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Application of Hydraulic Flow Unit Technique for Permeability Prediction in one Iranian Gas Reservoirs, Case Study

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ABSTRACT

Estimating reservoir permeability in un-cored intervals-wells are a generic problem common for all reservoir engineers. In this paper, routine core analysis and well log data of an actual existing gas reservoir, from southwest west of IRAN, were used to develop a model of matrix permeability in un-cored well by using Hydraulic Flow Unit Approach (HFU). The Graphical Clustering Methods such as histogram analysis and probability plot are used to identify the number of hydraulic flow units. Also, the sum of square errors (SSE) method was used as criterion for confirming the optimal number of HFU's. Permeability data can be obtained from well tests, cores or logs. Normally, using well log data to derive estimates of permeability is the lowest cost method. Formation permeability controls the strategies involving well completion, stimulation, and reservoir management.

Results showed that six HFUs were identified from core data and each unit has its own mean Flow Zone Indicator (FZI). In addition, a correlation between FZI calculated from core data and that obtained from well log data was developed for estimating permeability in un-cored intervals-wells with R-Squared Value of 0.60. Also, Lorenz plot shows that the flow units 3 and 6 have a good porosity and high permeability.

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1. Introduction

Permeability is one of rock properties whose quantity is essential to know, in order to measure the flowing capability of a rock (Kadkhodaie et. al., 2013; Susilo, 2010). Permeability data can be obtained from well tests, cores or logs. However, because the costs to cut and analyze cores are so high, few core measurements are routinely available. Normally, one of the methods to calculate permeability, especially in the zone, which does not have any core data is through using the empirical relationship with rock porosity (Figure 1), (Hatampour et. al., 2015; Shenawi and White, 2007, and Elarouci and Mokrani, 2010).

Rock permeability is an extremely important parameter in reservoir characterization and simulation, because it influences the hydrocarbon rate of production, ultimate recovery, optimal placement of wells, pressure and fluid contacts evolution (Nelson, 1994 and 2005). Thus, the proper determination of the permeability is of paramount importance because it affects the economy of the whole venture of development and operation of a field. Therefore, permeability is a key parameter in any reservoir characterization that governs in great extension its handling and development (Iravani et. al., 2018; Soto and Torres, 2001).

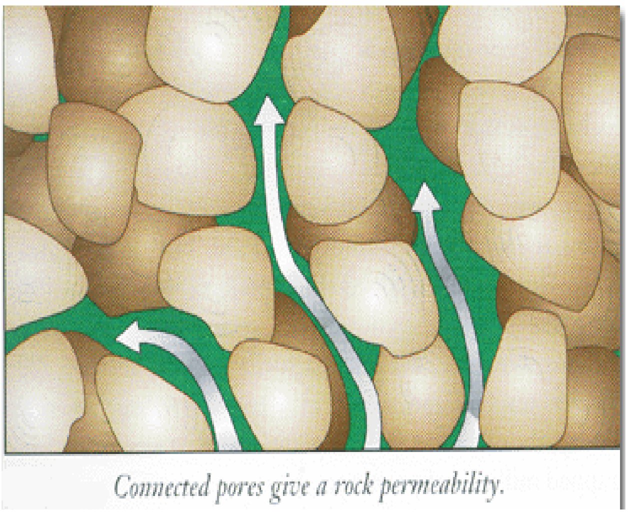

Figure 1: Permeability and Pore Size Distribution

Although permeability values are best determined from core data, most wells are not cored. Consequently, permeability values in un-cored wells are usually estimated from porosity and permeability relationships developed from core data (Oliveira et. al. 2016; Maghsood and Fujimoto, 1995).

The regression models assume that a linear relationship between logarithmic permeability and porosity exists. This method is an empirical method that does not have any basic theory which is applicable for homogeneous reservoir.

$$\text{Log } K = a\,(\text{Ø}) + b \qquad (1)$$

This method proposed by Canas and Malik, (2000) but ignores the scatter of the data around the fitted line and attributes any scatter to measurement errors. The routine core analysis data of an actual existing gas reservoir were used and show in (Figure 2).

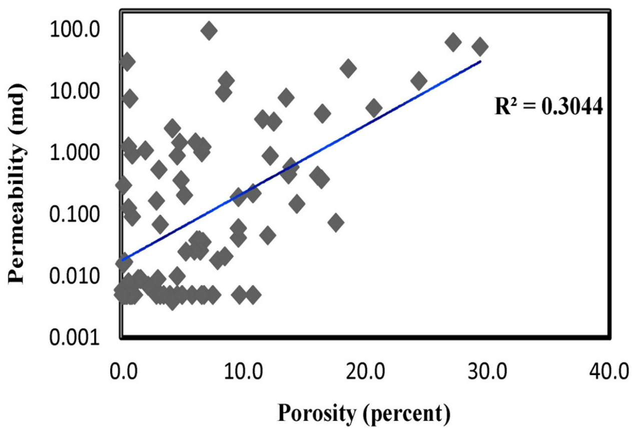

Figure 2: Conventional Porosity - permeability Relationship

Thus, the best correlation between porosity and permeability can be obtained if rocks with similar fluid flow properties are identified and grouped together. Each group is referred to as a hydraulic flow unit.

The objective of this work is to develop a model of matrix permeability by using the Flow Zone Indicator for permeability prediction in un-cored well. All the datasets are gained from routine core analyses and well log data performed in the gas reservoir. Three approaches, such as Histogram analysis, probability plot and sum of square error method are used to identify the number of hydraulic flow units. Predicted permeability was compared with core measured permeability achieved from the core lab database.

2. Application of Hydraulic Flow Unit (HFU) in Reservoir Characterization

Flow unit is defined by Ebanks (1990) as the mappable portion of the reservoir rock within which geological and petrophysical properties that affect fluid flow are internally consistent and predictably different from properties other rock volumes.

There is no unique way to determine rock flow characteristics. This results from the fact that the flow characteristics depend on a variety of parameters such as porosity, permeability, wettability and to some extent on fluid properties. Typically rock typing is accomplished based on several methods each of them has its own engineering basis. The most commonly used methods are porosity-permeability cross plot, Archie's formula based method, capillary pressure, Leverett J-function and flow zone indicator (Saboorian and Mowazi, 2010) .However, none of the above techniques except The FZI method gives rise to a right way to develop a permeability model for this reservoir.

3. Flow Zone Indicator (FZI) Concept

Amaefule and Altunbay, (1993) considered the role of the mean hydraulic radius in defining hydraulic flow units and correlating permeability from core data. Their approach was essentially based on a modified Kozeny-Carmen (1958) equation coupled with the concept of mean hydraulic radius. The equation indicates that for any hydraulic flow unit, a log-log plot of a "Reservoir Quality Index" (RQI) versus "Normalized porosity index" that is the pore volume to grain volume ratio ($\emptyset_z$) should yield a straight line with a unit slope. The intercept of unit slops with $\emptyset_z$ =1, designate as "The Flow Zone Indicator", and is a unique parameter for each hydraulic flow unit. The computations are as follows: (Abbaszadeh and Fujimoto, 1996, Kozeny, 1927)

Normalized Porosity Index,

$$\emptyset_z = \frac{\emptyset}{1-\emptyset} \tag{2}$$

Reservoir Quality Index,

$$\mathrm{RQI} = 0.314\sqrt{\frac{k}{\emptyset}} \tag{3}$$

Flow Zone Indicator,

$$\mathrm{FZI} = \frac{\mathrm{RQI}}{\emptyset_z} \tag{4}$$

So if Eq. (4) is switched to a logarithm, the equation becomes:

$$\mathrm{Log\ RQI} = \mathrm{Log}\ \emptyset_z + \mathrm{Log\ FZI} \tag{5}$$

Samples having a similar FZI value will lie on similar lines with similar gradient value as one, in a log-log plot between RQI and $\emptyset_z$. These samples have similar pore throat attributes and thereby constitute a hydraulic flow unit. On the other hand, samples having a different FZI will lie on other parallel lines (Williams and Batarseh, 2010, Elarouci and Mokrani, 2010).

4. Data analysis

4.1. Core data

All the data sets of permeability and porosity are taken from core samples with a depth range of 2823 to 2873 m (Table 1). The core samples have very wide ranges of porosity (0.1 to 29.4 Percent) and permeability (0.004 to 95.65 md).

Table 1: Routine Core Analysis Data, Permeability and Porosity

Porosity(fraction)	Permeability(md)	$(Ø)_z$	RQI	FZI
0.046	0.906	0.048	0.139	2.890
0.075	0.005	0.081	0.008	0.099
0.058	0.005	0.061	0.009	0.149
0.02	1.095	0.020	0.232	11.38
0.046	0.005	0.048	0.010	0.214
0.029	0.005	0.029	0.013	0.436
0.062	0.038	0.066	0.024	0.371
0.022	0.007	0.022	0.017	0.787
0.066	0.005	0.070	0.008	0.122
0.042	2.512	0.043	0.242	5.538
0.011	0.005	0.011	0.021	1.903
0.032	0.005	0.033	0.012	0.375
0.009	0.092	0.009	0.100	11.05
0.066	1.021	0.070	0.123	1.747
0.04	0.005	0.041	0.011	0.266
0.048	1.48	0.050	0.174	3.458
0.176	0.074	0.213	0.020	0.095
0.161	0.428	0.191	0.051	0.266
0.116	3.51	0.131	0.172	1.316
0.12	0.046	0.136	0.019	0.142
0.084	9.56	0.091	0.334	3.652
0.005	0.005	0.005	0.031	6.248
0.002	0.016	0.002	0.088	44.31
0.003	0.005	0.003	0.040	13.47
0.144	0.148	0.168	0.031	0.189
0.035	0.005	0.036	0.011	0.327
0.067	1.251	0.071	0.135	1.889
0.005	30.13	0.005	2.437	485.0
0.096	0.042	0.106	0.020	0.195
0.029	0.167	0.029	0.075	2.522
0.096	0.193	0.106	0.044	0.419
0.014	0.009	0.014	0.025	1.773
0.067	0.036	0.071	0.023	0.320
0.064	0.038	0.068	0.024	0.353
0.086	14.91	0.094	0.413	4.394
0.244	14.79	0.322	0.244	0.757
0.135	7.87	0.156	0.239	1.536
0.186	23.46	0.228	0.352	1.543
0.125	3.207	0.142	0.159	1.113
0.207	5.35	0.261	0.159	0.611
0.272	62.59	0.373	0.476	1.274

0.294	53.19	0.416	0.422	1.014
0.165	4.35	0.197	0.161	0.815
0.032	0.069	0.033	0.046	1.394
0.031	0.534	0.031	0.130	4.073
0.061	1.489	0.064	0.155	2.388
0.002	0.005	0.002	0.049	24.77
0.065	0.026	0.069	0.019	0.285
0.096	0.06	0.106	0.024	0.233
0.164	0.375	0.196	0.047	0.242
0.139	0.586	0.161	0.064	0.399
0.137	0.448	0.158	0.056	0.357
0.108	0.222	0.121	0.045	0.371
0.009	0.938	0.009	0.320	35.29
0.03	0.009	0.030	0.017	0.556
0.06	0.026	0.063	0.020	0.323
0.108	0.005	0.121	0.006	0.055
0.053	0.025	0.055	0.021	0.385
0.079	0.018	0.085	0.014	0.174
0.122	0.889	0.138	0.084	0.610
0.042	0.004	0.043	0.009	0.221
0.046	0.01	0.048	0.014	0.303
0.052	0.205	0.054	0.062	1.136
0.049	0.358	0.051	0.084	1.647
0.072	95.65	0.077	1.144	14.75
0.068	0.005	0.072	0.008	0.116
0.097	0.005	0.107	0.007	0.066
0.085	0.021	0.092	0.015	0.168
0.066	0.005	0.070	0.008	0.122
0.006	0.128	0.006	0.145	24.02
0.002	0.3	0.002	0.384	191.9
0.006	0.008	0.006	0.036	6.006
0.001	0.006	0.001	0.076	76.83
0.007	7.6	0.007	1.034	146.7
0.006	1.264	0.006	0.455	75.50
0.004	0.005	0.004	0.035	8.741
0.05	0.005	0.052	0.009	0.188
0.007	0.005	0.007	0.026	3.764
0.009	0.005	0.009	0.023	2.577
0.011	0.005	0.011	0.021	1.903
0.016	0.009	0.016	0.023	1.448
0.009	0.005	0.009	0.023	2.577
0.008	0.005	0.008	0.024	3.078
0.001	0.005	0.001	0.070	70.14
0.003	0.017	0.003	0.074	24.84

4.2. Log data

In this study, the well log data, especially primary porosity (Recorded by the sonic log), at the corresponding depth of core data, was used to develop a model of matrix permeability. A combination of porosity logs was used, in order to correct for variable lithology effects in the reservoir. Permeability can be estimated from well log data by using suitable empirical relationship which must be calibrated for each hydraulic flow unit to more direct measurement. Predicted permeability was compared with core measured permeability achieved from the core lab database.

(Figure 3) corresponds to log-log plot of RQI against $Ø_z$ for core data of the gas reservoir. This figure shows a scatter plot of permeability versus porosity for core data from all core samples used in this study. The variability porosity and permeability is an evidence of the existence of microscopic-pore level heterogeneity. The scatter of these plots could be attributed to the existence of more than one rock type, with different fluid flow properties. The regression models using classical RQI-Φ_z plot is the simplest analysis, but it is clearly not sufficient to distinguish between different rocks HFU and estimate their boundaries.

5. Determination of HFU by Using Core Data

5.1. Graphical Clustering Method

In order to investigate the variability and continuity of the hydraulic flow units through a set of gathered data, some of the graphical cluster analysis, such as histogram analysis, and probability plot were used. Graphical clustering methods of histogram analysis and probability plot provide a general visual image of a FZI distribution to determine the number of HFU's.

A histogram of FZI (with the log scale on the x-axis) shown in (Figure 4). This figure shows the number of populations based in the number of normal distributions, thus separating the samples in six HFU. Another Graphical Clustering Method is probability plot. A normal probability plot has a specially arranged coordinate system where a normal distribution forms a distinct straight line. Hence, the number of straight lines identifies the number of HFU's. The cumulative probability plot allows picking out at least 6 HFU and estimate FZI boundaries for these rock types (Figure 5). The probability method is more useful than the histogram method because the scatter in the data is reduced on this plot and it is easier to identify straight lines visually.

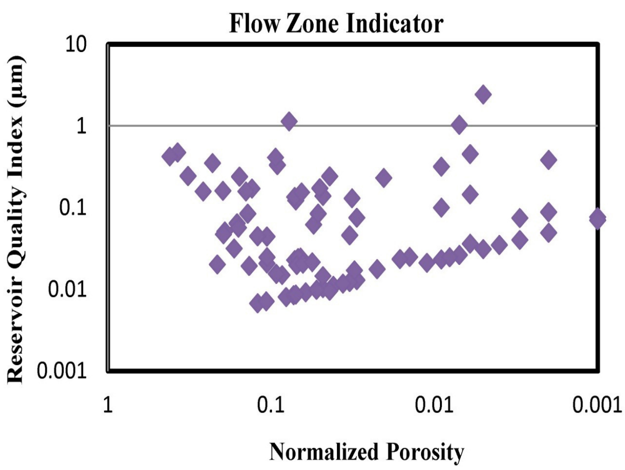

Figure 3: Reservoir Quality Index against Normalized Porosity

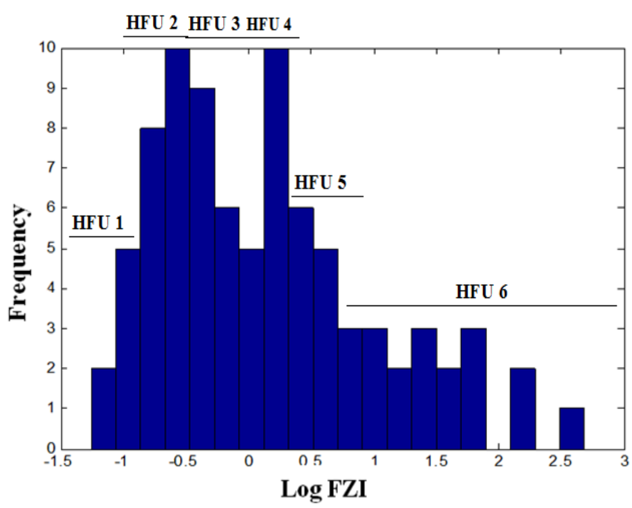

Figure 4: Graphical Clustering Methods of Histogram Analysis

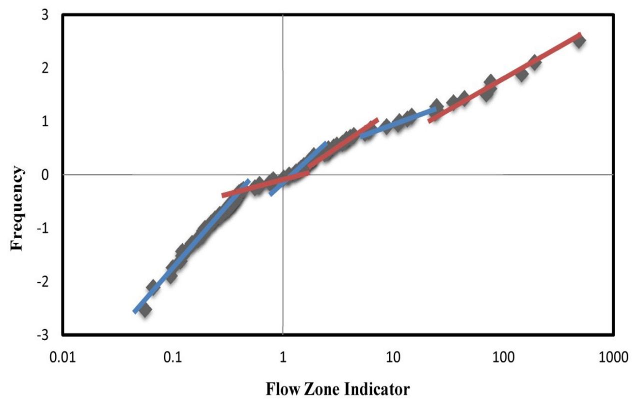

Figure 5: Graphical Clustering Methods of Probability Plot

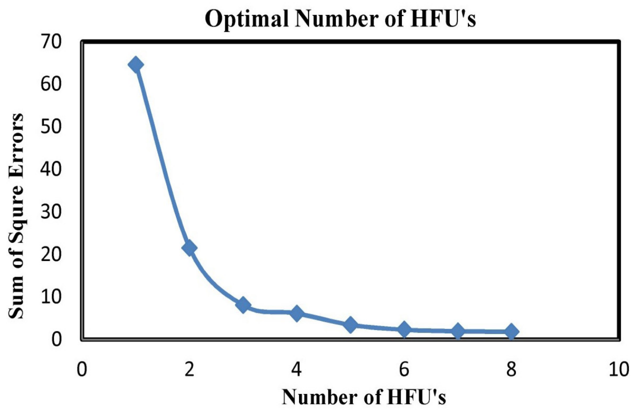

Figure 6: Optimal Number of HFU's by Using SSE

5.2. Graphical Clustering Method

Graphical clustering methods may carry some biased errors because they are based on visual interpretation. Moreover, the overlapped individual distributions and the transition zones between HFU's may cloud the judgment on their identity. The optional number of HFUs that exists in the reservoir can be determined by applying the sum of square method. The proposed method is outlined in the following steps:

1. Compute the values of FZI from equations (4) using the core data.
2. Assume that there exists only one rock type in the reservoir and plot RQI versus $Ø_z$ in logarithmic space and after that calculate the Sum of Square Error.
3. Using K-means clustering analysis for Log (FZI) and decided which data belonged to each unique HFU and consider there are two rock types in the reservoir and computes the SSE's.
4. Increased the number of HFU's in the reservoir by using K-means clustering analysis, until the sum of square error is a minimum for the desired number of HFUs.

By applying the above procedure to core data, the resulting of sum of square error are plotted against number of HFU's in (Figure 6). This figure shows that the optimal number of HFUs is equal to six. This means that six rock types exist in the studied reservoir.

6. Stratigraphic Modified Lorenz Plots

Stratigraphic modified Lorenz plots (Chekani and Kharrat, 2009) is a plot of cumulative flow capacity versus cumulative storage capacity ordered in Stratigraphic sequence. As it is shown in (Figure 7) flow units 1 and 2 have a good porosity and low permeability. Flow units 3 and 6 have a good porosity and high permeability. Flow unit 3 is considered to be the major production zone because of its thickness and permeability while flow unit 2 is a major contribution to the total production. Flow unit 4 and 5 correspond to a very thin and low permeability zones.

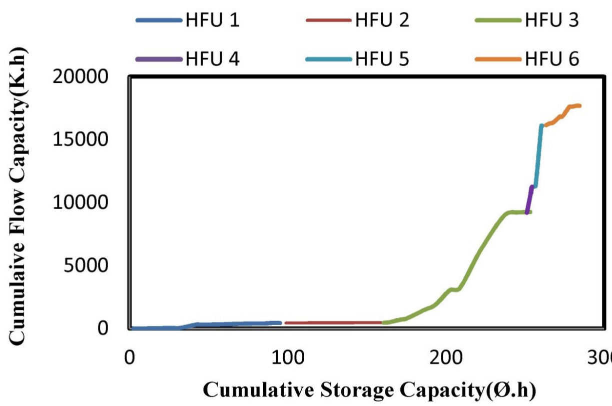

Figure 7: Stratigraphic Modified Lorenz Plots

7. Permeability Modeling

On the basis of the optimal HFU's from the Multi-linear Regression Clustering Technique, a combined RQI versus $Ø_z$ graph is made for all the core data, as shown in (Figure 8). The six unit slope lines are drawn through segments of data according to mean FZI (Table 2) values calculated for each group of data that belong to the same HFU.

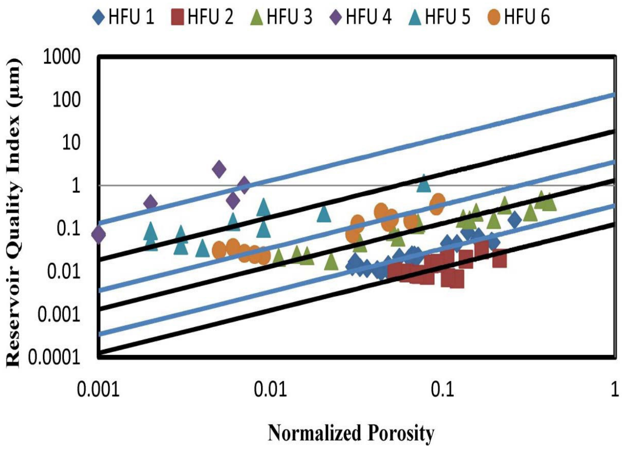

Figure 8: Unit Slope Lines of Six HFU's

Table 2: Mean Flow Zone Indicator for each HFU's

HFU	(FZI) mean
1	0.34
2	0.13
3	1.33
4	133.10
5	18.64
6	3.60

The values of mean FZI (The intercept of unit slops with $Ø_z$ =1) are used to calculate permeability from the following equation (Rearrange Equation 4 with respect to K):

$$K = 1014.\,(FZI_{mean})^2 \times \frac{Ø^3}{(1-Ø)^2} \quad (6)$$

To check the permeability model the calculated permeability from core data is plotted against the measured ones in (Figure 9). This cross-plot indicates the closeness of the data to the 45° straight line, and the reliability of the trend and accuracy of the forecast between calculated permeability and the measured ones is equal to 0.933.

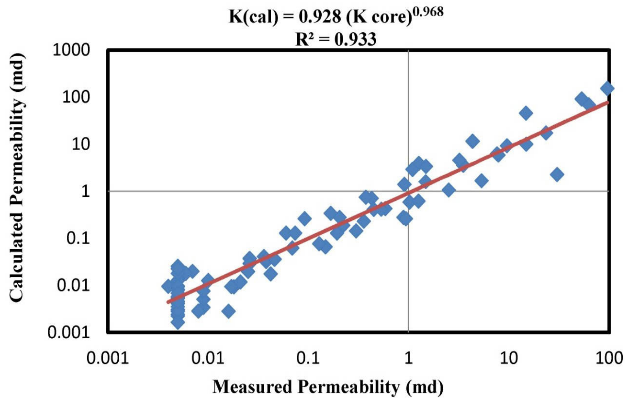

Figure 9: Measured Permeability vs. Calculated Permeability by Using Core Data

8. Predicting Permeability in Un-Cored Wells

The concept of hydraulic flow units must be applied to the wells where only well-log data are available. In this study, the values of mean FZI calculated from core data were correlated with porosity determined from log data, and the evaluation is given in (Figure 10). It indicates a good correlation and the fitted equation is:

$$FZI\ mean = 0.025(Ø_{Log})^{-1.13} \quad (7)$$

Matrix Permeability estimation using the HFU method was extended to un-cored wells by substituting Equation (7) in Equation (6), as follows:

$$K_{Log} = 0.63375 \times \frac{Ø_{Log}{}^{0.74}}{(1-Ø_{Log})^2} \quad (8)$$

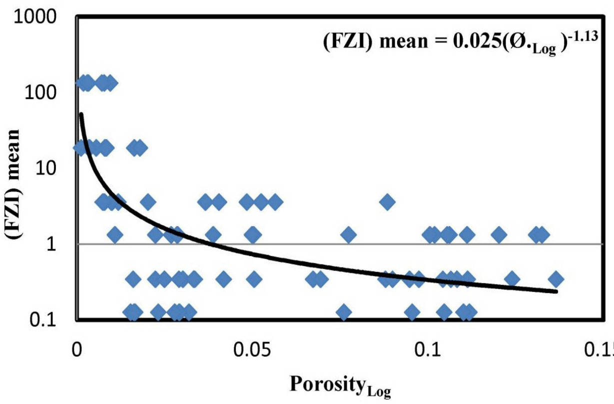

Figure 10: Mean FZI Correlation with Well Log Data

The above equation can be used to estimate the permeability in un-cored wells by using the porosity calculated from well log data at the corresponding depth of core data. To determine the accuracy of Equation (8), it was used to calculate the permeability from well log data and then compared with the corresponding ones of core data. The evaluation is given in (Figure 11). This cross-plot indicates the closeness of the data to the 45° straight line. In addition, the reliability of the trend and accuracy of the forecast between calculated log permeability and the measured ones is equal to 0.589.

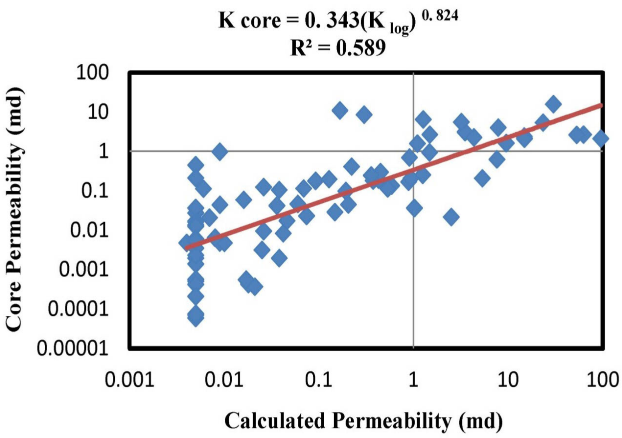

Figure 11: Measured Permeability vs. Calculated Permeability by Using Log Data

9. Conclusion

In this study a technique based on HFU's has been developed that allows for better estimation of permeability in un-cored wells and the following conclusions obtained:

- The results indicate that the permeability profiles of the log-derived HFU agree with core data, and also the R- squared value is 0.59.
- A combination of graphical approaches with regression analysis and analytical clustering methods would be most useful in better delineation of the hydraulic flow units.
- When the number of HFU's increased, the amounts of SSE decreased and by applying an HFU's Approaches to the data of a gas reservoir determine the existence of six flow units.
- Lorenz plot shows that the flow units 3 and 6 have a good porosity and high permeability.

Nomenclature

FZI = Flow Zone Indicator, μm

HFU = Hydraulic Unit, Integer

K = Permeability, mD

RQI = Reservoir Quality Index, μm

Ø = Porosity, Fraction

$Ø_z$ = Pore Volume to Grain Volume Ratio, Fraction

Subscripts

R^2 = Coefficient of Determination

RQI = Reservoir Quality Index

SSE = Sum of Square Errors

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چکیـــــــده

تخمین تراوایی در چاههای فاقد مغزه یکی از چالش های مهندسین مخازن است. در این مطالعه، از داده های آنالیز متداول مغزه به همراه داده های چاه پیمایی یکی از مخازن گازی جنوب غرب ایران به منظور تعیین مدل تراوایی با استفاده از مفهوم واحد جریان هیدرولیکی استفاده شده است. روش های آنالیز خوشه بندی شامل آنالیز هیستوگرام و نمودار احتمال نرمال جهت تعیین تعداد گروه های سنگی مورد استفاده قرار گرفت. همچنین، روش خطای حداقل مربعات جهت تعیین تعداد بهینه گروه های سنگی در نظر گرفته شده است. داده های تراوایی از طریق آنالیز چاه آزمایی، مغزه و چاه پیمایی به دست می آید. با این وجود استفاده از داده ای چاه پیمایی از ارزان ترین روش ها است. اهمیت تراوایی سازند در تکمیل چاه، تحریک سازند و مدیریت مخزن تاثیر می گذارد. نتایج نشان می دهد که ۶ واحد جریان هیدرولیکی وجود دارد که هرکدام شاخص ناحیه جریانی مربوط به خود را دارد. علاوه براین، یک معادله تجربی بر اساس داده های مغزه و چاه پیمایی جهت تخمین تراوایی با دقت ۰/۶۰ ارایه گردید. همچنین، نمودار لرنز نشان می دهد که واحد جریانی ۳ و ۶ دارای تراوایی و تخلخل قابل توجهی هستند.

واژگان کلیدی: شاخص ناحیه جریانی، واحد های حریانی هیدرولیکی، مخازن گازی، آنالیز هیستوگرام، نمودار احتمال، خطای حداقل مربعات