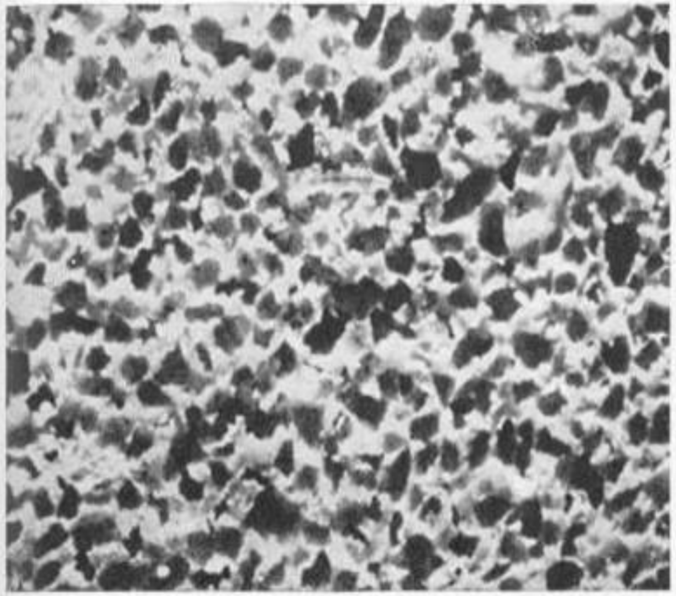
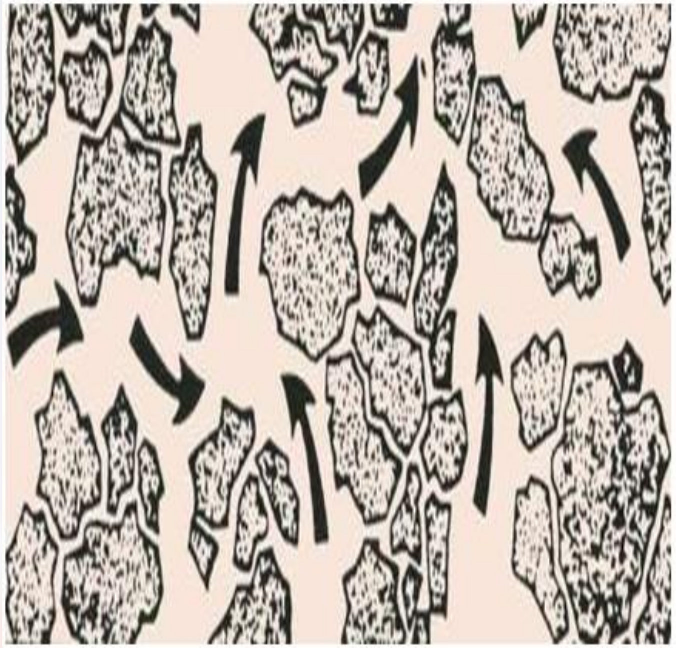
Permeability

- Permeability is a property of the porous medium that measures the ability of the formation to transmit fluids. It's the measure of the ease with which the rock will permit the passage of fluids. This depends on how well the pore spaces within that rock are interconnected.
- The rock permeability, k, is a very important rock property because it controls the directional movement and the flow rate of the reservoir fluids in the formation
- Unlike porosity, permeability cannot be defined apart from fluid flow. For a rock to be Permeable, it must contain inter-connected pores
- Permeability is an INTENSIVE property of a porous medium (e.g. reservoir rock)
- Reservoir permeability is usually quoted in millidarcies, (md).





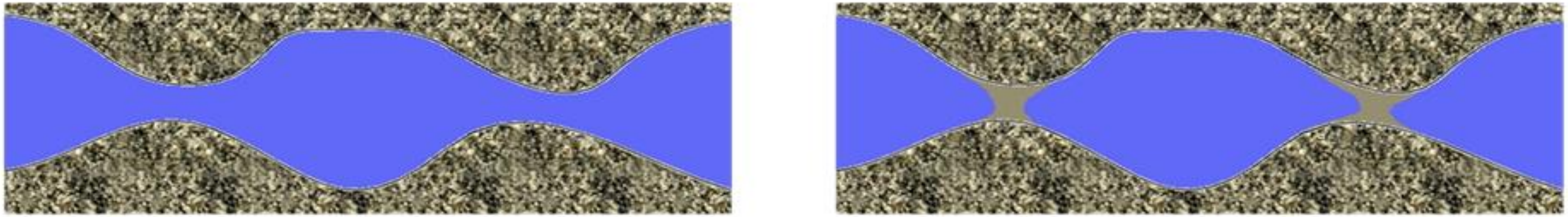
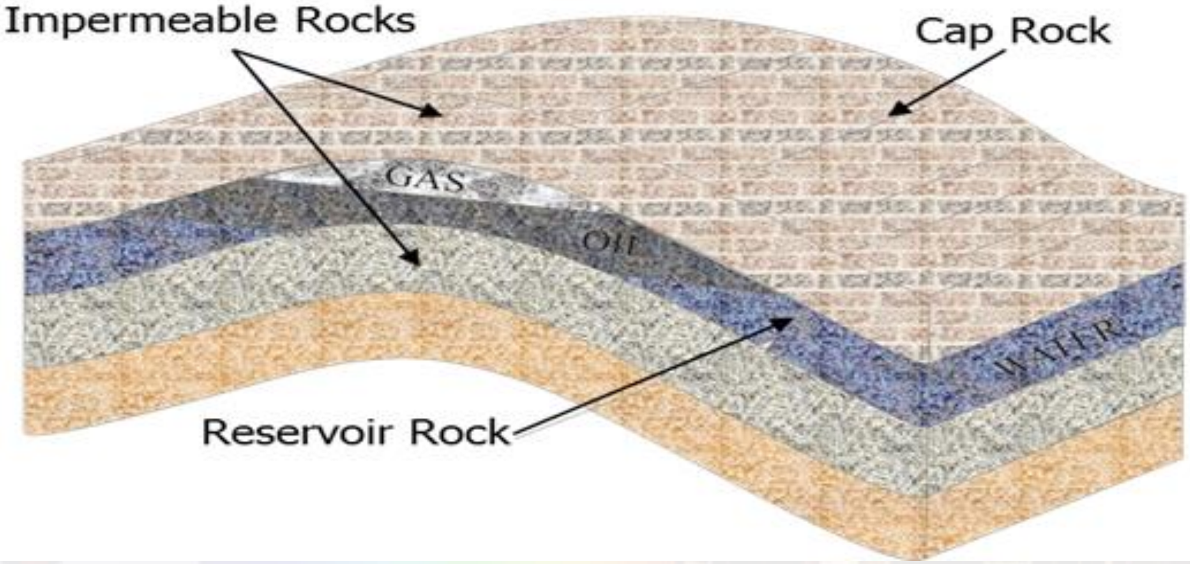


Illustration of pore and pore channels in a rock.

These two figures have the same porosity (same pore space).

In the figure to the right the pore channels are closed and the permeability is zero.

Impermeable rock (cap rock) traps hydrocarbons in the reservoir. Cap rock may be porous, but the pore channels must be "closed" to stop fluids from escaping.



Permeability Classification

Three types of permeability

- **Absolute permeability** – the permeability of a porous medium with only one fluid present (single-phase flow).
- When two or more fluids are present permeability of the rock to a flowing fluid is called **effective permeability** (ko, kg, kw). [i.e. Effective permeability is the permeability of a flowing phase which does not saturate 100% of the rock]
- **Relative permeability** is the ratio of absolute and effective permeabilities kro=ko/k, krg=kg/k, krw=kw/k.

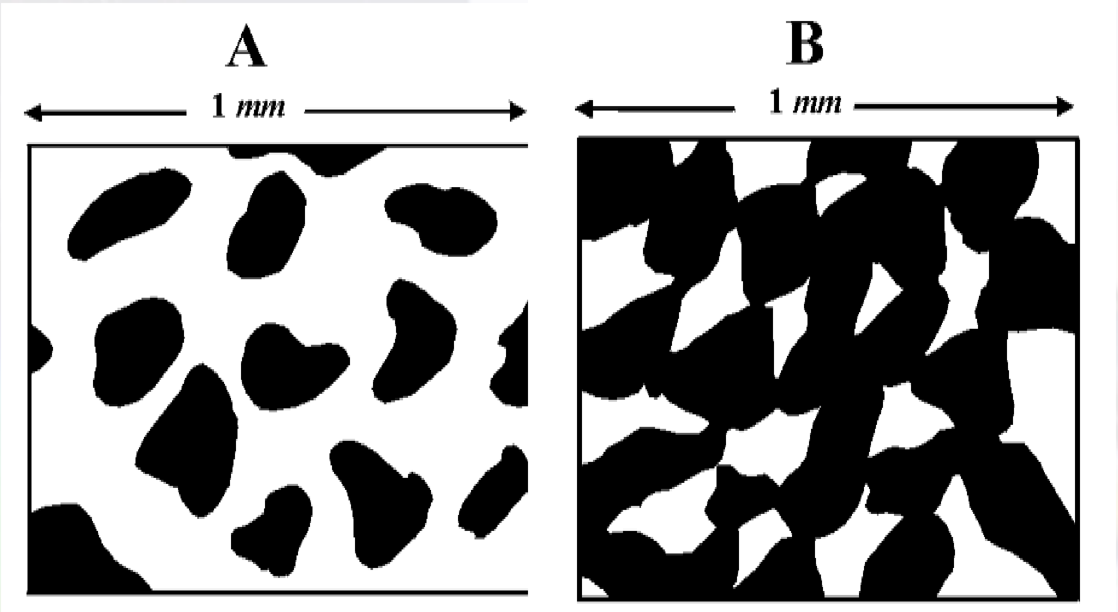
<u>Note:</u> The effective permeability is always less than the absolute value of k for the rock.

Permeability Scale

Generally the permeability is termed as :

- Poor if; $k<1$,
- Fair if; $1<k<10$,
- Moderate if; $10<k<50$,
- Good if; $50<k<250$,
- Very good if; $k>250$.

Note: This scale changes with time, for example 30 years ago $k<$ 50 was considered poor.



Good Permeability **Poor Permeability**

Note:

- If a single fluid is present in a rock, its relative permeability is 1.
- The relative permeability of a fluid is a function of its saturation.

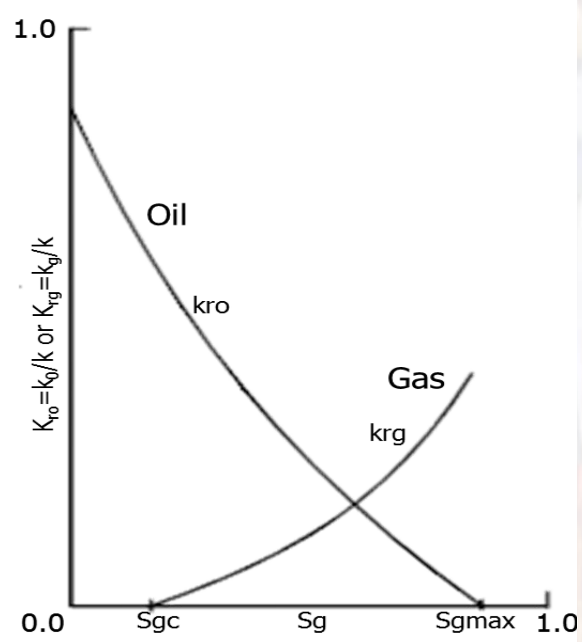
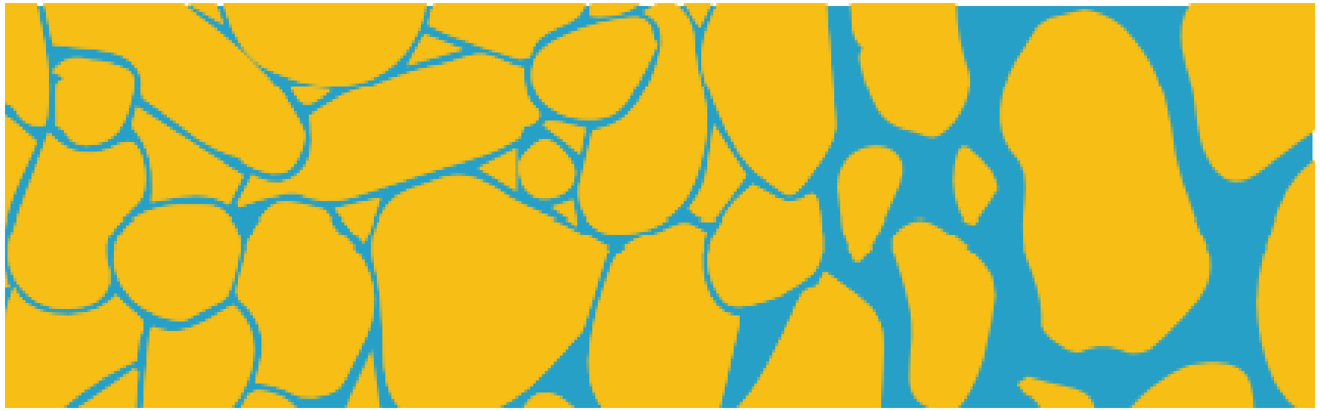


Fig.: Gas-oil relative permeability

Permeability

❖ *The factors affecting* the magnitude of Permeability are:

- Shape and size of grain sizes (pore system),
- Cementation
- Sorting
- Lithology or rock type
- fracturing and Dissolution



Low permeability reigon

High permeability reigon

❖ *The Source of Permeability is* determined by:

- Core analysis
- Well test analysis (flow testing)
  - RFT (repeat formation tester) provides small well tests
- Production data
  - production logging measures fluid flow into well
- Log data
  - MRI (magnetic resonance imaging) logs calibrated via core analysis

Darcy's law helps us to measure the degree of permeability.

$$Q = -\frac{K\,A}{\mu}\frac{dP}{dL}$$

$$Q = \frac{KA}{\mu L}(p_1 - p_2)$$

- Darcy's "K" was determined to be a combination of
  - k, permeability of the sand pack (porous medium, e.g. reservoir rock), Darcy.
  - A = cross sectional area [cm^2]
  - μ = viscosity of the liquid [cp]
  - Q = volumetric flow [cm^3/s]
  - dp/dL, Pressure gradient (atm/cm)

Note that P1>P2

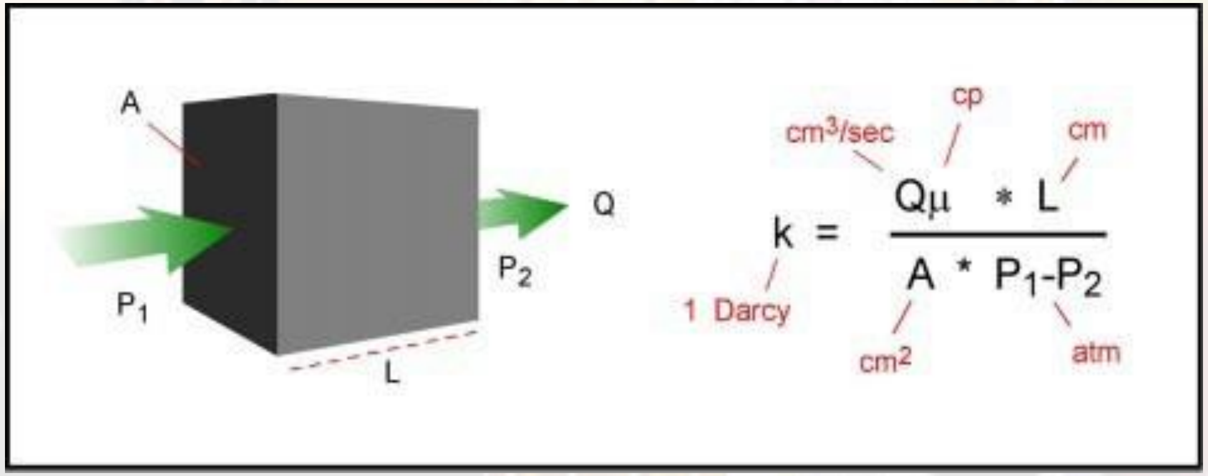
Assumptions Used in Darcy Equation:

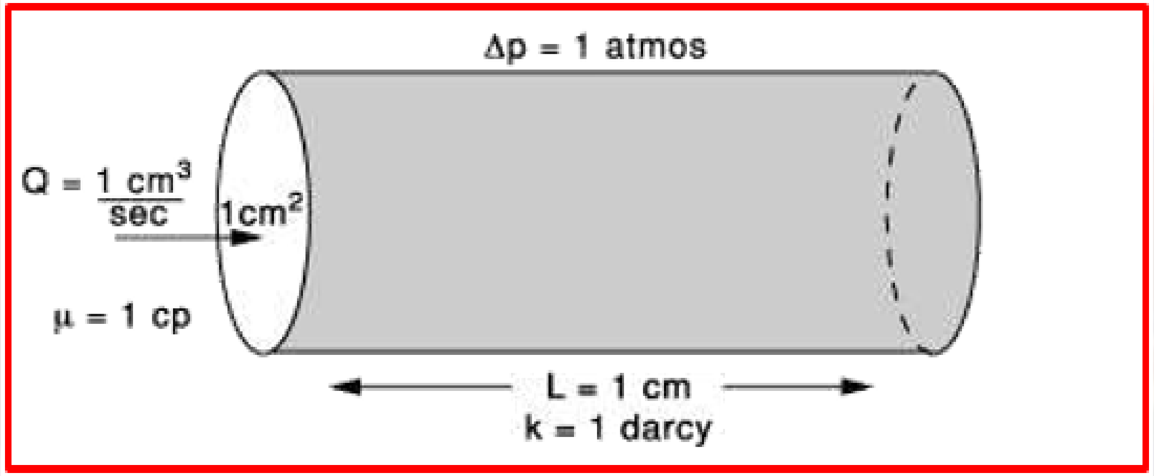
1. Steady state flow, under laminar regime i.e. $Q_{in} = Q_{out}$
2. Viscous flow – rate of flow directly proportional to pressure gradient
3. The flowing fluid is incompressible.
4. Porous media 100% saturated with fluid which flowed
5. Fluid and porous media not reacting(i.e. no chemical exchange or reactions between them)

What is Darcy ?

A practical definition of a Darcy is as follows;

A porous medium has a permeability of one Darcy, when a single-phase fluid of one centipoises viscosity (1 cp) , that completely fills the voids of the medium will flow through it at a rate of one cubic centimeter cross sectional area (1 cc/sec/cm2), and under a pressure or equivalent hydraulic gradient of one atmosphere per centimeter (1 atm/cm).





Units of Permeability

- Two sets of units are generally used in reservoir engineering:
  Darcy units and Oil-field units

- For the purpose of the mathematical derivations, a system of units commonly referred to as Darcy units are used. These units are: $K = Darcy;\ g = cm/sec^2;\ dp/ds = atm/cm$

- For application to field data of the various mathematical expressions, the second system of units called the practical oil-field units are used.
- From dimensional analysis, the dimension for K is $[L]^2$. We could use ft^2, ins^2, or cm^2 for measure of permeability, but these units are all too large to be applied in porous media.

- So Darcy unit is used and recommended ,but in many cases the millidarcy (mD) are used.

- 1 Darcy = 1000 miliDarcy
- 1 Darcy = 0.987×10^{-12} m^2
- 1 Darcy = 1.062×10^{-11} ft^2
- 1 miliDarcy ~ 10^{-9} mm^2

Required :

1- prove $k = L^2$

2- permeability conversion factor

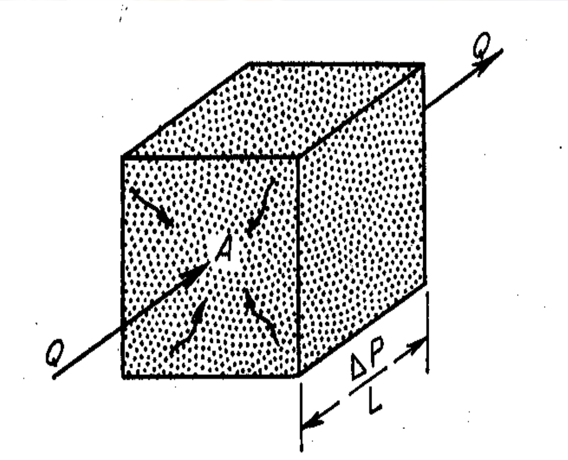
Common Oil Field Units

Quantity	Symbol	Dimension	Oilfield Units	SI Units
Mass	m	m	lbm	Kg
Moles	n	n	lbmol	Kmol
Force	F	ML/t^2	lbf	N
Length	L	L	ft	m
Area	A	L^2	acres	m^2
Volume-liquids	v	L^3	bbl	m^3
Volume-gases	v	L^3	ft^3	m^3
Pressure	p	m/Lt^2	psi	kPa
Temperature	T	T	R	K
Flow rate-liquids	q	L^3/t	bbl/d	m^3/d
Flow rate -gases	q	L^3/t	Ft^3/d	m^3/d
Viscosity	μ	m/Lt	cP	mpa.s
Permeability	k	L^2	md	m^2

Linear Flow System

Darcy's Law for one dimensional linear horizontal flow (incompressible fluid)
Field Units

$$q = -1.127x10^{-3} \frac{kA}{\mu B_o} \frac{\Delta p}{\Delta l}$$



q = production rate stb/d

k = permeability mD

A = cross sectional area to flow ft^2

$\frac{\Delta p}{\Delta l}$ = pressure gradient psi/ft

μ = fluid viscosity cp

B_o = oil formation volume factor rb/stb

Field units of permeability are Darcy, D and milliDarcy, mD

Darcy's Law for one dimensional linear horizontal flow (compressible fluid)
Field Units

$$Q_{sc} = \frac{0.111924\, A\, k\, (p_1^2 - p_2^2)}{T\, L\, z\, \mu_g}$$

k = absolute permeability, Darcys

μg = gas viscosity, cp

T = temperature,˚R

Z = gas compressional factor.

p1 = inlet (upstream) pressure, psia

p2 = outlet (downstream) pressure, psia

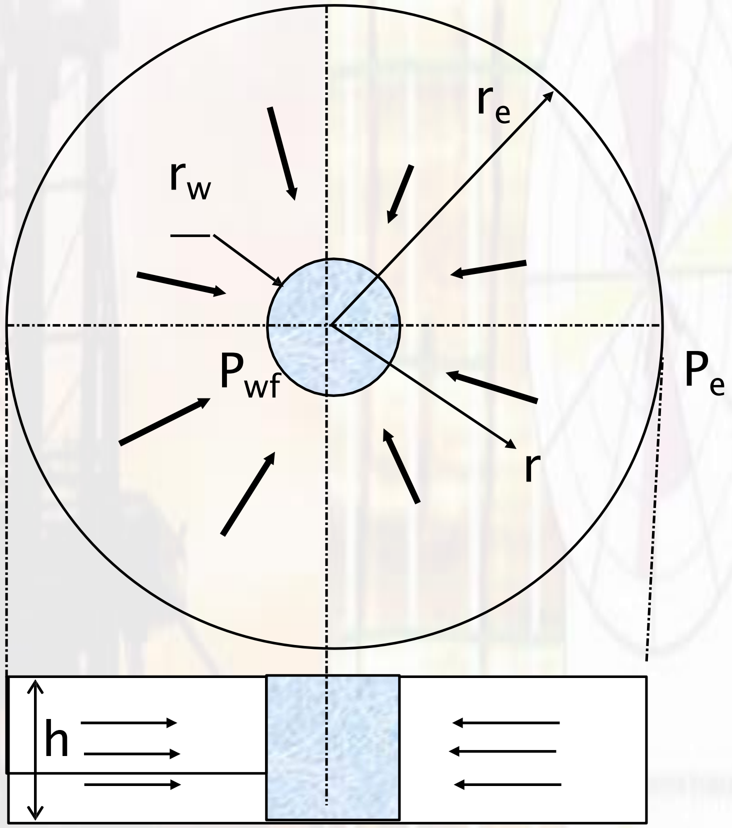
L = length of the core, ft

A = cross-sectional area, ft^2

Qgsc = gas flow rate at standard conditions, STB/day

Radial Flow System

- Fluid not compressed
- Steady flow (stream mass was constant)



$$Q = \frac{2\pi hk}{\mu} \frac{(P_e - P_w)}{\ln(\frac{r_e}{r_w})}$$

- Where :
- Q = flow rate, m^3/sec
- K = permeability, m^2
- h = thickness, m
- P_e = pressure drainage radius, N/m^2
- P_{wf} = flowing pressure, N/m^2
- μ = fluid viscosity, N/m^2
- re = drainage radius, m
- r_w = the well-bore radius, m

- In field unit the above equation becomes as:

$$\boxed{Q = \frac{7.08 * 10^{-3} hk}{\mu} \frac{(P_e - P_w)}{\ln(\frac{r_e}{r_w})}}$$

The External (Drainage) Radius

The external (drainage) radius re is usually determined from the well spacing by equating the area of the well spacing with that of a circle, i.e

$$\pi r_e^2 = 43{,}560\ A$$

$$r_e = \sqrt{\frac{43{,}560\ A}{\pi}}$$

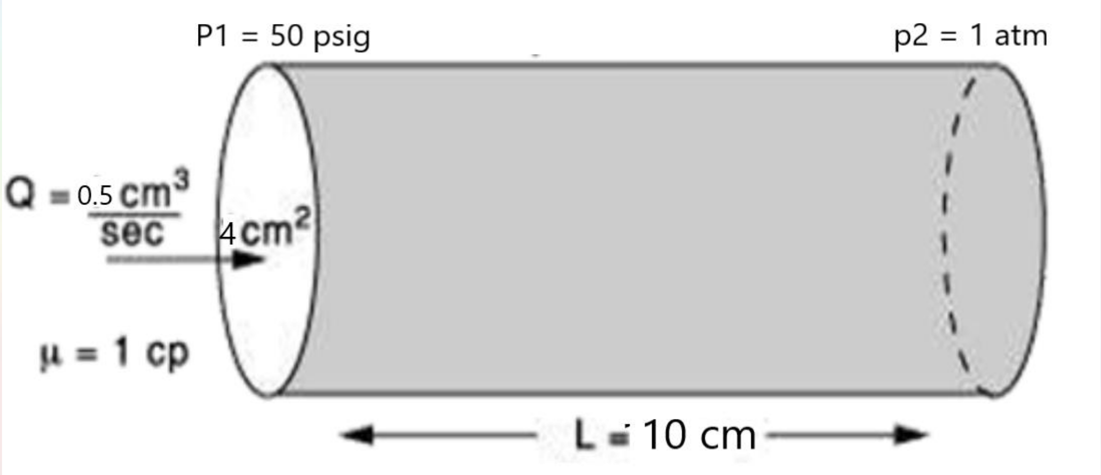
Where A is the well spacing in acres.

Examples

Example – 1:

Calculate the k of cylindrical core sample subjected to linear flow using water if the following data are available :

μ_w = 1 cp., core diameter = 4 cm, core length = 10 cm, flow rate = 0.5 cc/sec., p1 = 50 psig and p2 = 1 atm.



Solution:

$$Q = -\frac{K\ A}{\mu}\frac{dP}{dL}$$

$$P1 = \frac{50+14.7}{14.7} = 4.40 \quad \text{and} \quad P2 = 1$$

$$K = \frac{Q\ \mu}{A}\frac{L}{dP}$$

K= 0.117 Darcy

1 atm = 14.7 Psia
Psia = Psig +14.7

Example – 2:

What is the flow rate of a horizontal rectangular system when the conditions are as follows:

permeability = k = 1 Darcy

Area = A = 6 ft^2

viscosity = μ= 1.0 cp

length = L = 6 ft

inlet pressure = P1 = 5.0 atm.

outlet pressure = P2 = 2.0 atm

Solution:

We must insure all the variables are in the correct units.

k = 1 darcy ,

A = 6 ft^2 (144 in^2 /1 ft^2) (6.45 cm^2/1 in^2) = 5572.8 cm^2

L = 6 ft (12 in/1 ft) (2.54 cm/1 in) = 182.88 cm

P1 = 5.0 atm and P2 = 2.0 atm

$$Q = -\frac{K\,A}{\mu}\,\frac{(P2 - P1)}{L} \Rightarrow Q = -\frac{(1)\,(5572.8)}{(182.88)}\,\frac{(2\ -5)}{1}$$

$$Q = 91.42\ cm^3/sec$$

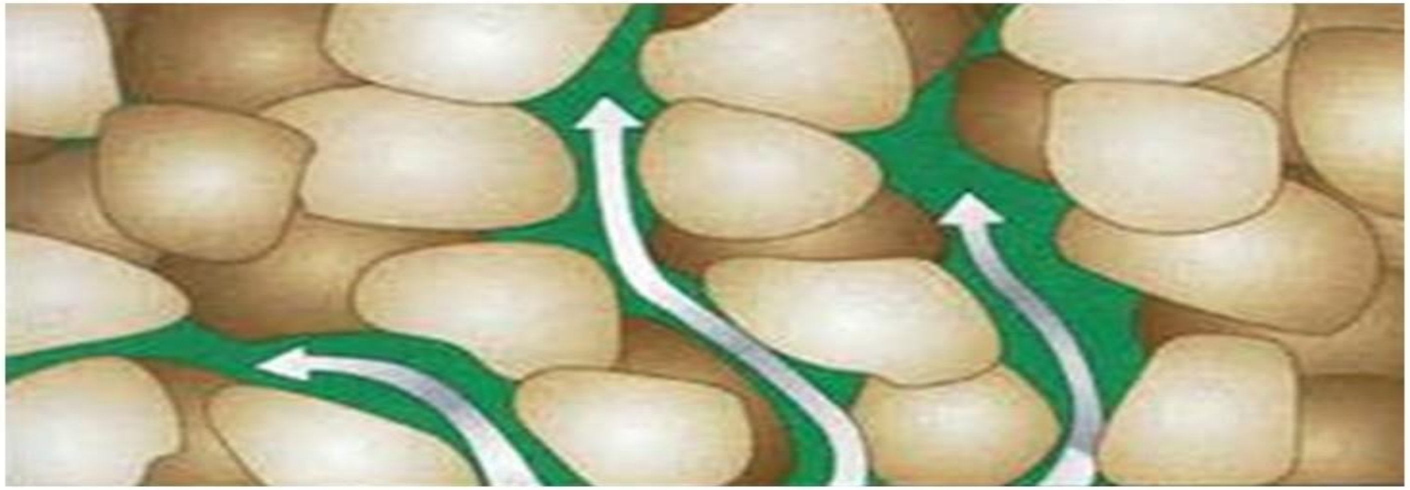
Horizontal Permeability

Permeability in the direction parallel to the bedding plane is of greatest interest in vertical wells traversing perpendicular, horizontal hydrocarbon-bearing reservoirs

Vertical Permeability

Permeability in the direction perpendicular to the bedding plane controls flow caused by gravitational forces. This is the permeability of interest in long, horizontal wells.

Reservoir Permeability



Rock permeability is not equal in all directions

- In general . . . $k_x \neq k_y \neq k_z$
- Isotropic Reservoir: $k_x = k_y$
- Anisotropic Reservoir: $k_x \neq k_y$

Sediments shape, size, distribution, and depositional environment control whether $k_X = k_Y$

Averaging Permeability

It is necessary to determine an average value of permeability. Three common types of computed averages are as follows:

i) Arithmetic average permeability(Weighted-average permeability)

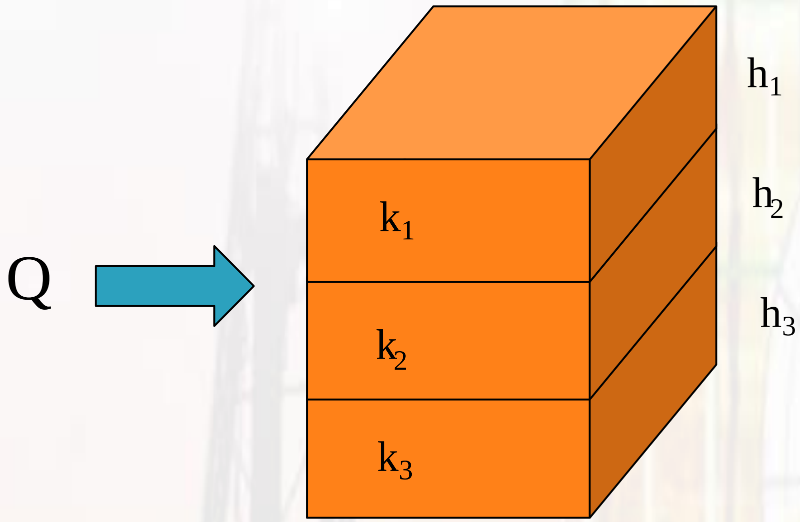
ii) Harmonic average permeability

ii) Geometric average permeability

Selection of the averaging technique should be based primarily on the geometry of the flow system.

Parallel Flow

Arithmetic Average



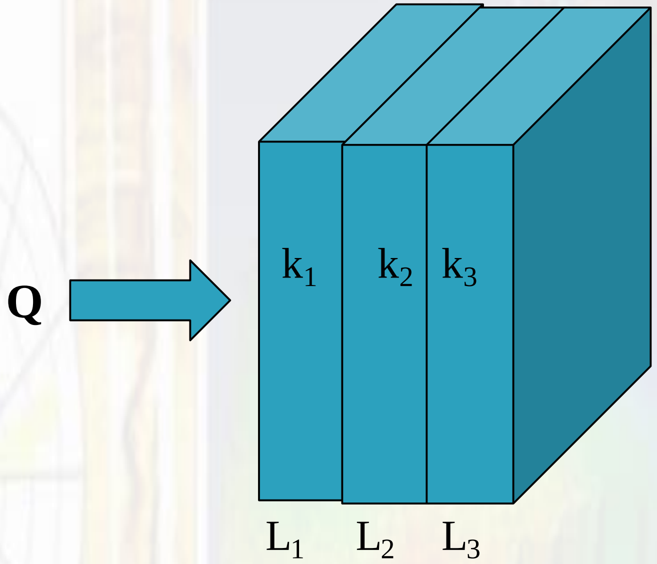
$$\bar{k}_A = \frac{\sum k_i h_i}{\sum h_i}$$

- For variable layers width then the permeability calculated from the below eq.

$$k_{avg} = \frac{\sum_{j=1}^{n} k_j A_j}{\sum_{j=1}^{n} A_j}$$

Series Flow

Harmonic Average



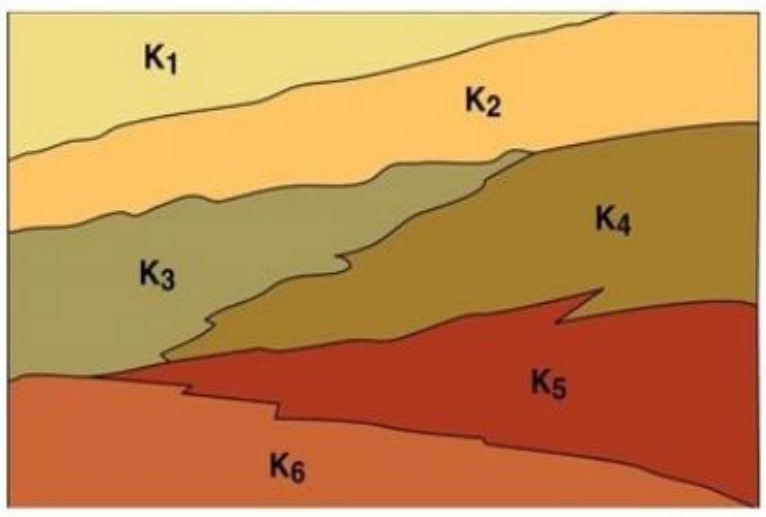
$$\bar{k}_H = \frac{\sum L_i}{\sum L_i / k_i}$$

Radial, Series Flow

$$k_{avg} = \frac{\ln (r_e / r_w)}{\sum_{j=1}^{n} \left[\frac{\ln (r_j / r_{j-1})}{k_j} \right]}$$

Random Flow

Geometric Average



$$k_G = (k_1 \times k_2 \times k_3 \times \cdots \times kn)^{1/n}$$

(All permeabilities must represent layers of the same thickness)

- For different thickness then the permeability calculated from the below eq.

$$k_{avg} = \exp \left[\frac{\sum_{i=1}^{n} (h_i \ln (k_i))}{\sum_{i=1}^{n} h_i} \right]$$