Extracting Pore Throat Size and Relative Permeability from MRI-based Capillary Pressure Curves

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1. Introduction

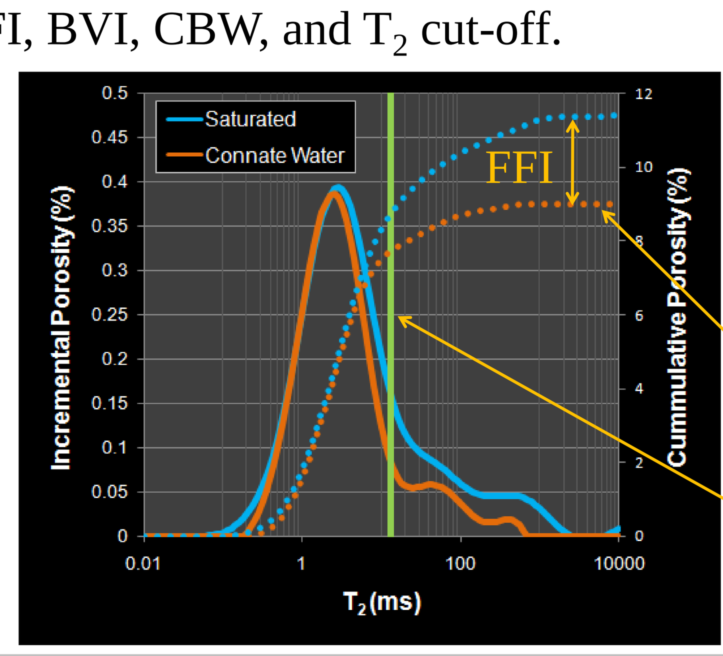
- The pore throat size and its distribution is important in many fluid transport processes in porous media (like reservoir rock)[1]. The pore throat size affects the fluid saturation distribution, porosity, permeability and, to some extent, wettability.
- Capillary pressure curves acquired using an MRI-based technique called GIT-CAP can be used to determine pore throat size distributions by calculating the saturation change at each pressure and converting the pressure into a pore throat size.
- Relative permeability is the ratio of the permeability of one fluid with a second fluid present compared to having no second fluid present.
- Relative permeability can be modeled from capillary pressure curves.

2. T_2 NMR Pore Size Distribution

- The T_2 NMR relaxation parameter is related to the surface, S, to volume, V, Ratio by the following equation:

$$\frac{1}{T_2} = \frac{1}{T_{2\text{-}Bulk}} + \rho\frac{S}{V} + (\gamma G T_E)^2 \frac{D_O}{12}$$

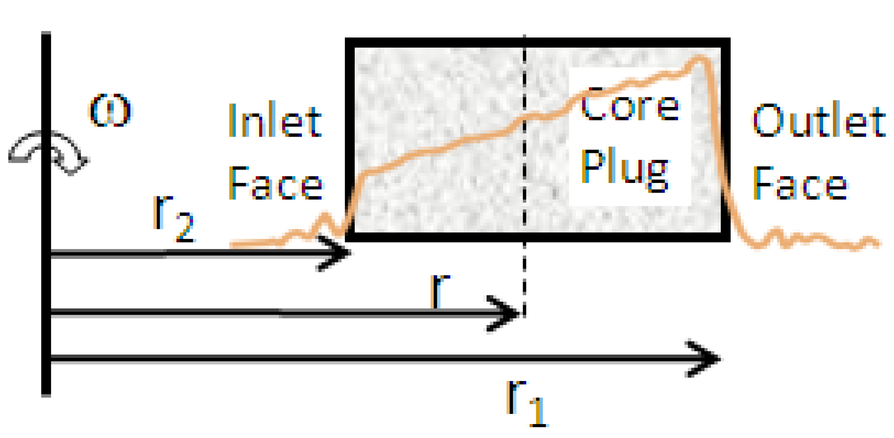
- Laboratory measurements of T_2 with the rock fully saturated and again at the connate saturation can be used to compute the FFI, BVI, CBW, and T_2 cut-off.



Sandstone
Porosity = 11.4%
Perm. = 0.22mD

3. MRI-based Capillary Pressure Curves (GIT-CAP)

- MRI-based capillary pressure measurements are acquired by using a centrifuge to create a distribution of pressures and saturations inside the rock and then using MRI to determine the saturation profile [3, 4].
- The capillary pressure, Pc, can be calculated at any position, r, along the rock using the Hassler-Brunner equation:



$$P_c(r) = \frac{1}{2}\Delta\rho\omega^2(r_1^2 - r^2)$$

4. Pore Throat from Pc

- The pore throat distribution can be plotted by converting the capillary pressure, Pc, into radius, r, using the Washburn equation, and plotting that against the incremental change in water saturation at that pressure.
- The capillary pressure can be related to radius by the Washburn equation [5]

$$r = \frac{2\sigma\cos(\theta)}{Pc}$$

- This pore throat distribution can then be compared to the T_2 pore size distribution to derive the NMR relaxivity parameter, ρ.
- Assuming a cylindrical geometry, ignoring the bulk and diffusion terms in the T_2 equation, the relationship reduces to:

$$\frac{1}{T_2} = \rho\frac{2}{r}$$

5.1 Relative Permeability from Pc

- Relative permeability can be calculated from capillary pressure using a number of existing techniques including the Burdine model [6].
- The wetting K_{rw} and non-wetting, k_{rnw}, relative permeability are:

$$k_{rw} = (\lambda_{rw})^2 \frac{\int_{S=0}^{S=Sw} \frac{dS}{P_c^2}}{\int_{S=0}^{S=1} \frac{dS}{P_c^2}} \qquad \lambda_{rw} = \frac{\tau_w(1.0)}{\tau_w(S_w)} = \frac{S_w - S_m}{1 - S_m}$$

$$k_{nrw} = (\lambda_{rnw})^2 \frac{\int_{S=Sw}^{S=1} \frac{dS}{P_c^2}}{\int_{S=0}^{S=1} \frac{dS}{P_c^2}} \qquad \lambda_{rnw} = \frac{\tau_{nw}(1.0)}{\tau_{nw}(S_w)} = \frac{1 - S_w - S_e}{1 - S_m - S_e}$$

5.2 Relative Permeability from Pc

- The capillary pressure data can be modeled and the conversion to relative permeability can be applied directly using the modeled constants.
- Below is a Brooks-Corey capillary pressure model equation.

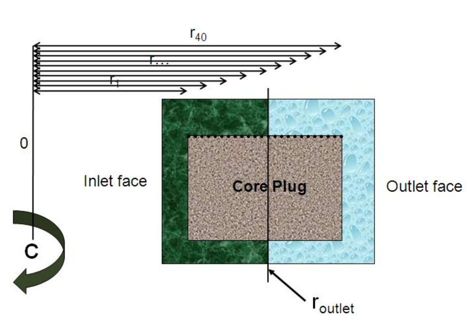
$$P_C = p_e (S_W^*)^{-\frac{1}{\lambda}} \quad \text{where} \quad S_w^* = \frac{S_w - S_{wr}}{1 - S_{wr}}$$

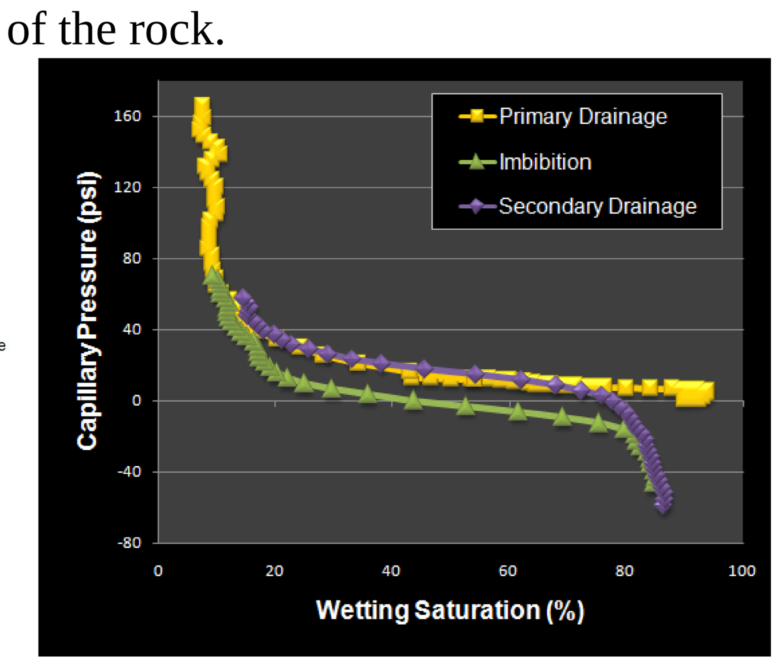
- Applying the Purcell model directly to the Brooks-Corey Pc model yields:

$$k_{rw} = (S_W^*)^{\frac{2+3\lambda}{\lambda}} \qquad k_{nrw} = (1 - S_W^*)^2\left[1 - (S_W^*)^{\frac{2+\lambda}{\lambda}}\right]$$

6. Imbibition and Drainage Pc

- Oil/Brine imbibition and drainage (1st and 2nd) can be acquired using the MRI-based technique [4].
- A unique quality of MRI-based Pc is that both positive and negative pressures can be measured by moving the oil/brine contact to the middle of the rock.

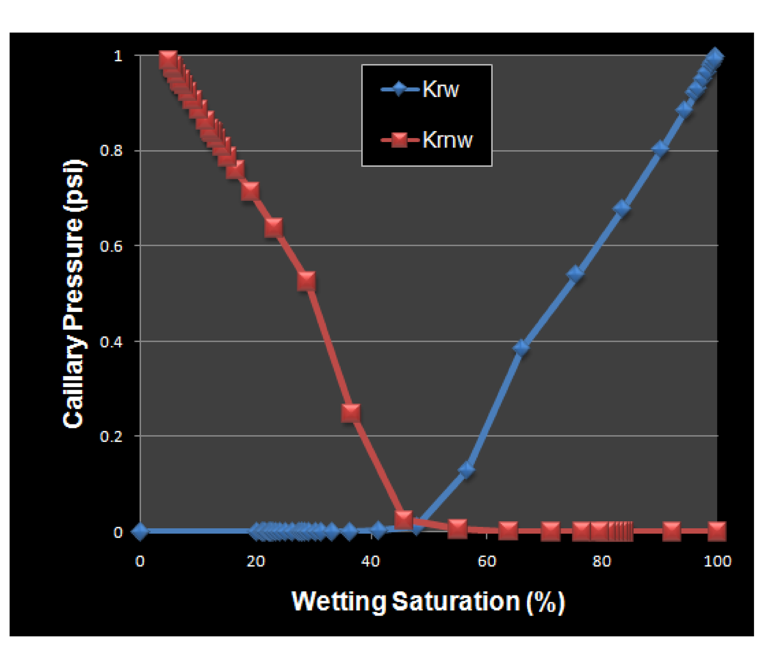




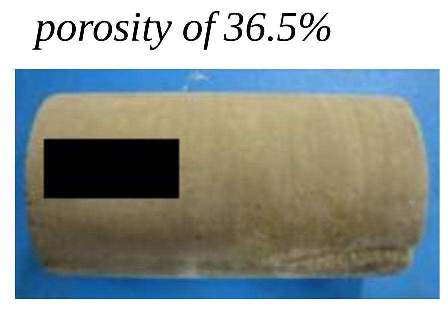
Graphed results show kerosene/brine capillary pressure on 1-½" diameter chalk sample, porosity 36.5%

7. Results (Relative Permeability from Pc)

- The relative permeability model can be directly applied to the Pc data.
- The difficulty lies in selecting the correct irreducible or residual saturation value, S_{wr}.

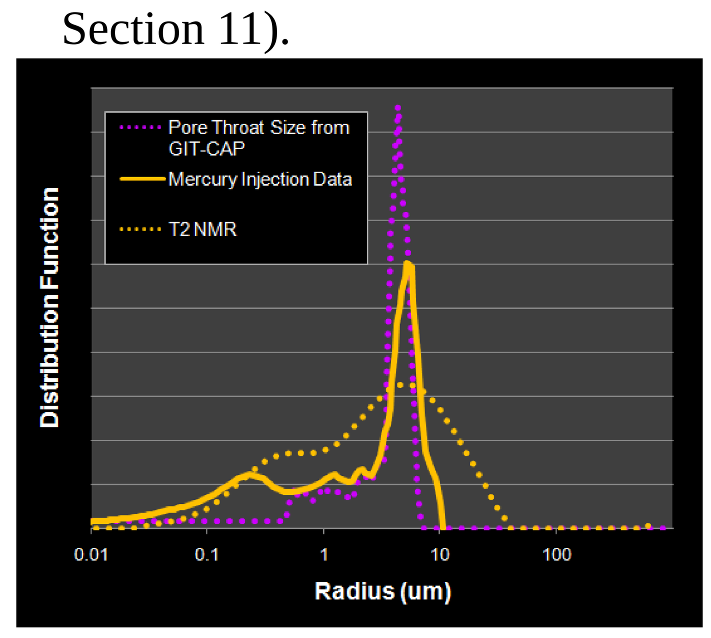


Relative permeability from the oil/brine imbibition Pc data shown in Section 6. Chalk sample porosity of 36.5%



8. Pore Size/Throat Comparisons

- The graph below shows an overlay of the pore size distribution from the T_2 NMR data; mercury injection pore throat size; and the pore throat size derived from the MRI-based Pc.
- The T_2 NMR data was scaled using a relaxivity value of 6.24 um/s (additional results are shown in the table in Section 11).

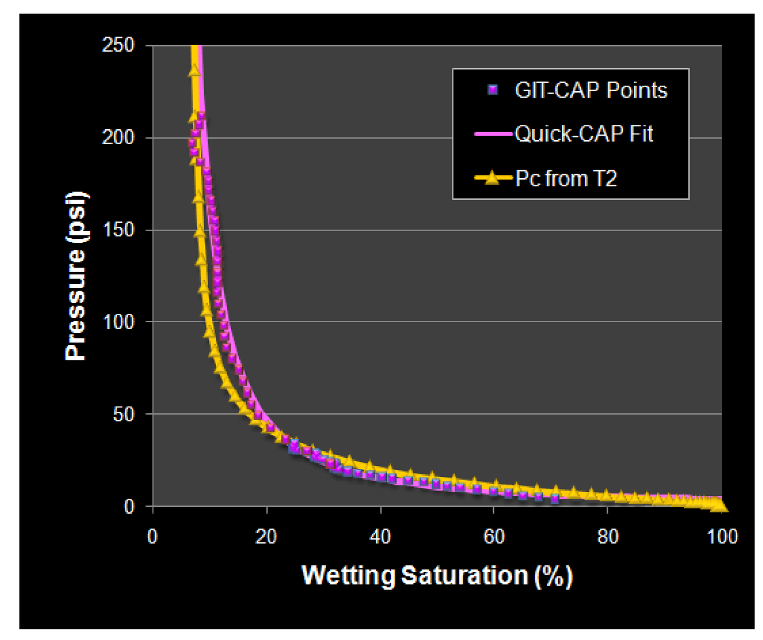


1 ½" Sandstone plug
Porosity = 22.5%
Permeability = 158mD

NOTE: Pore size is related to pore throat size but they are not equal.

9. Capillary Pressure Comparisons

- Once the relaxivity value is known, the T_2 NMR pore size distribution can be used to model a Pc curve (similar to mercury injection).
- Below is a comparison of the MRI-based Pc measurement; a Brooks-Corey fit of the MRI-based data; and the T_2 NMR derived Pc curve.



1 ½" Carbonate plug
Porosity = 18.9%

11. Conclusions

- The pore throat size acquired from GIT-CAP is non-destructive and uses reservoir fluids so there is no impact on the clays, pore matrix or wettability.
- Determination of the NMR relaxivity value allows for the T_2 pore size distribution to be quantified and capillary pressure can be modeled.
- Relative permeability can be modeled directly from the Pc data or from the model applied to the Pc data.
- Standard T_2 cut-off values are not valid in tight rocks.

Table of rock results

Sample	Permeability	Porosity	Lithology	Relaxivity
1	29.3 mD	23.9 %	Sandstone	8.71 um/s
2	158 mD	25.5 %	Sandstone	6.24 um/s
3	1.36 mD	17.4 %	Sandstone	9.21 um/s
4	Unknown	18.9 %	Carbonate	5.47 um/s
5	0.002 mD	7.25 %	Sandstone	2.66 um/s
6	Unknown	36.5 %	Carbonate (chalk)	1.65 um/s

12. References

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4. Green, D.P., Dick, J,R., McAloon, M., Cano-Barrita, P.F. de J., Burger, J. and Balcom, B.J., "Oil/Water imbibitions and Drainage Capillary Pressure Determined by MRI on a Wide Sampling of Rocks", SCA Annual Conference, SCA2008-16, Abu Dhabi, UAE, 2008
5. Kleinberg, R.L., Utility of NMR T_2 Distributions, connection with Capillary pressure, Clay Effect and Determination of the Surface Relaxivity Parameter, Magnetic Resonance Imaging, 14, 761-767 (1996)
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