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INTRODUCTION

Porosity deals with the storage capacity of rocks, that is, with the openings in rocks which may hold fluids. Permeability refers to the rocks' characteristic of permitting movement of fluid through them. The invisible storage of potable waters in the earth's rocks is most important as is the deeper storage of oil and gas. Of equal importance is the characteristic of most rocks which permits fluids to flow through them, sometimes for long distances.

This discussion considers the characteristics of porosity in rocks, from the shape of the individual pores and the complexity of the distribution of the pore system throughout the rock to the influence of the individual pore shape and pore distribution on the conductivity of the rocks to fluids moving through them.

POROSITY

Fluids are invisibly stored in the earth in openings in the rocks, openings called pore spaces generally of microscopic dimensions. Such rock openings collectively are called "porosity". Porosity of rocks is important because the amount of porosity in a rock determines the amount of space available for the storage of fluids. Further, the shapes of the pores and the distribution of the porosity in the rock is most important to the conductivity of the rock to fluids.

The character of the openings in sandstone and limestone rocks are generally in the forms of: 1. interstitial openings, 2. cracks, 3. fissures, 4. caverns, 5. vugs, and 6. intercrystalline openings. There are large variations in amount of and geometrical distribution of porosity in formations, laterally and in thickness, because of 1. mechanical depositional variations, 2. cementation, 3. chemical leaching or solution, and 4. post depositional fracturing and cracking. Porosity is defined as the ratio, expressed in percent, of the pore or void space to the total rock volume or bulk volume (bulk volume is the sum of the void space plus the mineral grain volume), or percent porosity $= \frac{\text{void volume}}{\text{bulk volume}} \times 100$. Porosities of rocks may vary from less than one percent to more than 40. Most oil rocks have porosities ranging from about 12 to 25 percent. Porosity created with the rock's formation is called "Primary Porosity" while any porosity developed subsequently through whatever means is called "Secondary Porosity".

Porosity in Sandstones: Since the character of the pore space in sandstones differs greatly from that in limestones, the porosity in sandstone rocks will be discussed first. In sandstones the porosity development is quite regular and uniform in distribution. This regularity is due to the packing of sand grains of rounded shapes up to spherical, one against the other in various arrangements and assortments of grain shapes and sizes to leave openings between the rounded surfaces of the grains, despite contact with each other. In general, the openings between the sand grains are inter-connected and uniformly distributed throughout the rock in a regular network of pores. Small grains may lodge within large pores formed by large grains, and the entire assemblage of grains may be more or less cemented to form a consolidated mass.

The shape and distribution of the pore spaces in sandstone are affected by the following:

1. Arrangement of sand grains, i.e., packing arrangement (For spherical grains).
   a. Cubic packing or loose arrangement, maximum porosity = 47.6 percent.
   b. Hexagonal packing or tight arrangement, maximum porosity = 25.9 percent.

2. Sorting, i.e., range of grain sizes.
   a. Small grains fit in the spaces formed by the larger grains —this reduces porosity and complicates pore shape.
   b. Percent porosity is the same for uniform size spheres regardless of grain size.

c. For very fine grain sizes the percent porosity is affected by grain size because with a greater number of fine particles there is a greater chance of bridging, an effect which increases porosity with fineness of grain.

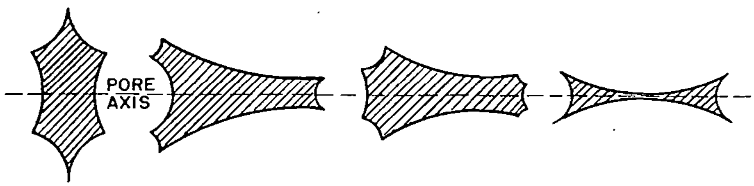
3. Grain shape.
   a. Spherical grains give most open and rounded pore structure.
   b. Flat grains will generally pack flat and give small porosity and thin pore shapes.
4. Grain orientation.
   a. Flat grains may orient to give tight packing and close contact of grains. This gives a low porosity and flat shape of pore space.
5. Cementation.
   (Materials may be: quartz, calcite, gypsum, limonite, clays, silts, bentonite).
   a. Reduces porosity in degree of amount present.
   b. Changes pore shape, particularly at the throat or passage from one pore to another.

Average oil sand grain diameters are from 0.05 millimeters to 0.5 millimeters. Average oil sand pore diameters are from 0.01 millimeters to 0.1 millimeters. The two and one half billion barrels of oil annually produced in the United States must flow and pass through these minute rock channels.

Shape of Pore Spaces: The shape of the pore space is most important to the flow of fluid through it as it is then acting as a conductor or conduit to contain and guide the fluid moving through it, and from one pore to another. The flow path through a pore is complex, since the pore diameter from point to point is constantly varying from the maximum diameter at the center of the pore to a minimum or even vanishing diameter at the entrance of a pore. Some possible pore shapes are shown in Fig. 1 and Fig. 2. If a single pore space from the tightest grain packing arrangement (25.9 percent porosity) already discussed is sliced like a loaf of bread into cross-sections across the long axis of one half the pore – from the center of the pore to the narrow entrance, the shapes shown in Figs. 1 and 2 are obtained.

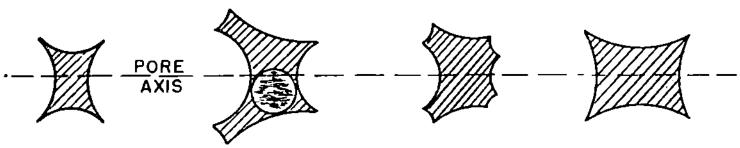
CROSS-SECTION OF AN INDIVIDUAL PORE SPACE

(grains equal spheres)



ONE ORIENTATION OF TIGHTEST GRAIN PACKING

Fig. 1.



SECOND ORIENTATION OF TIGHTEST GRAIN PACKING

Fig. 2.

The other half of the pore is a mirror-image of these shapes. If the sand grains are oriented differently but with the same tight packing (25.9 percent porosity), the new and different cross-section shapes are shown in Fig. 2.

If there is poor sorting, with a wide range of grain sizes, small grains will lodge in the pore spaces between the larger grains and increase the complexity of the pore space. If small particles are placed in the foregoing cross-section (see Fig. 2), there will be less pore space but greater complexity of shape.

Limestones: Porosity in limestones, in general, is unlike that found in sandstones, and is found as joints, fractures, fissures, and intercrystalline openings. Solution processes also create porosity and increase already existing openings. In limestones the pore development is very irregular and non-uniform in distribution. Two extremes of porosity distribution in limestones – with infinite intermediate variations – are 1. mass of the limestone with widespread but poorly developed fine pore spaces super-imposed by a highly developed main jointing system giving high intercommunication throughout the formation, and 2. mass of the limestone with well developed porosity but lacking in intercommunication throughout the formation because of a poorly developed main jointing system.

The first example is exemplified by a large oil field in the Middle East where the main mass with fine pores merely allows the oil to ooze slowly through it with difficulty. But the well developed jointing system provides the "highway" path for flow long distances through the rock to the oil wells. Such an oil field must be operated differently than a normal field in order to produce oil efficiently.

The second example is exemplified by the large West Edmond Field in Oklahoma which has well developed porosity in the limestone but a poorly developed jointing system. The oil cannot flow easily from its place in the rock to the oil wells some hundreds of feet away.

Grain Surface of Reservoir Rocks: Mineral grain surface exposed in the pores of buried rocks is of great importance to the ease or difficulty of fluid flow through porous rocks and of the retention of oil and water by adhesion. Two rocks of identical pore space (i.e., percent porosity) may have entirely different pore development and distribution. For example, one piece of rock may have only a single cylindrical opening or pore space passing through it and giving a minimum mineral surface area for the given volume of pore space, while another rock may have the same amount of porosity highly disseminated throughout the piece of rock as a complex network system of many fine interconnecting openings and giving a large mineral surface area exposed for the given volume of pore space.

The amount of mineral surface area exposed in a theoretical sandstone composed of spheres may be calculated. It may be considered that the grains are all of the same size. For a given volume of rock if the grain diameter is decreased by ½, the number of grains (for the same original rock volume) increases 8 times and the exposed mineral grain surface increases 2 times; if the grain diameter is decreased to ¼, the number of grains increases 64 times and the grain surface by 4; if the grain diameter is decreased to ⅛, the number of grains increases to 512 and the grain area 8 times, etc. Thus, the smaller the particles composing the sandstone the greater the mineral surface exposed in the pore spaces and the area exposed increases rapidly with decrease in grain diameter. The grain diameters of average oil sandstones have a range of 10 to 1. Two factors which further increase the values of the above theoretical grain surface calculation are grain shape and heterogeneous grain size distribution. When a grain of given volume is distorted from the spherical a greater surface area is required to enclose the given volume. Most sand grains are rarely spherical and are considerably misshapen. Sandstones generally have poor sorting and are composed of a wide range of grain sizes with the smaller often lodging inside of the pores formed by the larger grains. This type of packing further increases the amount of mineral surface exposed.

Total Porosity and Effective Porosity: All pore spaces in a rock are not always in fluid communication with each other but because of cementation, principally, some pores may be completely isolated. The isolated pores do not contribute to active pore capacity of the rock for storage of water, oil, and gas, nor do they assist in the fluid conductivity of the rock.

Absolute or *Total Porosity* of a rock represents all of the pores in a rock, both the active and the isolated, while *Effective Porosity* represents only the active and intercommunicating pores. The effective porosity is important to the oil man as the active pores are the only ones in the rock which yield oil and gas to an oil well. In oil sands the actual differences found between total and effective porosities is not much more than 10 percent.

PERMEABILITY

The permeability of a porous rock is of the greatest importance to life on the earth and of the utmost importance to the economic life of the oil industry. The characteristic of permeability of a rock is the flow of fluids through it. Without permeability buried aquifers could not conduct water long distances underground nor soils absorb or yield water, and oil formations could not yield their valuable oil and gas to oil and gas wells.

Permeability may be defined as the ease or difficulty with which a porous rock permits fluids to flow through it. Porosity and permeability are not related. Two rocks may have the same porosity but differ greatly in permeability. This is due to the actual size of the pore spaces (the greater the actual openings the greater the permeability), the complexity of the cross-sections of the pore spaces (discussed under porosity), the amount of mineral surface area exposed, and the amount of cementation which may accumulate at the constrictions between pore spaces. A small amount of cementation (from any materials—quartz, calcite, silt, clays, etc.) in strategic places in pores may block almost entirely any fluid movement through them.

Permeability is defined as a numerical coefficient which expresses the fluid flow properties of a rock in a single number. This number includes all of the geological factors inherent in a particular rock of pore size openings, grain size and size distribution, particle packing, grain shape, degree of cementation, grain surface exposed, etc. In the oil industry the symbol used for permeability is "k" and is a composite number expressing the above geometrical properties of the porous rock. The units of k which expresses the permeability of a rock is the darcy, and its subdivision, the millidarcy—which is 1/1000 of a darcy.

A rock with a high fluid conductivity or permeability of one darcy would be and do the following: a porous rock of one square cm. in cross-section, one cm. long, acted upon by a pressure difference of one atmosphere across its ends, and conducting a fluid of one centipoise absolute viscosity (water at room temperature has an absolute viscosity of nearly one centipoise) will transmit or allow to pass through it a volume of fluid of one milliliter per second. Beach sands and some aquifers sometimes have permeabilities of several darcies but most oil sands have permeabilities of 1/10 to 1/20 darcies (or about 100 millidarcies to 50 millidarcies). The Williston

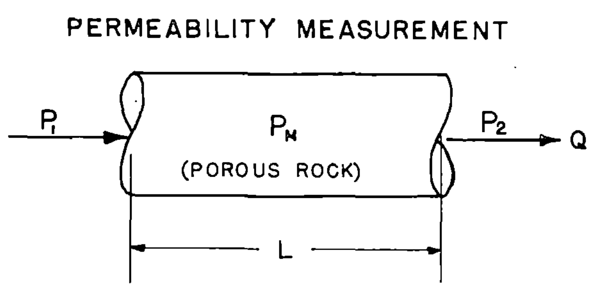


Fig. 3.

Basin Madison Limestone which is the main oil producer in North Dakota has a low permeability of about 5 to 10 millidarcies.

Precisely, the permeability of a rock is expressed as follows—for linear flow with compressible fluid (air) (see Fig. 3):

$$K = \frac{\mu \; Q_m L}{A \; (P_1 - P_2)}$$

when K=permeability in darcies

μ=viscosity of air or nitrogen=(0.018± centipoise)

Q_m=ml/sec of air transmitted, reduced to mean pressure

L=length of rock sample, cm.

A=Cross-sectional area of rock sample, cm^2

P_1=Input pressure, expressed as atmospheres

P_2=Discharge pressure, expressed in atmospheres

and where mean pressure $P_m = \frac{P_1 + P_2}{2}$

and $Q_m = \frac{QP_2}{P_m}$

where Q=ml/sec of air or nitrogen measured at discharge pressure P_2

Note: Q_m will be numerically smaller than Q (slightly)

The assumptions are that:

1. There is only one fluid present (single phase).
2. The pore spaces are completely filled with the fluid.
3. Rate of flow is in the viscous region of flow.

Permeability in Oil Rocks: In soils and aquifers the only fluid filling the pores and wetting the pore wall surface is water and their permeabilities are uniquely expressed by the permeability equation. The pore spaces are filled only with one kind of fluid (called single phase)—water.

In oil rocks the pore spaces are generally filled with a combination of three substances, oil, water, and gas, all sharing a pore space in proportion to the quantities of each present. Further, the distribution of the 3 fluids (water and oil are "wetting" and gas "non-wetting") in the pore space generally follows a strict arrangement: the water generally wets the mineral wall surfaces of the pore and much of it is tightly bound to the wall and immovable because of the surface forces of the solid; next, the oil occupies the space between the water (on the walls) and towards the center of the pore; and finally the gas, because of its great mobility compared to water or oil, occupies the center of the pore along its axis and the position of easiest flow.

When an oil rock whose pores are filled with oil, water, and gas in the distribution as described, is acted upon by a differential force which causes the pore fluids to flow, usually two—the gas and oil—and sometimes all three fluids flow simultaneously under the same flowing forces and emerge at the discharge end where each fluid may be measured accurately (see Fig. 4).

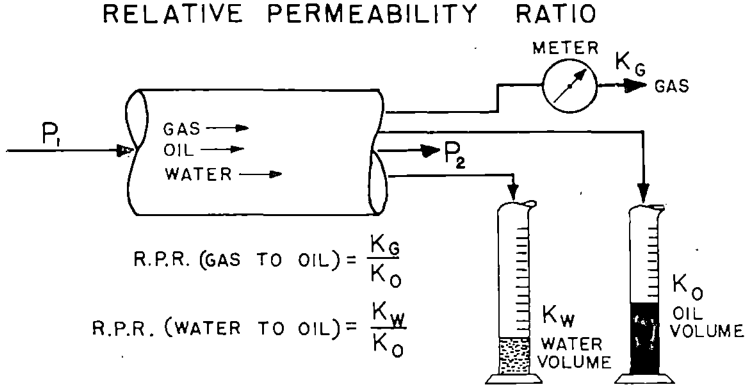


Fig. 4.

Thus, a given rock behaves in its flow properties to each fluid differently than with any one of the fluids alone. The language used would be: "the permeability of the rock to oil is x millidarcies"; "the permeability of the rock to gas is y millidarcies"; and "the permeability of the rock to water is z millidarcies".

If the permeability of a rock to a single phase fluid (e.g., oil only) is measured starting with the pore spaces completely filled, the standard permeability value is obtained and uniquely expresses the permeability of the rock, i.e., the Specific Permeability. But if the amount of oil in the pore spaces is decreased, i.e., the oil saturation of the sample is decreased, the conductivity or the permeability of the rock to oil is decreased, decreasing rapidly at first with small decreases of oil saturation, then more slowly, and finally becoming zero at a finite oil saturation of 20-35 percent.

In the previous example with three fluids present in the pore spaces and all moving simultaneously, the saturation of each in the pore spaces is less than 100 percent; therefore, the permeability of the rock to each fluid (oil, water, gas) for that particular moment will be less than for each fluid alone completely occupying the pore space (i.e., 100 percent saturation).

As flow proceeds, and the saturations of each fluid (oil, water, gas) in the pore spaces changes with flow and time, so does the permeability of the rock for each fluid. Usually the permeability of the rock to oil and water decreases very rapidly while the permeability of the rock to gas increases rapidly.

Thus, the fluid conductivity of an oil rock to oil, water, and gas during production of an oil field constantly changes in a complex manner, and changes in such a way that oil is produced less and less efficiently while gas is undesirably produced in greater and greater quantities.

Because of the complex permeability behavior of oil rocks under simultaneous flow of oil, gas, and water, several kinds of permeability are defined:

1. *Specific Permeability*—(k) permeability of a rock to a single phase fluid saturating the pores 100 percent. Expressed in Darcies or millidarcies (see Fig. 3).
2. *Effective Permeability*—(K_{eff}, or Ko, Kg, Kw) permeability of a rock to a single phase fluid at some pore saturation less than 100 percent. K_{eff} decreases with fluid saturation. Expressed in darcies or millidarcies.
3. *Relative Permeability*—($\frac{K_{eff}}{K}$) ratio of the effective permeability (K_{eff}) of the rock to a given fluid to the permeability of the rock to the same fluid at 100 percent saturation. This

is expressed in percent and varies from 0 to 100 percent. This is one of the most important relationships in petroleum engineering.

4. *Relative Permeability Ratio* (R.P.R.) ($\frac{Kg}{Ko}$) (a mobility ratio) (see Fig. 4). This ratio takes the effective permeabilities of two fluids under simultaneous flow and expresses how many times easier one fluid is transmitted through the rock compared to the other fluid, e.g., if the effective permeability of the rock to gas and the effective permeability of the rock to oil is measured for the given pore saturations of each under the same conditions of flow and their ratios are taken, i.e., $\frac{Kg}{Ko}$, then the dimensionless numerical value obtained is the Relative Permeability Ratio and expresses the mobility of the gas in the pores compared to the mobility of the oil. The numerical values vary from zero to infinity. For example: if the gas saturation in the pores is low, the gas effective permeability of the rock is nearly zero; and if the oil saturation in the pores is high, the oil effective permeability of the rock is high, therefore, the R.P.R. is nearly zero or zero. If the pore saturations for the gas and oil are reversed, then the effective permeability of rock for each is reversed and the R.P.R. then is large and can go to infinity.

Fixed water on pore wall surface: Permeability is affected by water in the pores tightly bound to the wall surfaces. The water acts as part of the pore wall and because of its thickness, in effect, reduces the diameter of the pore space and hence its conductivity (or permeability) to oil and gas. The new radius of the pore, due to the bound water, is called a "hydraulic radius" and is smaller than the true geological pore radius. The hydraulic radius effect increases considerably in rocks with small dimension pores ("tight formations") and decreases the permeability much below that if the pores were not water-wet.