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Comparison of Permeability Correlations for Different Rock Fabric

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Abstract: Estimation of rock permeability (k) is an important aspect of petroleum engineering, often accomplished by using correlations based on water saturation or pore configuration or both. However, utilizing a correlation to determine k without knowing the pore configuration of the rock for which the correlation was originally developed can yield ambiguous results. An erroneous k can lead to incorrect reservoir performance estimation and improper development plans. This study demonstrates the need for defining the pore configuration in order to select a specific model for k estimation with a greater degree of confidence. To accomplish this, thin section petrography and petrophysical properties of several rock samples were analyzed. The measured k values of these rock samples were compared with the k values estimated from several published correlations. The accuracy of each correlation as compared to the measured values was categorized on the basis of rock fabric. Thus, an intuitive guideline was developed as to which correlations are applicable to a given rock.

Key words: Permeability estimation, permeability correlations, pore configuration, rock fabric, rock type

INTRODUCTION

Permeability and capillary pressure are two important parameters for formation evaluation and reservoir management. Permeability is the ability of a rock to permit the flow of fluid while capillary pressure has an influence on the displacement mechanism in porous media. Reliable measurement of these parameters is possible through laboratory core analysis, however, some well logging tools developed in recent years are able to provide some rough estimates. Unfortunately, finding accurate values require that core plugs be retrieved deep from the formation, preserved and transported to the laboratory for measurement (Hematpour *et al*., 2016). Coring is an expensive operation and core measurement in the lab are also time-consuming and expensive while realizing that hundreds of cores have to be analyzed from a single well of a single formation.

In the absence of core analysis data from the lab and/or from well logs, statistical correlations have to be relied upon for permeability estimation despite their subpar accuracy (Tiab and Donaldson, 2015). There is no universally accepted correlation; each correlation having its own limitations and a narrow range of validity. Some of these correlations are sensitive to irreducible water saturation while others are sensitive to pore configuration (size and distribution) and yet a few others are sensitive to both.

Irreducible water saturation is also determined during the laboratory capillary pressure measurements (Thomeer, 1960). The pore configuration is determined by "thin sectioning" of the rock. Thin sectioning has been widely used to study the type of rock and the pore configuration. The previous studies conducted on the petrophysical rock properties lack in terms of designing the criteria for the selection of suitable permeability estimation correlation.

As a result, the difficulty is experienced in the selection of permeability estimation correlation and consequently, the fluid flow in the porous media cannot be modeled accurately. Since, the existing permeability estimation correlations are based on water saturation or pore configuration, therefore, there is a need to develop a sound approach for the selection of a particular correlation to estimate permeability according to the specific pore structure.

Purcell (1949) presented apparatus and method for the measurement of capillary pressure by mercury injection and computed permeability from capillary pressure curve in 1949. Burdine *et al.* (1950) extended Purcell's work and presented a method to estimate permeability from capillary pressure data using pore-size distribution in 1950. Thomeer (1960) developed a correlation to estimate pore geometrical factor from capillary pressure curve and concluded that the shape of capillary pressure curve reveals pore configuration

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characteristics of the rock sample in 1960. Nelson (1994) studied models based on grain size and sorting to estimate permeability of sandstone samples (1994). He also studied the Swanson's correlation to understand the permeability and capillary pressure relationship in 1994. Nelson (1994) estimate permeability based on irreducible water saturation for sandstone samples in 1994. Morris and Biggs (1967), Timur (1968) studied estimation of permeability based on irreducible water saturation for sandstone samples.

In this study rock samples of sandstones with different pore configurations were selected on the basis of thin sectioning and the effective porosity of these samples was measured in the laboratory. Irreducible water saturation was determined from capillary pressure data. Using this extended data, the permeability of each of these rock samples was calculated with the help of well-established correlations and their results were compared with the laboratory measured permeability. As a result, an understanding was emerged as to which correlations are suitable for which type of pore configurations as characterized by grain diameter, sorting, fineness of grains, cementing, sphericity and the pore size distribution. The following correlations that are commonly used to estimate permeability were examined in this study to determine their accuracy. These correlations are based on water saturation or pore configuration.

Correlations primarily based on grain size: Baaren proposed to estimate permeability on the basis of grain size:

$$k = aD^{b} \tag{1}$$

Where:

k = Permeability in millidarcy
D = Grain diameter in mm
a and b = Intercept and slope of a straight line

Nelson (1994) expanded Berg's correlation by including the porosity ($\varnothing$) and percentile deviation (p) as follows:

$$k = 80.8\varnothing^{5.1}D^{2}e^{-1.395p} \tag{2}$$

Correlations based on water saturation: Wyllie and Rose (1950) describe the relationship between permeability, irreducible water saturation and porosity as shown in Eq. 3:

$$k = \frac{a\varnothing^{b}}{S_{wir}{}^{c}} \tag{3}$$

Where:

a, b and c = Fitting coefficients that could be determined statistically
$\varnothing$ = Porosity
S_{wir} = Irreducible water saturation

Using this relationship, Timur (1968), Morris and Biggs (1967) have proposed correlations that are based on Wyllie and Rose (1950) (Eq. 3). Whereas fitting coefficients a, b and c were determined statistically, the porosity and irreducible water saturation could be determined from well logs if core data is not available. Timur (1968) correlation:

$$k = 8.58102\frac{\varnothing^{4.4}}{S_{wir}{}^{2}} \tag{4}$$

Morris and Biggs (1967) correlation:

$$k - 62.5\left(\frac{\varnothing^{3}}{S_{wir}}\right)^{2} \tag{5}$$

Correlation based on pore size distribution: Utilizing the theory by Purcell (1949) and Burdine *et al.* (1950) in combination with the fitting parameters of Brooks and Corey (1966) and using the data of a variety of rock samples whose permeability ranged from 6-8 millidarcy and porosity from 0.3-34%, Huet *et al.* (2005) proposed the following correlation for the estimation of absolute permeability:

$$k = 81718.8669\frac{1}{P_{d}^{1.7946}}\left(\frac{\lambda}{\lambda+2}\right)^{1.6575}\times (100S_{wir})^{0.5475}(\varnothing^{1.6498}) \tag{6}$$

Where:

P_d = Displacement pressure (psi)
λ = Characteristic constant based on rock fabric
S_{wir} = Irreducible water saturation
$\varnothing$ = Effective porosity

MATERIALS AND METHODS

The following steps were taken in order to accomplish:

- Outcrop sandstone core samples were collected
- Thin section slides were made out of the collected samples
- Thin section slides were examined under an optical microscope and their rock fabrics were categorized
- Permeability of these rock samples was determined in the lab along with their porosity and capillary pressure vs saturation plot was generated
- Permeability of these core samples was estimated using each of the above mentioned correlations while using the the laboratory determined data in previous steps
- Comparison of experimentally measured permeability with the estimated permeability

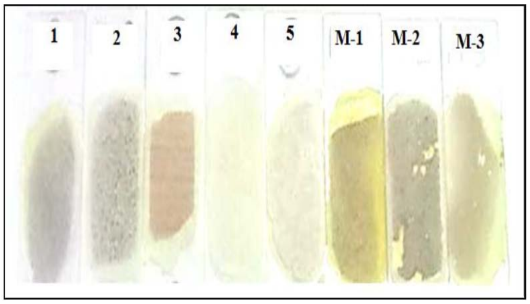

Fig. 1: Thin sections of eight sandstone samples

- Screening of each correlation for their validity in estimating permeability accurately for each of the rock types

Eight sandstone outcrop rock samples were collected from different locations of Pakistan to represent a wide variety of rock fabrics. The porosity of these samples ranged between 9.3-21.6% and permeability from 0.4-60 mD. The diameter of these core plugs was 1.5 inch (3.8 cm) and the length varied from 0.75-3 inch (7.62 cm). Thin sections (microscopic slides) of these core samples were prepared Using geo cutter, geoform thin sectioning system, vacuum impregnation unit and automatic lapping-polishing system and examined under petrographic microscope which consists of a polarizer, an analyzer, a variable focus condenser and a triple nosepiece to describe pore configuration. The eight thin sections of sandstone specimens used in this study are pictured in Fig. 1.

All core samples were cleaned using soxhlet extractor before petrophysical property were measured. Toluene was used as the cleaning agent before start any experiment. Helium porosimeter was used to measure the effective porosity of interconnected pores according to Boyle’s law. Next, gas permeability of the eight samples were experimentally measured by a gas permeameter. Upstream pressure (Inlet) was measured using Bourdon Gauge whereas downstream pressure was assumed to be 1 atm since the outlet was open to the atmosphere.

The core plugs were then saturated in the laboratory using manual saturator with a prepared brine of 1.01 g/cc density. Next, capillary pressure versus saturation relationship was established for each of these cores using porous plate method. In this method, fully water-saturated cores are placed on a porous plate of wettability matching to the core wettability (water-wet in this case). A small gas pressure is applied to the chamber to slightly de-saturate the core. After de-saturation is complete, samples are taken out and weighed in order to determine water-saturation. Pressure is then increased step-wise, measuring water saturation at each step. Thus, a complete Pc vs. Sw drainage curve is obtained.

After porosity and permeability of each core sample were measured in the laboratory and capillary pressure of these core samples were determined at various saturations, the measured data was compared with correlations and their match was analyzed.

RESULTS AND DISCUSSION

Core samples data has been divided into two main sections; the thin sectioning data and the petrophysical properties. Data of both sections have been applied on existing permeability correlations based on either pore configuration or water saturation. The objective was to determine the deviation of a correlation by comparing permeability estimated from the correlation with the permeability measured experimentally.

Analysis of thin sectioning data: The micro-texture of sandstones was analyzed from prepared thin sections. Average grain diameter was determined by measuring and averaging the diameters of the grains. Sorting and sphericity were visually predicted on the basis of standard sorting/sphericity classification by Blatt and Tracy (1994) by using visual charts and particle class of grains and rock type was confirmed by standard scale for clastic rocks. Degree of cementation was visually estimated without identification of cementing materials. Thin sectioning results are given in Table 1.

It is noteworthy to mention that none of the pore configuration attributes, i.e., grain diameter, fineness, cementing, sphericity, sorting, or rock type had any correlation with porosity. This is a reflection that the rock samples in this study have widely diversified rock fabrics. The porosity of unconsolidated sample (#1) being less than the porosity of consolidated samples (M-2, M-3, 3 and 4) can be explained by noting that sample (#1) was poorly sorted, while samples (M-2, M-3,3 and 4) were “very well” to “well” sorted.

Analysis of petrophysical data: Pore volume, absolute permeability and capillary pressure of the eight samples of this study were experimentally measured. Table 2 shows the results of pore volumes and porosity of various samples. Permeability to gas was measured at two mean pressures and the equivalent liquid permeability was found by extrapolation. Figure 2 and Table 3 shows gas permeability of core samples measured at different mean pressures. The permeability of the samples increased as sorting increased such that the poorly sorted samples had lower permeability than well-sorted samples.

Table 1: Thin section analysis of sandstones samples

Sample's Id	1	2	3	4	5	M-1	M-2	M-3
Grain diameter (mm)	0.244	0.374	0.058	0.159	0.53	0.214	0.08	0.063
Porosity (%)	13.4	9.3	21.6	17	9.3	12.8	18.9	20
Fineness	Fine sand	Medium sand	Very fine sand	Fine sand	Coarse sand	Fine sand	Very fine sand	Very fine sand
Cementing	No	Poor	Poor	Very poor	Highly	Poor	Very poor	Poor
Sphericity	Angular	Angular	Rounded	Sub angular	Rounded	Very angular	Rounded	Sub rounded
Sorting	Poor	Very poor	Well	Very well	Well	Poor	Well	Well
Rock type	Classic unconsolidated sandstone	Classic unconsolidated sandstone						

Table 2: Results of measured porosity of core sample used in this study

Sample's Id	Pore volume (cm^3)	Porosity (%)
1	10.6	13.9
2	7.4	9.30
3	10.9	21.6
4	14.9	17.0
5	8.1	9.30
M-1	11.2	12.8
M-2	4.1	18.9
M-3	17.4	20.0

Table 3: Measured permeability of core samples used in the study

	Measured gas pearmeability (mD)		
Sample's Id	K(g)^1	K(g)^2	Equivalent liquid permeability (mD)
1	9.99	8.98	4.0
2	1.57	1.45	0.4
3	40.51	38.11	26.0
4	125.24	118.65	60.0
5	41.68	39.76	30.0
M-1	2.50	2.41	2.0
M-2	38.06	35.38	25.0
M-3	36.89	34.13	20.0

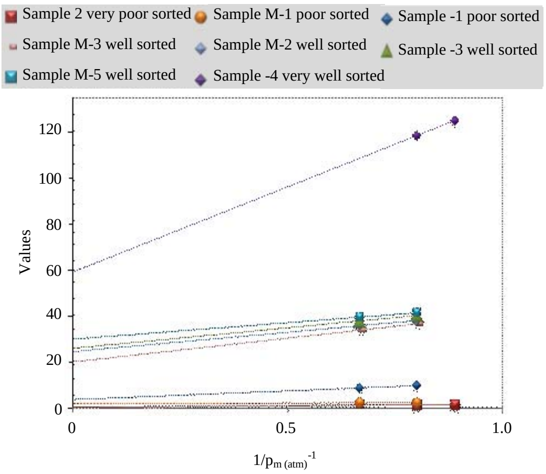

Fig. 2: Gas permeability of core samples versus different mean pressures

Each sample in this study was fully saturated with water and its drainage capillary pressure curves was derived. Displacement pressures and irreducible water saturations were specially noted as they varied due to the variations in pore configuration. From Fig. 3, it can be seen that poorly sorted samples have higher irreducible water saturations and higher displacement pressures than the "well sorted" samples.

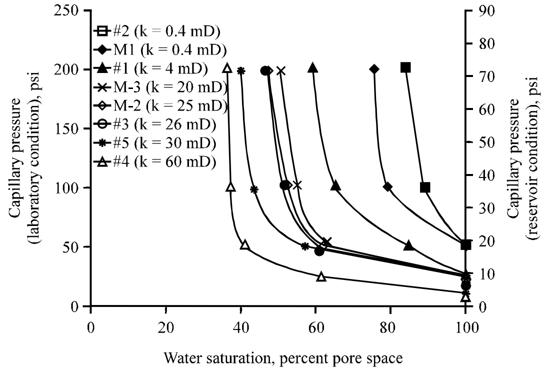

Fig. 3: Measured drainage capillary pressure curves

Comparison of correlations derived based permeability versus lab measured permeability: Permeability was estimated using the selected correlations based on water saturation and pore configuration and compared with experimentally measured permeability as discussed.

Correlation permeability based on grain size: It was observed from Fig. 4 that the permeability from correlations did not match well with measured permeability for core 1, 2 and M-1 whereas other cores matched very well. The three non-matching cores had large grain diameter and were poorly sorted. Thus, Berg's correlation can be applied more confidently in rocks not having these attributes.

Correlation result based on water saturation Timur correlation results: Figure 5 shows that Timur's correlation failed to estimate permeability for cores 3, 4, 5 and M-3. The common characteristic of these four samples was that they were all well sorted and their permeability was relatively higher (20-60 mD) as compared to the permeability of others cores 1, 2, M-1 (0.4-2 mD).

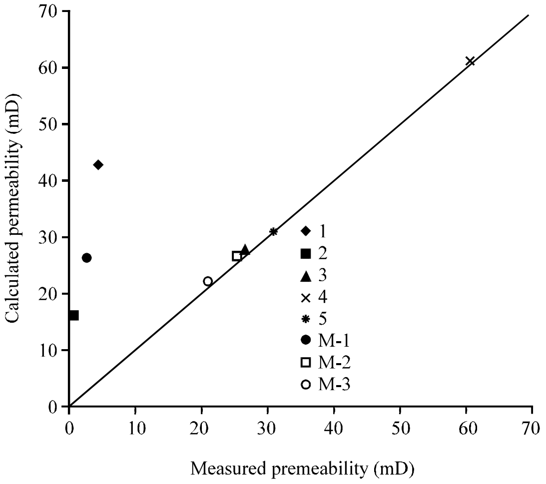

Fig. 4: Comparison between measured and calculated permeability (Berg's correlation)

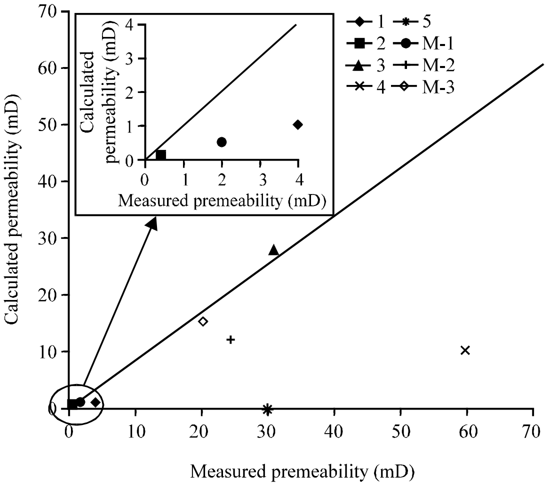

Fig. 6: Comparison between measured and calculated permeability Morris and Biggs (1967) correlation

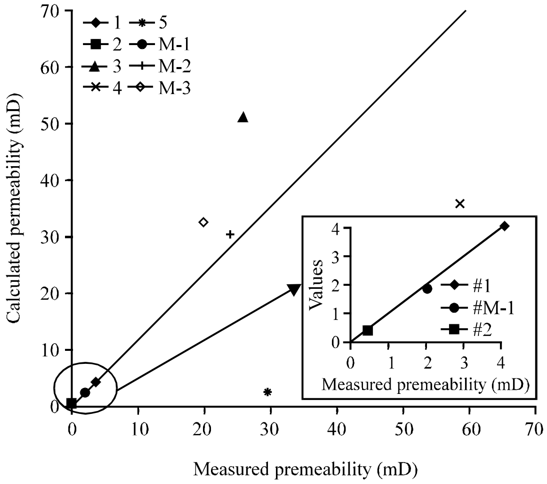

Fig. 5: Comparison between measured and calculated permeability Timur (1968)'s correlation

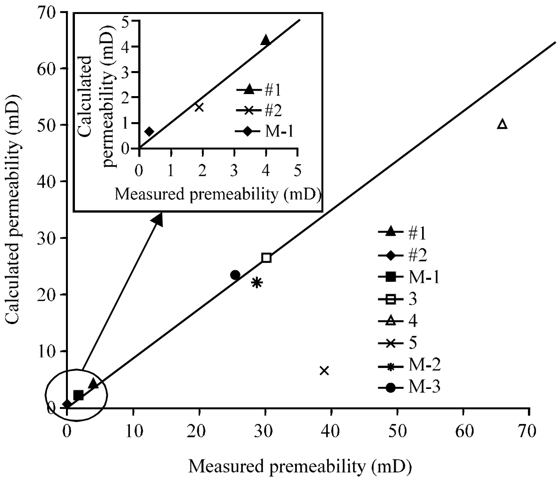

Fig. 7: Comparison between measured and calculated permeability Huet *et al.* (2005)'s correlation

It is not clear why Timur (1968)'s correlation was able to predict the permeability of core M-2 very well even though it was well sorted as well as it had reasonably high permeability (25 MD).

Morris-Biggs correlation results: Figure 6 shows that the permeability from correlation did not match well with measured permeability for most of the cores except core 2, 3 and M-3. No obvious correlation was found except to say that Morris ansd Biggs (1967) correlation gave a lower permeability estimate than Timur (1968)'s correlation for all samples except core 3. It was also able to estimate the very low permeability core 2 reasonably well. Thus, Morris and Biggs (1967) correlation should be used only to increase the level of confidence for cores whose estimated permeability matches closely with Timur (1968)'s.

Correlation based on pore size distribution: Figure 7 shows that this correlation reasonably estimated the permeability of most samples (1, 3, M-1, M-2 and M-3). It deviated significantly for Core 5 which was the only highly cemented and only coarse sand grain sample. The correlation estimated the permeability to an acceptable accuracy for Core 4 which was the highest permeability core. Both of these cores that the correlation had some difficulty in predicting had a high permeability (30-60 mD) and had the lowest S_{wir} (≈40%). Therefore, care should be exercised when using this correlation for highly-cemented, coarse-grain, samples of high permeability and low irreducible water saturation.

CONCLUSION

The reliability and accuracy of estimated permeability can be improved if rock fabric information is obtained by thin section analysis and used for selection of an appropriate correlation. Berg's correlation can be used confidentially for "very well sorted" to "well sorted" samples and it's not suitable for the cores with large grain diameter and poorly sorted. Opposite to Berg's correlation, Timur (1968)'s correlation gave a very accurate estimate of permeability for "very poorly sorted" samples. Morris and Biggs (1967) correlation gave a lower permeability estimate than Timur's correlation, however, it shows less deviation of calculated permeability for small "grain diameter" and high "porosity" samples used in this study.

Morris and Biggs (1967) correlation was also able to estimate the very low permeability core reasonably well. Thus, Morris and Biggs (1967) correlation should be used only to increase the level of confidence for cores whose estimated permeability matches closely with Timur (1968)'s. Huet *et al.* (2005) correlation (correlation based on pore size distribution) gave the best result compare to the other correlation but it had some limited applicability in the samples of this study. It may be considered for "grain diameters" ranging from 0.06-0.25 mm, degree of sorting from "very well sorted" to "poorly sorted", porosity from 12.8-21.6% and fineness ranging from "very fine sand" to "fine sand". It should be avoided to estimate permeability for "very poorly sorted" rocks. Extreme caution should be exercised for highly cemented rocks having the combination of low porosity, course and well-rounded grains and also for poorly sorted rocks having the combination of low porosity, medium fineness and angular sphericity.

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