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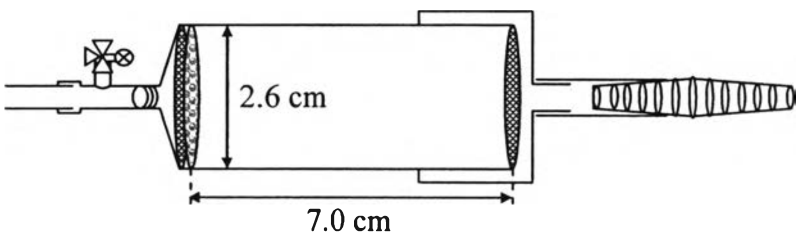
APPENDICES

Appendix A Sand-pack Calculations for Sand pack Without Channel

A.1 Pore Volume and Porosity Calculations

Without channel



Volume of sample can be divided into three parts i.e. Sand-pack body, Inlet part and Outlet part.

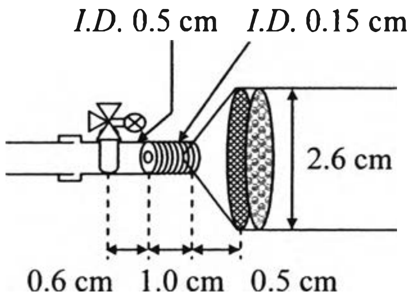
Sand-pack body:

Inside Diameter 2.6 cm, Length 7 cm

Volume = $\frac{\pi}{4} \cdot I.D.^2 \cdot L$ where $I.D.$ = Inside Diameter, L = Length

$$= \frac{\pi}{4} \cdot 2.6^2 \cdot 7.0 = 37.1650 \text{ cm}^3$$

Inlet part:



Inlet part can be separated into three parts

1. Valve: Inside Diameter 0.5 cm, Length 0.6 cm

$$\text{Volume} = \frac{\pi}{4}\cdot I.D.^2 \cdot L \quad \text{where } I.D. = \text{Inside Diameter, } L = \text{Length}$$

$$= \frac{\pi}{4}\cdot 0.5^2 \cdot 0.6 = 0.1178\ \text{cm}^3$$

2. Connection: Inside Diameter 0.15 cm, Length 1 cm

$$\text{Volume} = \frac{\pi}{4}\cdot I.D.^2 \cdot L \quad \text{where } I.D. = \text{Inside Diameter, } L = \text{Length}$$

$$= \frac{\pi}{4}\cdot 0.15^2 \cdot 1.0 = 0.0177\ \text{cm}^3$$

3. Cone shape: Big cone, Inside Diameter 2.6 cm, Length 0.7647 cm
   Small cone in connection,
   Inside Diameter 0.9 cm, Length 0.2647 cm

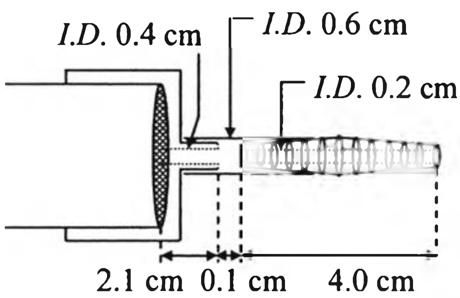
$$\text{Volume} = \left[\frac{\pi}{3}\cdot\left(\frac{I.D.}{2}\right)^2 \cdot L\right]_{big\ cone} - \left[\frac{\pi}{3}\cdot\left(\frac{I.D.}{2}\right)^2 \cdot L\right]_{small\ cone\ in\ connection}$$

where $I.D.$ = Inside Diameter, L = Length

$$= \left[\frac{\pi}{3}\cdot\left(\frac{2.6}{2}\right)^2 \cdot 0.7647\right] - \left[\frac{\pi}{3}\cdot\left(\frac{0.9}{2}\right)^2 \cdot 0.2647\right] = 1.2972\ \text{cm}^3$$

Total Volume in Inlet part: 0.1178 + 0.0177 + 1.2972 = 1.4327 cm^3

Outlet part:



Outlet part can be separated into three parts

1. Cap: Inside Diameter 0.4 cm, Length 2.1 cm

$$\text{Volume} = \frac{\pi}{4}\cdot I.D.^2 \cdot L \quad \text{where } I.D. = \text{Inside Diameter, } L = \text{Length}$$

$$= \frac{\pi}{4}\cdot 0.4^2 \cdot 2.1 = 0.2639\ \text{cm}^3$$

2. Connection: Inside Diameter 0.6 cm, Length 0.1 cm

   Volume = $\frac{\pi}{4} \cdot I.D.^2 \cdot L$ where $I.D.$ = Inside Diameter, L = Length

   $= \frac{\pi}{4} \cdot 0.6^2 \cdot 0.1 = 0.0283 \text{ cm}^3$

3. Outlet end: Inside Diameter 0.2 cm, Length 4.0 cm

   Volume = $\frac{\pi}{4} \cdot I.D.^2 \cdot L$ where $I.D.$ = Inside Diameter, L = Length

   $= \frac{\pi}{4} \cdot 0.2^2 \cdot 4.0 = 0.1257 \text{ cm}^3$

Total Volume in Outlet part: 0.2639 + 0.0283 + 0.1257 = 0.4178 cm^3

<u>Porosity Determination by Liquid Saturating Method</u>

1. Weight of sample container, $W_{container}$ = 31.02 g.
2. Weight of dry sand sample, W_{dry} = 68.48 g.
3. Weigh the saturated sample, W_{sat} = 113.97 g.
4. Calculate the saturated distilled water weight,

   $W_{water} = W_{sat} - W_{dry} - W_{container}$

   $= 113.97 - 68.48 - 31.02 = 14.47$ g.
5. Calculate the total volume of water displaced in whole sample,

   $V_{water} = W_{water} / \rho_{water}$ where $\rho_{water} = 1.0 \text{ g/ cm}^3$

   $= 14.47/1.0 = 14.47 \text{ cm}^3$.
6. Calculate the pore volume by subtracted the volume of water in inlet part and outlet part,

   $V_p = V_{water} - V_{Inlet} - V_{Outlet}$

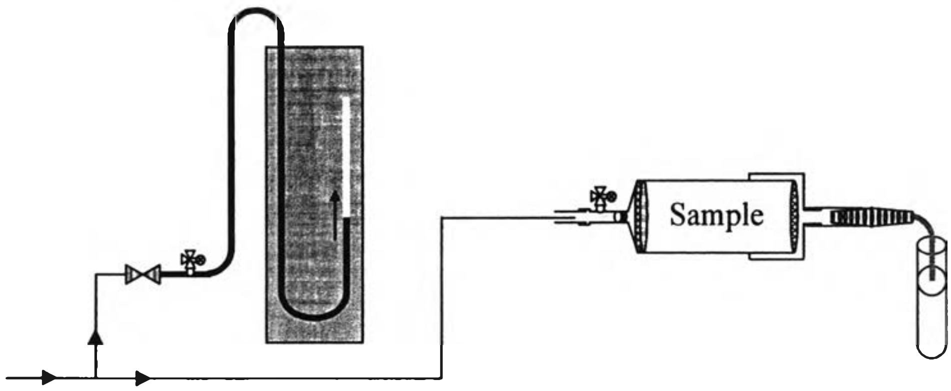
   $= 14.47 - 1.4327 - 0.4178 = 12.62 \text{ cm}^3$.
7. Calculate the porosity,

   $\phi = V_p/V_b$ where V_b = Volume in sand-pack body = 37.1650 cm^3

   $= 12.62/37.1650$

   $= 0.3395 = 33.95\%$

A.2 Permeability Calculations



Sand-pack body:

Inside Diameter 2.6 cm, Length 7 cm

Cross-sectional area, $A = \frac{\pi}{4} \cdot I.D.^2$ where $I.D.$ = Inside Diameter

$$= \frac{\pi}{4} \cdot 2.6^2 = 5.3093 \text{ cm}^2$$

Absolute Permeability Measurement of Water

1. Record the water level difference in manometer under and operational flow rate measured by volume of water produced from the system in a period of time.

Experiment #	**1**	**2**	**3**	**4**	**5**
Volume of water produced, V_w (cm^3)	8	8	8	8	8
Period of time, ΔT (sec)	344	441	588	1022	2727
Water level difference in manometer, h (cm)	3.4	2.9	2.3	1.5	0.8

2. Calculate the operational flow rate in cm^3/sec and pressure drop in atm.

For Example: Experiment # 1

2.1 Operational flow rate in cm^3/sec.

$$\text{Flow rate} = \frac{Volume\ of\ water\ produced,\ V_w\ (cm^3)}{Period\ of\ time,\ \Delta T\ (\text{sec})}$$

$$= \frac{8}{344} = 0.0233 \text{ cm}^3/\text{sec}$$

2.2 Pressure drop in atm.

Level of water in manometer, h = 3.4 cm = 0.034 m

Pressure drop = $\rho g h$, when ρ (density of water) = 1000 kg/m^3

g (gravity force) = 9.81 m/s^2

$$= 1000 \cdot 9.81 \cdot 0.034$$

$$= 333.54 \text{ Pa} \cdot \frac{1\, atm}{101325\, Pa} = 0.0033 \text{ atm}$$

Experiment #	1	2	3	4	5
Flow rate, Q_w (cm^3/sec)	0.0233	0.0181	0.0136	0.0078	0.0029
Pressure drop, ΔP (atm)	0.0033	0.0028	0.0022	0.0015	0.0008

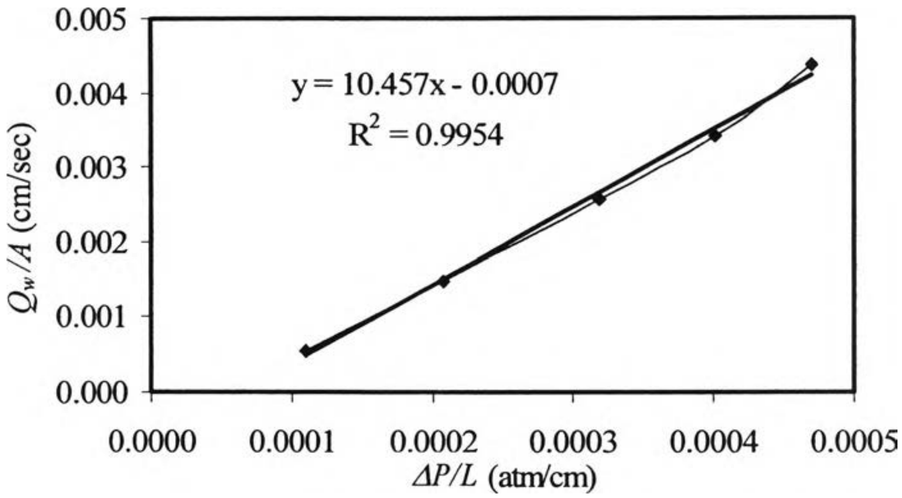
3. From Darcy's Law, the equation can be rewritten as followed,

$$\frac{Q_w}{A} = \frac{K}{\mu}\frac{\Delta P}{L}$$

where Q_w is the flow rate, in cm^3/sec, A is the cross-sectional area = 5.3093 cm^2, K is the permeability, in Darcys, μ is the water viscosity = 1 cP, ΔP is the pressure drop, in atm, L is the length = 7 cm.

Therefore, a plot of $\Delta P/L$ and Q_w/A give a slope of K/μ.

Experiment #	1	2	3	4	5
$\Delta P/L$ (atm/cm)	0.0005	0.0004	0.0003	0.0002	0.0001
Q_w/A (cm/sec)	0.0044	0.0034	0.0026	0.0015	0.0006



4. Calculate K from slope,

   Slope = K/μ , when Slope = 10.457 cm^2/atm·sec and μ = 1cP

   $\therefore K$ = Slope·μ = 10.457 cm^2/atm · sec · 1 cP

   = 10.457 Darcys = 10,457 mD ~ 10,460 mD

A.3 Fluid Saturations in Sample

Based on the Frontal Advanced Rate (FAR) of 2 ft/day, the flow rate used in the experiment was calculated into cm^3/min by

Flow rate = $A \cdot FAR \cdot \phi$ when A is the cross-sectional area = 5.3093 cm^2

FAR is Frontal Advanced Rate = 2 ft/day

ϕ is porosity = 0.3395

$$\text{Flow rate} = 5.3093\ \text{cm}^2 \cdot 2\ \text{ft/day} \cdot \frac{30.48\ cm}{1\ ft} \cdot \frac{1\ day}{24\ hr} \cdot \frac{1\ hr}{60\ \text{min}} \cdot 0.3395$$

= 0.0763 cm^3/min

In order to saturate the sample 1 PV, the approximately total time was

$$\text{Total time for 1 PV} = \frac{Pore\ volume\ ,V_p}{Flow\ rate}$$

$$= \frac{12.62\ cm^3}{0.0763\ cm^3/\text{min}} \cdot \frac{1\ hr}{60\ \text{min}}$$

= 2.76 hr

The sample was saturated first with water and then oil under this flow rate. To correct end effect, high flow rate of oil was used in the last step. The total water removed after saturated with oil was measured in order to calculate the initial oil saturation and the irreversible water saturation in the sample. Initial oil saturation in the sand-pack body was calculated from the total water removed subtracted by water in the inlet part (1.4327 cm^3) and the outlet part (0.4178 cm^3).

Total water removed = 13.30 cm^3

Initial oil saturation in the sand-pack body = 13.30 – 1.4327 – 0.4178

= 11.45 cm^3

Irreversible water saturation in the sand-pack body was calculated from the pore volume, V_p (12.62 cm^3) subtracted by initial oil saturation in the sand-pack body (11.45 cm^3).

Irreversible water saturation in the sand-pack body = 12.62 – 11.45 = 1.17 cm^3

From the above calculations, the percentages of initial oil saturation and irreversible water saturation in the sand-pack body were calculated by

$$\text{Initial oil saturation} = \frac{11.45}{12.62} \cdot 100 = 90.73\%$$

$$\text{Irreversible water saturation} = \frac{1.17}{12.62} \cdot 100 = 9.27\%$$

Aftėr flooding process, waterflooding was proceeded in this sample, the amount of oil recovery was recorded to calculate residual oil saturation and oil recovery. Oil recovery from sand-pack body was calculated from the total oil recovery subtracted by oil in the inlet part (1.4327 cm^3) and the outlet part (0.4178 cm^3).

Total oil recovery after waterflooding = 10.50 cm^3

Oil recovery from sand-pack body = 10.50 – 1.4327 – 0.4178 = 8.65 cm^3

Residual oil saturation in the sand-pack body = 11.45 – 8.65 = 2.8 cm^3

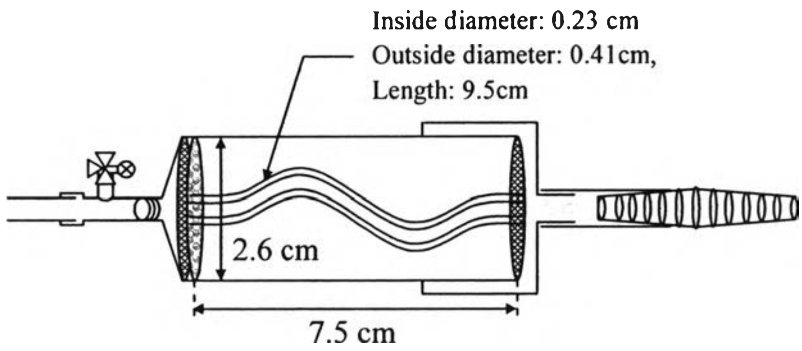
$$\text{Percentage of oil recovery} = \frac{8.65}{11.45} \cdot 100 = 75.55\%$$

$$\text{Percentage of residual oil saturation} = \frac{2.8}{11.45} \cdot 100 = 24.45\%$$

Appendix B Sand-pack Calculations for Channel sample # 1

B.1 Pore Volume and Porosity Calculations

Channel sample # 1



Channel volume:

Inside Diameter 0.23 cm, Length 9.5 cm

Volume = $\frac{\pi}{4} \cdot I.D.^2 \cdot L$ where $I.D.$ = Inside Diameter, L = Length

$= \frac{\pi}{4} \cdot 0.23^2 \cdot 9.5 = 0.395 \text{ cm}^3$

Sand-pack body:

Volume = $\frac{\pi}{4} \cdot I.D._{syringe}^2 \cdot L_{syringe} - \frac{\pi}{4} \cdot O.D._{channel}^2 \cdot L_{channel}$

where $I.D.$ = Inside Diameter, $O.D.$ = Outside Diameter, L = Length

$= \frac{\pi}{4} \cdot 2.6^2 \cdot 7.5 - \frac{\pi}{4} \cdot 0.41^2 \cdot 9.5 = 38.565 \text{ cm}^3$

Total Volume in Inlet part: 1.4327 cm^3 (from Appendix A.1)

Total Volume in Outlet part: 0.4178 cm^3 (from Appendix A.1)

Porosity Determination by Liquid Saturating Method

1. Weight of sample container (including channel), $W_{container}$ = 38.22 g.
2. Weight of dry sand sample, W_{dry} = 71.28 g.
3. Weigh the saturated sample, W_{sat} = 124.47 g.

4. Calculate the saturated distilled water weight,

   $W_{water} = W_{sat} - W_{dry} - W_{container}$

   $= 124.47 - 71.28 - 38.22 = 14.97$ g.

5. Calculate the total volume of water displaced in whole sample,

   $V_{water} = W_{water} / \rho_{water}$ where $\rho_{water} = 1.0$ g/ cm^3

   $= 14.97/1.0 = 14.97$ cm^3.

6. Calculate the pore volume by subtracted the volume of water in inlet part and outlet part,

   $V_p = V_{water} - V_{Inlet} - V_{Outlet}$

   $= 14.97 - 1.4327 - 0.4178 = 13.12$ cm^3.

7. Calculate the porosity,

   $\phi = V_p/V_b$ where V_b = Volume in sand-pack body = 38.565 cm^3

   $= 13.12/38.565$

   $= 0.3402 = 34.02\%$

B.2 Permeability Calculations

Sand-pack body:

Inside Diameter 2.6 cm, Length 7 cm

Cross-sectional area, $A = \frac{\pi}{4} \cdot I.D.^2_{syringe} - \frac{\pi}{4} \cdot O.D.^2_{channel}$

where $I.D.$ = Inside Diameter, $O.D.$ = Outside Diameter

$$= \frac{\pi}{4} \cdot 2.6^2 - \frac{\pi}{4} \cdot 0.41^2 = 5.177 \text{ cm}^2$$

Absolute Matrix Permeability Measurement of Water

1. Record the water level difference in manometer under and operational flow rate measured by volume of water produced from the system in a period of time.

Experiment #	**1**	**2**	**3**	**4**	**5**
Volume of water produced, V_w (cm^3)	8	8	8	8	8
Period of time, ΔT (sec)	332	400	535	807	1641
Water level difference in manometer, h (cm)	2.8	2.5	1.8	1.5	0.7

2. Calculate the operational flow rate in cm^3/sec and pressure drop in atm.

For Example: Experiment # 1

2.1 Operational flow rate in cm^3/sec.

$$\text{Flow rate} = \frac{Volume\ of\ water\ produced, V_w\ (cm^3)}{Period\ of\ time, \Delta T\ (\text{sec})}$$

$$= \frac{8}{332} = 0.0241\ \text{cm}^3/\text{sec}$$

2.2 Pressure drop in atm.

Level of water in manometer, $h = 2.8$ cm = 0.028 m

Pressure drop $= \rho\, g\, h$, when ρ (density of water) = 1000 kg/m^3

g (gravity force) = 9.81 m/s^2

$$= 1000 \cdot 9.81 \cdot 0.028$$

$$= 274.68\ \text{Pa} \cdot \frac{1\ atm}{101325\ Pa} = 0.0027\ \text{atm}$$

Experiment #	**1**	**2**	**3**	**4**	**5**
Flow rate, Q_w (cm^3/sec)	0.0241	0.0200	0.0150	0.0099	0.0049
Pressure drop, ΔP (atm)	0.0027	0.0024	0.0017	0.0015	0.0007

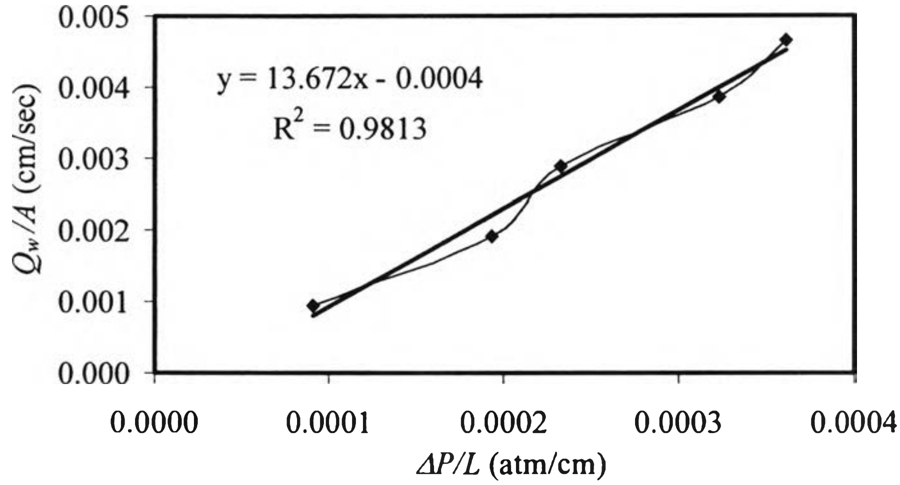
3. From Darcy's Law, the equation can be rewritten as followed,

$$\frac{Q_w}{A} = \frac{K_{matrix}}{\mu}\frac{\Delta P}{L}$$

where Q_w is the flow rate, in cm^3/sec, A is the cross-sectional area of sand pack body subtracting the channel = 5.177 cm^2, K_{matrix} is the matrix permeability, in Darcys, μ is the water viscosity = 1 cP, ΔP is the pressure drop, in atm, L is the length = 7.5 cm.

Therefore, a plot of $\Delta P/L$ and Q_w/A give a slope of K_{matrix}/μ.

Experiment #	**1**	**2**	**3**	**4**	**5**
$\Delta P/L$ (atm/cm)	0.0004	0.0003	0.0002	0.0002	0.0001
Q_w/A (cm/sec)	0.0047	0.0039	0.0029	0.0019	0.0009



4. Calculate K_{matrix} from slope,

   Slope = K_{matrix}/μ , when Slope = 13.627 cm^2/atm sec and μ = 1cP

   $\therefore K_{matrix}$ = Slope $\cdot\,\mu$ = 13.627 cm^2/atm $\cdot$ sec $\cdot$ 1 cP

   = 13.627 Darcys = 13,627 mD .

5. Calculate $K_{channel}$ from the following equation,

   $K_{channel} = 20\cdot 10^6\, I.D._{channel}^{\,2}$ where $I.D.$ = Inside Diameter of the channel in inch

   $$K_{channel} = 20\cdot 10^6 \cdot \left(0.23\ cm \cdot \frac{0.3937\ in}{1\ cm}\right)^2 = 163{,}990 \text{ Darcys}$$

6. Calculate $K_{average}$ from the following equation,

   $$K_{av}A = K_{matrix}(A - A_{O.D.\,channel}) + K_{channel}A_{I.D.\,channel}$$

   $$K_{av}\cdot\left(\frac{\pi}{4}\cdot 2.6^2\right) = 13.627\cdot\left(\frac{\pi}{4}\cdot 2.6^2 - \frac{\pi}{4}\cdot 0.41^2\right) + 163{,}990\cdot\left(\frac{\pi}{4}\cdot 0.23^2\right)$$

   $\therefore K_{av}$ = 1296.63 Darcys

CURRICULUM VITAE

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2004	Position:	Intern
	Company name:	Unocal Thailand, Ltd (Chevron Corporation)

Publications:

1. Romero-Zerón L., Ongsurakul, S., Li, L., and Balcom, B.J. (November, 2007) Magnetic Resonance Imaging of Phase Trapping and In-situ Permeability Modification in Unconsolidated Porous Media. Journal of Petroleum Science and Engineering, submitted.
2. Romero-Zerón L., Ongsurakul, S., Li, L., and Balcom, B.J. (August, 2007) Visualization of the Effect of Porous Media Wettability on Polymer Flooding Performance through Unconsolidated Porous Media using Magnetic Resonance Imaging. Journal of Petroleum Science and Engineering, submitted PETROL2167.
3. Romero-Zerón L., Ongsurakul, S., Li, L., and Balcom, B.J. (July, 2007) Visualization of Mobility-Control by Polymer Waterflooding through Unconsolidated Porous Media using Magnetic Resonance Imaging. Journal of Petroleum Science and Engineering, submitted PETROL2118.
4. Romero-Zerón L., Li, L., Ongsurakul, S., and Balcom, B.J. (February, 2007) Visualization of Immiscible Displacement through porous media using MRI. Journal of Petroleum Science and Engineering, submitted PETROL1946.

Presentations:

1. Ongsurakul, S., Romero-Zerón, L., Li, L., and Balcom, B.J. (2007, October 28-31) Imaging of Polymer Flooding using MRI. Oral presentation at 57th Canadian Chemical Engineering Conference, Edmonton, Alberta, Canada.
2. Li, L., Ongsurakul, S., Romero-Zerón, L., MacMillan, B., and Balcom, B.J. (2007, September 3-7) Visualization of Polymer Flooding in Heterogeneous Material with SPRITE Imaging Methodology. Poster presentation at 9th International Conference on Magnetic Resonance Microscopy, Aachen, Germany.