RELATIVE PERMEABILITY

Instructor:

Javid Shiriyev, Ph.D.

Relative Permeability

- In multiphase flow, the absolute permeability of the porous medium is not sufficient to calculate the flow rate of each phase or to calculate the total flow rate of all the fluids.
- The permeability of one fluid in the presence of the other immiscible fluids is known as the effective permeability to that fluid.
- Dimensionless form of effective permeability is given as relative permeability:

$$\boldsymbol{k_{\mathrm{rg}} = \frac{k_{\mathrm{g}}}{k}} \qquad \boldsymbol{k_{\mathrm{ro}} = \frac{k_{\mathrm{o}}}{k}} \qquad \boldsymbol{k_{\mathrm{rw}} = \frac{k_{\mathrm{w}}}{k}}$$

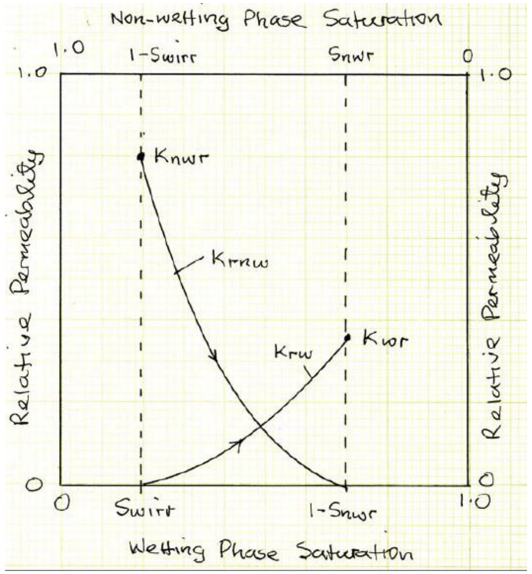
Relative Permeability

Imbibition relative permeability curves typically are used to perform the following reservoir performance calculations:

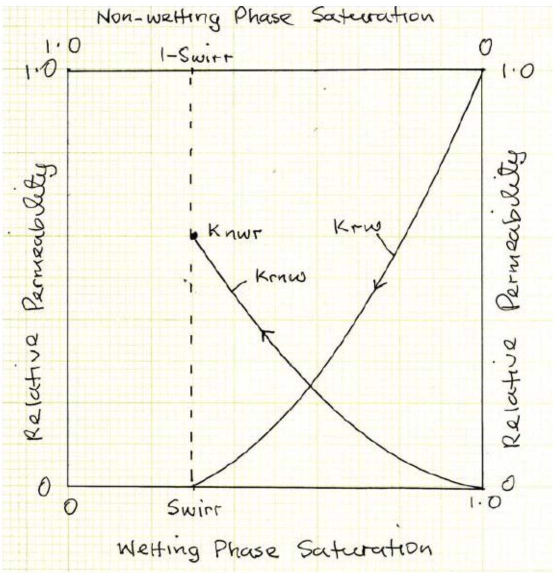
- Water-flood calculations in a water-wet reservoir in which water displaces oil and/or gas
- Natural water influx calculations in a water-wet reservoir in which water displaces oil and/or gas
- Oil displaces gas, which occurs when oil is forced into a gas cap

Drainage relative permeability curves typically are used to perform the following reservoir performance calculations:

- Solution gas drive calculations in which gas displaces oil
- Gravity drainage calculations in which gas replaces drained oil
- Gas drive calculations in which gas displaces oil and/or water
- Oil or gas displacing water in tertiary recovery processes.



Imbibition



Drainage

In multi-phase system, following inequality is always true:

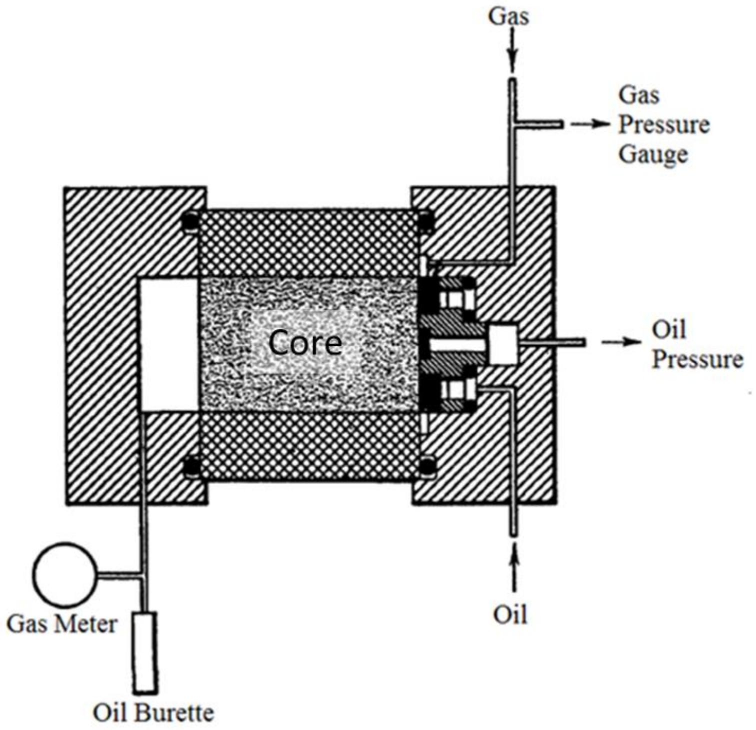
$$k_{rg} + k_{ro} + k_{rw} < 1$$

Outline

- Steady-state lab measurements
- Unsteady-state lab measurements
- Factors affecting relative permeabilities
- Three phase relative permeabilities
- Calculation from drainage capillary pressure curve
- Relative permeability hysteresis

Steady-State Lab Measurements

- The most straightforward laboratory measurement technique for relative permeabilities is the steady-state method.
- For imbibition relative permeability curves, we start with irreducible wetting phase saturation. Then a mixture of the two phases is injected until steady state is achieved.
- Steady-state is achieved when the pressure drop across the core no longer changes with time and the ratio of produced fluids is the same as the ratio of the injected fluids.
- It is necessary to minimize capillary end effect by keeping the total injection rate sufficiently high.
- This experiment is very slow, it is not unusual for a steady-state experiment to take several weeks to complete.
- An alternative and much faster technique is the unsteady state method or the dynamic displacement method based on immiscible displacement theory.



Hassler’s apparatus

Unsteady-State Lab Measurements

- For an imbibition test, we start as in the steady-state method. However, only the wetting phase is injected into the core to displace the non-wetting phase.
- By measuring the produced fractions of phases at the outlet end of the core and the pressure drop versus time, the relative permeability can be calculated using the immiscible displacement theory.

Ex: Unsteady-state relative permeability measurements

- Table on the next slide gives the experimental data for an unsteady-state relative permeability measurement for a sand pack.
- In the experiment, water was used to displace a viscous oil at a constant injection rate. The pore volume of water injected (W_i), the cumulative oil produced (Q_o) and the pressure drop (ΔP) across the sand pack were measured as functions of time.
- Calculate the oil-water relative permeability curves for the porous medium using the Johnson-Bossler-Neumann (JBN) method.

Injection rate	= 100 $\mathrm{cc/hr}$
Irreducible water saturation	= 11.90 %
Length of porous medium	= 54.7 cm
Diameter of porous medium	= 4.8 cm
Average porosity	= 30.58 cm
Absolute permeability	= 3.42 D
Oil viscosity	= 108.37 cp
Oil density	= 0.959 $\mathrm{g/cm^3}$
Water viscosity	= 1.01 cp
Water density	= 0.996 $\mathrm{g/cm^3}$
Oil-water interfacial tension	= 26.7 $\mathrm{dynes/cm}$
Effective permeability to oil at irreducible water saturation	= 3.16 D
Oil recovery at breakthrough	= 38.28 % IOIP
Final oil recovery	= 54.9 % IOIP

Ex: Unsteady-state relative permeability measurements

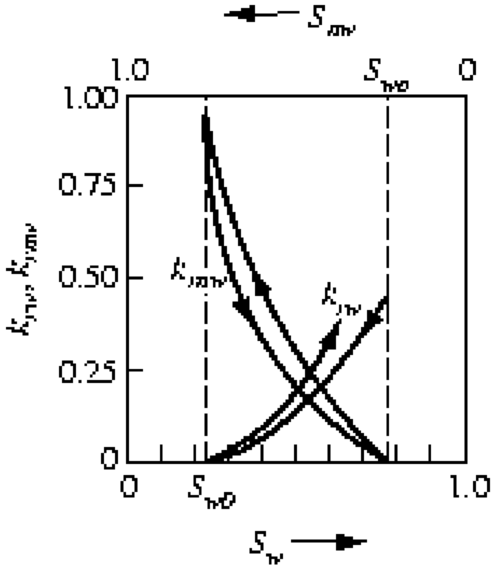
W_i (PV)	Q_o (% $IOIP$)	ΔP (psi)
0.339	38.28	9.02
0.351	38.95	8.30
0.395	40.10	6.91
0.439	40.91	6.07
0.502	41.92	5.42
0.587	42.95	4.87
0.670	43.77	4.55
0.840	45.11	4.00
1.137	46.55	3.32
1.604	47.96	2.78
2.029	48.96	2.52
2.624	50.08	2.42
3.225	50.78	2.30
4.346	51.78	2.13
5.719	52.67	1.99
7.092	53.23	1.90
8.464	53.67	1.83
10.516	54.16	1.79
11.203	54.34	1.75
12.578	54.60	1.74
13.271	54.71	1.70
14.644	54.82	1.70
16.016	54.90	1.70

Factors Affecting Relative Permeability

- Fluid Saturation
- Fluid Saturation History
- Wettability
- Interfacial Tension
- Pore Structure

Factors Affecting Relative Permeability

- The higher the fluid saturation, the higher the relative permeability to that fluid. In general, relative permeabilities are non-linear functions of fluid saturations.
- Like capillary pressure curves, relative permeability curves show saturation hysteresis.
- When plotted against the wetting phase saturation, the relative permeability curves for the oil-wet core and water wet core are close to each other. They are not identical because the degree of wettability preference may be different.



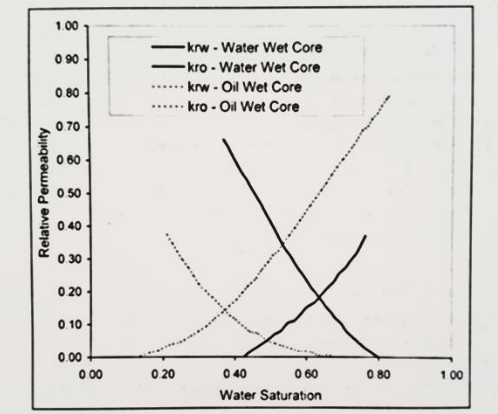


FIGURE 8.29 Effect of strong preferential wettability on steady state relative permeability curves.

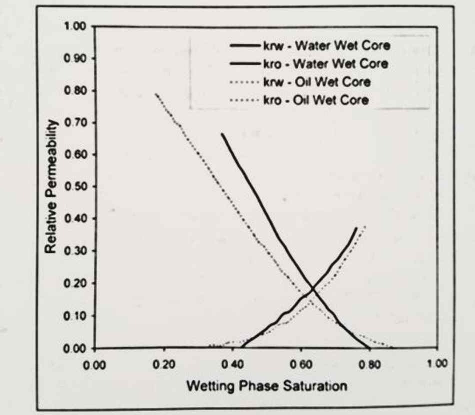


FIGURE 8.30 Relative permeability curves from Figure 8.29 replotted as functions of wetting phase saturation.

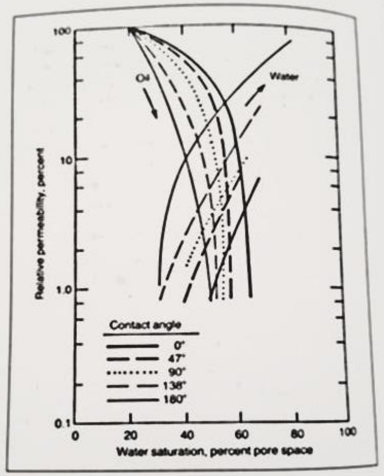
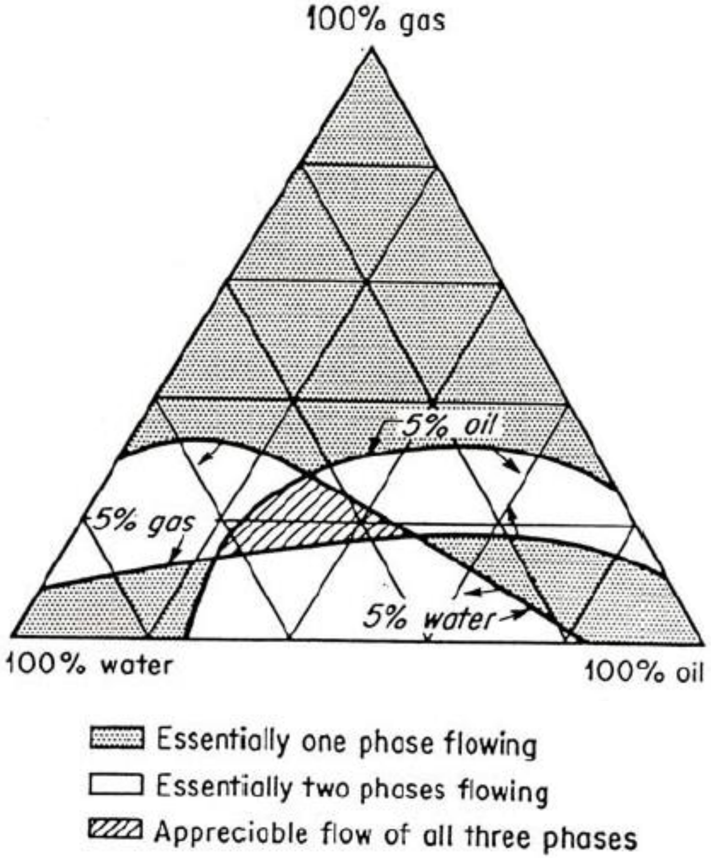
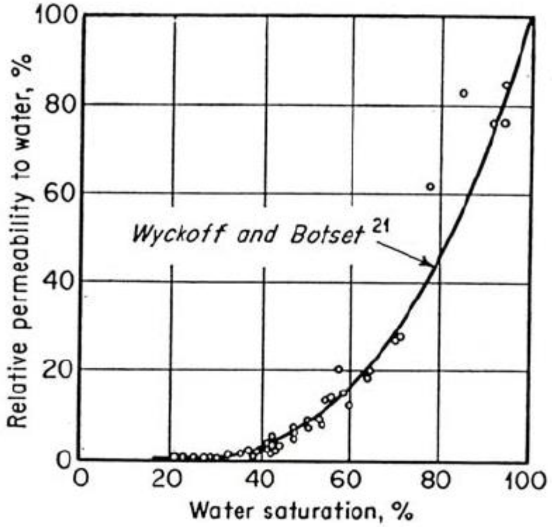


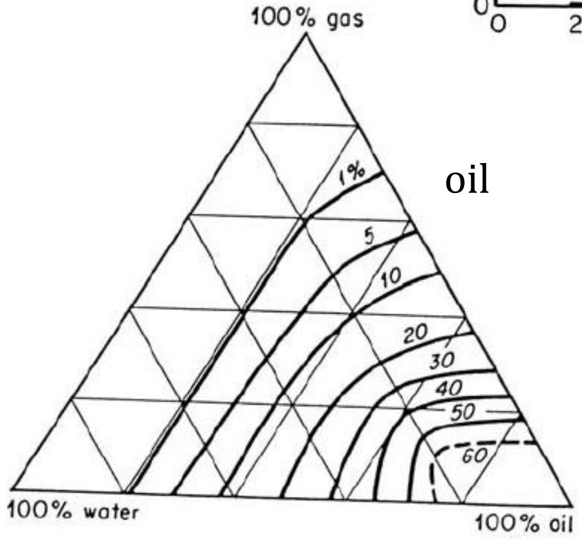
FIGURE 8.31 Relative permeabilities for a range of wetting conditions (Owens and Archer, 1971). © 1971 SPE. Reproduced with the permission of the copyright owner. Further reproduction is prohibited without permission.

Relative Permeability – Three Phase

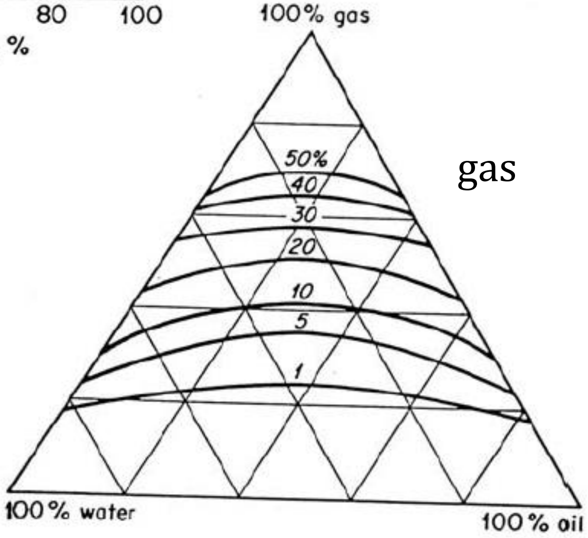




water



oil



gas

Leverett and Lewis, 1941

Calculation from drainage capillary pressure curve

- Burdine (1953) proposed the following normalized drainage relative permeability models:

$$\bar{k}_{rw}(S_w^*) = \frac{k_w(S_w^*)}{k_w(S_w^* = 1)} = (S_w^*)^2 \frac{\int_0^{S_w^*} \frac{1}{P_c^2} dS_w^*}{\int_0^1 \frac{1}{P_c^2} dS_w^*} \qquad \bar{k}_{rnw}(S_w^*) = \frac{k_{nw}(S_w^*)}{k_{nw}(S_w^* = 0)} = (1 - S_w^*)^2 \frac{\int_{S_w^*}^1 \frac{1}{P_c^2} dS_w^*}{\int_0^1 \frac{1}{P_c^2} dS_w^*}$$

- Where S_w^* is the normalized wetting phase saturation given by:

$$S_w^* = \frac{S_w - S_{wirr}}{1 - S_{wirr}}$$

Relative Permeability Theoretical Models

- For the numerical calculations, we need theoretical relative permeability curves to avoid numerical instabilities.
- Corey-type relative permeability curves
- End point relative permeabilities

imbibition

$$k_{\mathrm{rnw}} = k_{\mathrm{rnw}}^{\mathrm{o}}(1-S)^m$$

$$k_{\mathrm{rw}} = k_{\mathrm{rw}}^{\mathrm{o}} S^n$$

$$S = \frac{S_{\mathrm{w}} - S_{\mathrm{wirr}}}{1 - S_{\mathrm{wirr}} - S_{\mathrm{nwr}}}$$

drainage

$$k_{\mathrm{rnw}} = k_{\mathrm{rnw}}^{\mathrm{o}}(1-S)^2\left[1 - S^{\frac{2+\lambda}{\lambda}}\right]$$

$$k_{\mathrm{rw}} = k_{\mathrm{rw}}^{\mathrm{o}} S^{\frac{2+3\lambda}{\lambda}}$$

$$S = \frac{S_{\mathrm{w}} - S_{\mathrm{wirr}}}{1 - S_{\mathrm{wirr}}}$$

$$k_{\mathrm{rnw}}^{\mathrm{o}} = k_{\mathrm{rnw}}(S_{\mathrm{w}} = S_{\mathrm{wirr}})$$

$$k_{\mathrm{rw}}^{\mathrm{o}} = k_{\mathrm{rw}}(S_{\mathrm{w}} = 1 - S_{\mathrm{nwr}})$$

Ex: Calculation from drainage capillary pressure curve

- Use the air-water capillary pressure data to the right to calculate the drainage relative permeability curves by the method of Brooks and Corey for a core sample.

Saturation	Capillary Pressure (psi)
1.000	1.973
0.950	2.377
0.900	2.840
0.850	3.377
0.800	4.008
0.750	4.757
0.700	5.663
0.650	6.781
0.600	8.195
0.550	10.039
0.500	12.547
0.450	16.154
0.400	21.787
0.350	31.817
0.300	54.691
0.278	78.408