3405.

Hazanissadeh S.M. and Gray W.G. (1990) . Mechanics and thermodynamics of multiphase flow in porous media including interphase boundaries. *Adv.Water Resour.*,13, 169-186.

Oung O., Hassanizadeh S.M., A. Bezuijen (2005) Two-phase flow experiments in a geocentrifuge and the significance of dynamic capillary pressure. *Journal of Porous Media* 8(3), 247-257.

Oung O. and Bezuijen A.(2003). Selective pore pressure transducers for use in model tests to study two-phase flow in porous media. *IJPMG-International Journal of Physical Modeling in Geotechnics*, 4, 31-43.

Kalaydjian F. (1992) Dynamic capillary pressure curve for water/oil displacement in porous media: Theory vs. experiment, paper presented at the 67th annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Washington, D.C., 4-7 Oct.

Manthey S. (2006) Two-phase flow processes with dynamic effect in porous media- parameter estimation and simulation. PhD thesis.

Manthey S., Hassanizadeh S.M., Helming R. (2005) macro-scale dynamic effects in homogeneous and heterogeneous porous media. *Trans. Porous Media*, 58, 121-145.

Manthey S., Hazanissadeh S.M. Oung O., and Helmig R. (2004) Dynamic capillary pressure effects in two-phase flow trough heterogeneous porous media. Paper presented at the XV International Conference on Computational methods in Water Resources, Univ. of N.C., Chapel Hill, 13-17 June.

Topp G.C., Klute A., Peters D.B. (1967) Comparison of water content-pressure head data obtained by equilibrium steady-state and unsteady state methods, *Soil Sci. Soc. Am. Proc.*, 31, 312-314.

Van Genuchten M.T. (1980) Closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J.*, 44, 892-898.