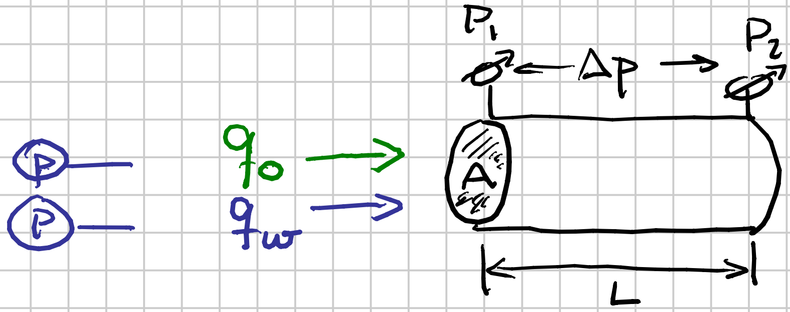
Note Title 4/25/2008

MULTI-PHASE FLOW

- Modifying Darcy's Law $v = \left(\frac{k}{\mu}\right) \cdot \frac{\Delta p}{L} = \frac{q}{A}$ (with $\frac{k}{\mu} = C$)
  - Relative Permeability



10 cm

Laboratory Experiments

$PV = V_b \cdot \phi$

(1) Steady State : q_o = const, q_w = const

Simultaneous Injection O+W into core

Phase k's → constant

(PV_{inj})

S_w	q_w cc/min	q_o cc/min	$k_w \to k_{rw}$ (D)	$k_o \to k_{ro}$ (D)	Δp
1	10	0			
	9	1			
	8	2			
	7	3			
	5	5			
	⋮				
0	0	10		0.8	

$$k_w = \frac{(q_w/A)\cdot\mu_w}{\Delta p}$$

$$k_o = \frac{(q_o/A)\cdot\mu_o}{\Delta p}$$

Relative Permeability:

$$k_{rw} \equiv \frac{k_w}{k}$$ ← Absolute

$$k_{ro} = \frac{k_o}{k}$$

$\rho_w = 1000\ kg/m^3$

1 g/cc

$\rho_o = 800\ kg/m^3$

$k_r(S)$

$k_{rw}(S_w)$
$k_{ro}(S_w)$

const.

$m_{core} = m_{rock} + m_w + m_o$

g

$m_w = V_w \cdot \rho_w$ ✓

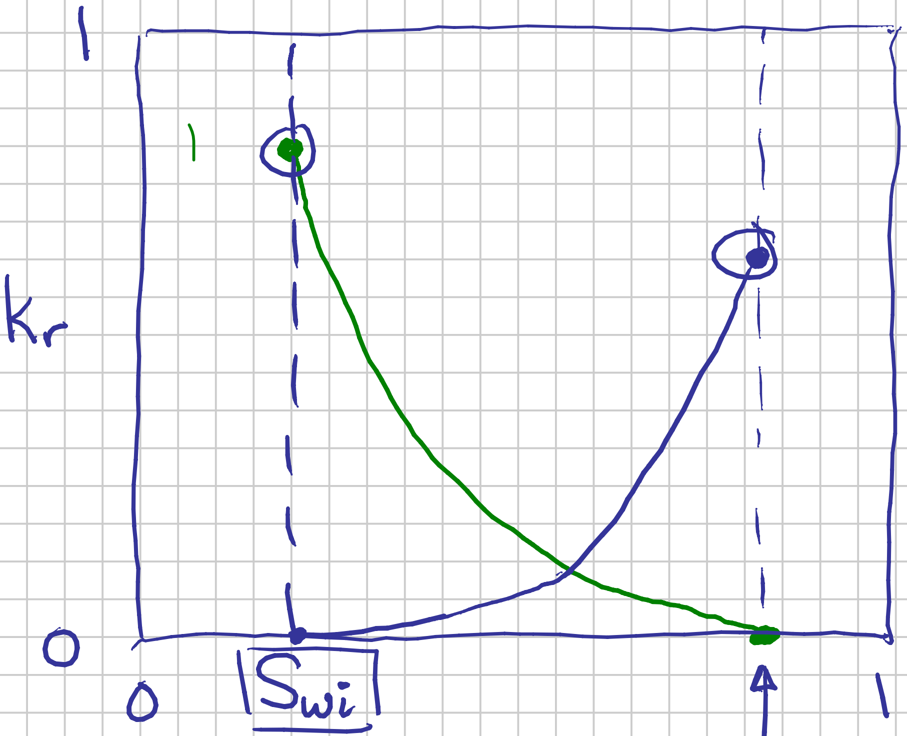
$m_o = V_o \cdot \rho_o$ ✓

$V_w + V_o = V_p$ const

$m_{core} = m_{Rock} + V_w \rho_w + (V_p - V_w)\rho_o$

$\Rightarrow V_w \Rightarrow S_w \equiv \frac{V_w}{V_p}$

$V_o \Rightarrow S_o \equiv \frac{V_o}{V_p}$



oil stops flowing

Irreducible
5–50%

$1 - S_{or}$ ↑ Residual Oil

S_{or} ~ 10–40%

End-Point Saturations!

$k_{rw} \propto S_w^{n_w}$ $n \sim \underline{\underline{2\text{-}4}}$ Lower ↓ Better

$k_{ro} \propto S_o^{n_o}$ $n_w \simeq n_o$

↑ Saturation Exponents

Rock Properties:

S_{wi}	$k_{ro}^*(S_{wi})$
S_{or}	$k_{rw}^*(S_{or})$
n	

$k_r(S_o, \ldots)$

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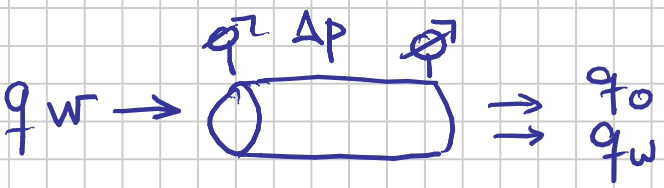
(2) Unsteady State

(a) Start with a core at S_{wi}

$k_{rw} = 0$

$k_{ro}^* = 0.72$ (e.g.)

(b)

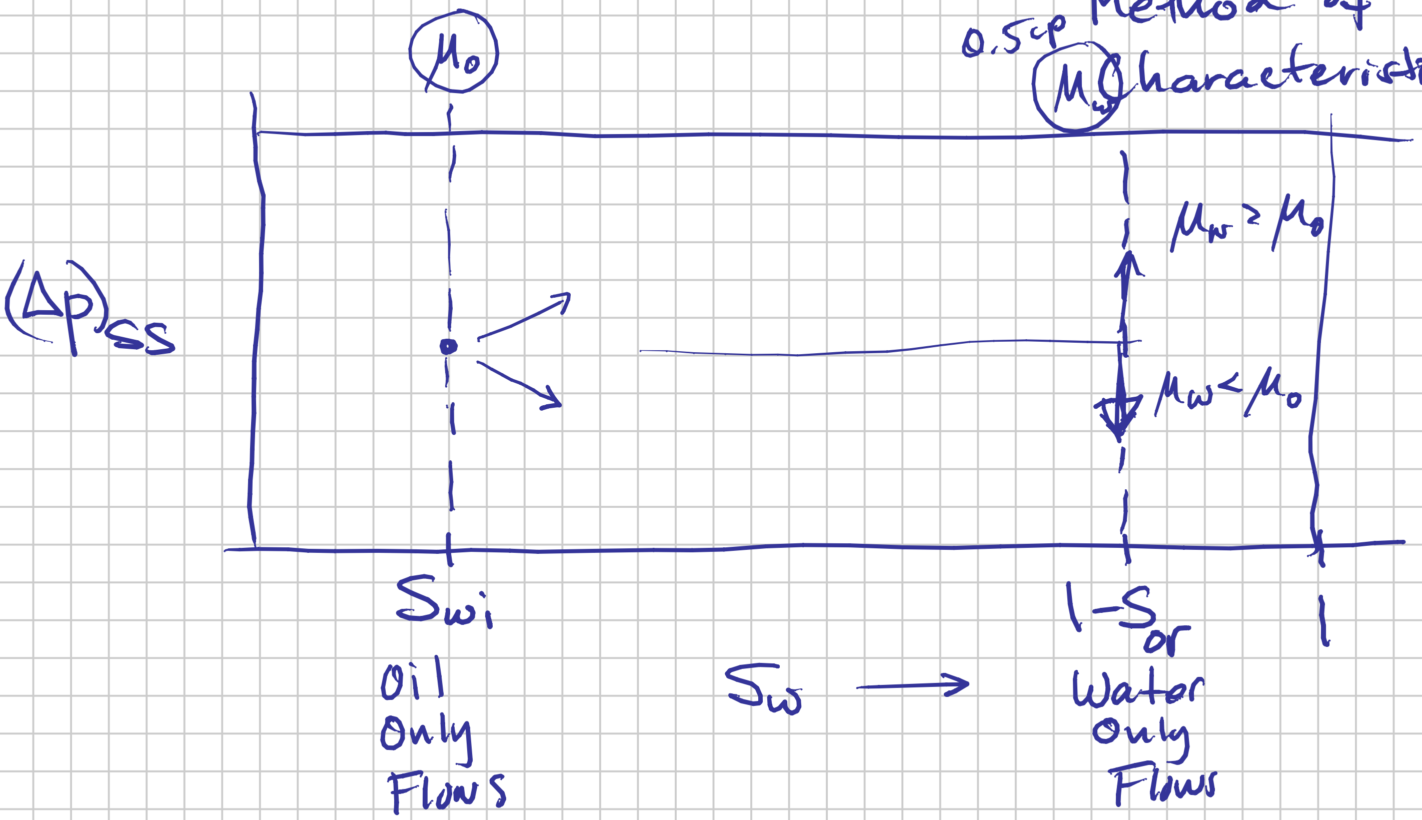


$k_r(S) \leftarrow \left[\text{Material Balance} \Rightarrow \bar{S}_w, \bar{S}_o - f(\text{time}) \right]$

$\Delta p(t) \Rightarrow k_{rw}(t)$, $k_{ro}(t)$

Displacement Flow Theory (Buckley, Leverett)

Method of Characteristics



$k_w + k_o < k$

$k_{rw} + k_{rw} < 1$

$\Delta p = v_p \cdot \frac{\mu_p}{k_p}$ ($k \cdot k_p^*$)

10 cc/min

$k_r\left(S, \frac{\Delta S_w}{\Delta t}, \underline{\text{Wettability}}\right) \ldots$

⊕ Icreasing $S_w \Rightarrow$ Imbibition ⊛

⊖ Decreasing $S_w \Rightarrow$ Drainage

CHALK

$L = 10\ cm$

$k \sim 5\ md$

$A = 10\ cm^2$

$\phi = 0.35$

$S_{wi} = 0.1$

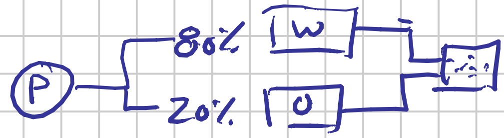
$1000\ md = D$

Steady State Test:

q_{pump}

$q_{winj} = 80\%$

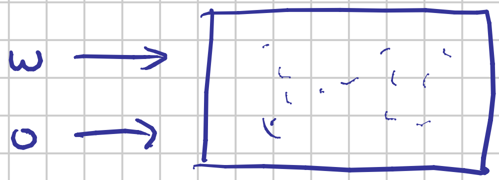
$q_{oinj} = 20\%$



$\Delta p_{max} = 5\ bar$

$\mu_o = 0.2\ cp$

$\mu_w = 0.55\ cp$



$$\Delta p = \frac{\mu_w}{k \cdot k_{rw}} \left(\frac{q_{tot}}{A} \right) L$$

$q_{pump} \cdot 0.8$

k_{rw} ? Correlation

0.2 .. 0.5

$$v = \frac{k}{\mu} \frac{\Delta p}{L}$$

$q \big|_{k_{rw}=1}$

$q \big|_{k_{rw}=0.5}$

$q \big|_{k_{rw}(S)=0.2}$

Solve for q_{pump}

$$q_{pump} = \Delta p \cdot \frac{k \cdot k_{rw}}{\mu_w} \cdot \frac{A}{0.8} \frac{1}{L}$$

Units

$\Delta p\,[atm] \sim 5\,[bar]$

$k\,[D] = 0.005\,D$

$A\,[cm^2] = 10\,cm^2$

$L\,[cm] = 10\,cm$

$q\,[cm^3/s]$ [ ]

$\mu\,[cp] = 0.55\,cp$

$q \left[\frac{cm^3}{s}\right] \times \left[\frac{60\,s}{min}\right]$