8º CONGRESSO BRASILEIRO DE PESQUISA E DESENVOLVIMENTO EM PETRÓLEO E GÁS

TÍTULO DO TRABALHO:

Hydraulic Flow Units Obtained from Distinct Permeability Models Based on Core Data of Carbonate Reservoir

AUTORES:

Waldir L. Roque[1], Moises D. dos Santos[1] and Tatiana A. Simões[2]

INSTITUIÇÃO:

[1]Departamento de Computação Científica, UFPB, [2]Programa de Pós-Graduação em Engenharia Mecânica, Centro de Tecnologia, UFPB

HYDRAULIC FLOW UNITS OBTAINED FROM DISTINCT PERMEABILITY MODELS BASED ON CORE DATA OF A CARBONATE RESERVOIR

Abstract

Hydraulic flow units (HFU) are regions of a reservoir that exhibit similar petrophysical and fluid flow properties. A HFU is characterized as a rock sample with a flow zone indicator (FZI) that lies on a unit slope line on a log-log scale. The FZIs are determined from core data and it is often used to uncored wells based on correlations with log data attributes. Distinct permeability models provide different FZIs, however it is important to find out the HFUs that are equivalent in these models. Theoretically, FZI is based on the Kozeny-Carman permeability model and may be estimated using the pore tortuosity, the shape factor and the specific surface area per unit grain volume, but these parameters are not easily obtained neither from core nor from well log data. On the other hand, FZI can be obtained from the effective porosity and permeability through the reservoir quality index (RQI), which can be estimated experimentally in a laboratory. Recently a model was proposed by Gholinezhad and Masihi (GM) which includes the presence of irreducible water saturation, and from this model a set of FZI were generated based on core data of an Iranian carbonate reservoir. An alternative physically-deduced model has been proposed by Izadi and Ghalambor (IG) modifying FZI to including irreducible water saturation. In this paper, we investigate the correspondence between the discrete rock types (DRTs) and FZIs obtained from the Laboratory, GM and IG models. Once equivalent DRTs and FZIs are identified, to be able to compare the models, an investigation of the limits of agreement was conducted with the Bland-Altman technique. A comparative analysis of the corresponding DRTs between GM and IG models, within 95% limit of agreement, has shown that the FZIs can be used indistinctly and consistently to accurately find out the HFUs of a reservoir. Although none of the models is in fact a gold standard model, the results are supporting that among the them the IG model produces refined FZIs, providing the most accurate and trustful HFUs.

Introduction

A hydraulic flow unit (HFU) is a representative volume of a total reservoir rock in which geological and fluid flow properties are internally consistent and predictably distinct from properties of other reservoir rocks. The determination of HFUs is an important step in reservoir characterization and for the identification of appropriate regions to well placement.

Amaefule et al. [1], based on the Kozeny-Carman (KC) model proposed the concepts of reservoir quality index (RQI) and flow zone indicator (FZI) and a relationship between these quantities as a mean to identify HFUs. FZI is one of the major techniques for a reservoir description, providing a relationship between permeability and porosity of a reservoir. The FZIs are determined from core data and it is often used to uncored wells based on correlations with log data attributes. Distinct permeability models provide different FZIs, however it is important to find out the HFUs that are equivalent in these models. Theoretically, FZI is may be estimated using the pore tortuosity τ, the shape factor F_s and the specific surface area per unit grain volume S_{gv}, but these parameters are not easily obtained neither from core nor from well log data. On the other hand, when the effective porosity and permeability are known experimentally, FZI can be obtained through the reservoir quality index (RQI) and from the set of FZI points HFUs are identified. However, when different permeability models are given, a set of different FZIs are generated, leading to distinct HFUs. Therefore, it is important to find out which HFUs are equivalent between the models and additionally which model provide the best HFU.

In this paper we estimate the FZIs and discrete rock types (DRT) for three distinct models and then identify the equivalent HFUs between the models. In particular, it is shown that the Izadi-Ghalambor model [2] gives a refined HFU and a comparative analysis based on the Bland-Altman plots shows that for the equivalents HFU the models are comparable within 95% limit of agreement.

Material and Methods

The data used in this paper are from a single well core sample of a southern Iranian carbonate reservoir from a depth of 2793 – 2867 meters [3]. The average irreducible water saturation (S_{wi}) obtained by well log analysis and capillary pressure determination were 10.1% with 1% fluctuations about this average value. Table 1 presents the laboratory effective porosity and permeability data.

AM Model

Amaefule et al. [1] proposed a technique to characterize HFU using the generalized KC model. They divided the KC equation by effective porosity φ_e and took the square root of both sides of the equation. For the permeability in millidarcies, they defined

$$0.0314\sqrt{\frac{k}{\varphi_e}} = \frac{1}{\sqrt{F_s}\,\tau\,S_{gv}} \times \frac{\varphi_e}{1-\varphi_e} \tag{1}$$

where the left hand side term and the first term on the right hand side in equation (1) are defined, respectively, as the reservoir quality index (RQI) and flow zone indicator (FZI), both in units of μm,

$$RQI_{AM} = 0.0314\sqrt{\frac{k}{\varphi_e}}\,, \qquad FZI_{AM} = \frac{1}{\sqrt{F_s}\,\tau\,S_{gv}}. \tag{2}$$

Equation (1) becomes

$$RQI_{AM} = FZI_{AM} \times \varphi_z, \tag{3}$$

where $\varphi_z = \frac{\varphi_e}{1-\varphi_e}$, is the normalized porosity. In a log-log plot of RQI_{AM} versus φ_z, equation (3) is

$$\log(RQI_{AM}) = \log(FZI_{AM}) + \log(\varphi_z), \tag{4}$$

and from that all samples with similar *FZIs* will lie on a straight line of slope one, and samples with different *FZIs* will lie on other parallel lines. The samples on the same line have similar pore throat attributes, constituting a HFU. Since *FZI* is a continuous variable, it is common to discretize it using the discrete rock type (DRT) [4]

$$DRT = round(2\ln(FZI) + 10.6), \tag{5}$$

where each *DRT* value characterizes a hydraulic flow unit. Therefore, the principle of the classification of 3D cells of a reservoir comprising distinct HFUs can be obtained from the set of *FZIs* that corresponds to a *DRT* value.

Equation (3) provides a relationship for *FZI* in terms of permeability and effective porosity. However, it has been a consensus that irreducible water saturation, S_{wi}, is an important quantity present in the pore space and as such has to be taken into account. Several authors have proposed models relating permeability to porosity and irreducible water saturation [5]. In what follows we consider two new models, compute and identify their main HFUs for each one and compare them to the AM model.

GM model

The permeability model proposed by Gholinezhad and Masihi (GM) in [3], is given by

$$k_{GM} = \alpha \times 10^{\beta\left(\varphi_z \frac{1-S_{wi}}{S_{wi}}\right)}, \tag{6}$$

where S_{wi} is the irreducible water saturation, and α and β are curve fitting constants that are adjustable according to the reservoir.

From equation (1) and (6), we get

$$RQI_{GM} = 0.0314\sqrt{\frac{k_{GM}}{\varphi_e}}. \tag{7}$$

Now, using equation (7), a similar relationship to AM model given by equation (3) is obtained for the GM model

$$RQI_{GM} = FZI_{GM} \times \varphi_z, \tag{8}$$

and then

$$\log(RQI_{GM}) = \log(FZI_{GM}) + \log(\varphi_z), \tag{9}$$

where $FZI_{GM} = FZI_{AM}$, and from equation (5) the corresponding DRT_{GM} are found.

IG model

In a recent paper, Izadi and Ghalambor (IG) [2] developed an alternative approach to the AM model for the determination of HFUs, taking into account the presence of irreducible water saturation in the KC equation. Their result lead to a modified relationship between *RQI* and *FZI*, according to the following equation

$$0.0314\sqrt{\frac{k}{\varphi_e}} \times \sqrt{(1 - S_{wi})} = \frac{1}{\sqrt{F_s\tau}\ S_{gv}} \times \frac{\varphi_e}{1-\varphi_e} \times (1 - S_{wi})^2, \tag{10}$$

where the term on the left of equation (10) has been defined as a modified *RQI*,

$$MRQI = 0.0314\sqrt{\frac{k}{\varphi_e}} \times \sqrt{(1 - S_{wi})}, \tag{11}$$

and the right hand side of equation (10) can be seen as the modified *FZI*, given by

$$MFZI = \frac{1}{\sqrt{F_s\tau}\ S_{gv}} \times (1 - S_{wi})^2, \tag{12}$$

resulting in similar relationship as in Amaefule et al. [1],

$$MRQI = MFZI \times \varphi_z. \tag{13}$$

Equation (12), in a log-log scale becomes

$$log(MRQI) = log(MFZI) + log(\varphi_z), \tag{14}$$

providing a unity slope for the *MFZI*. Notice that with this approach *MFZI* is no longer the original expression given in equation (2). However, to be able to keep a similar form of equation (1), alternatively, equation (10) can be rewritten as

$$0.0314\sqrt{\frac{k_{IG}}{\varphi_e}} = \frac{1}{\sqrt{F_s\tau}\ S_{gv}} \times \frac{\varphi_e}{1-\varphi_e}, \tag{15}$$

where the permeability k_{IG} has been defined as

$$k_{IG} = \frac{k}{(1-S_{wi})^3}. \tag{16}$$

Now, equation (15) exhibits a similar relationship as equation (1) and of equation (3), which in the form of equation (4) becomes

$$\log(RQI_{IG}) = \log(FZI_{IG}) + \log(\varphi_z), \tag{17}$$

where $FZI_{IG} = FZI_{AM}$, and

$$RQI_{IG} = 0.0314\sqrt{\frac{k_{IG}}{\varphi_e}}. \tag{18}$$

Results

Table 1 comprises the data of the porosity, permeability, *RQI*, *FZI* and *DRT* for the AM model, based on the laboratory porosity and permeability values, and for GM and IG models. The permeabilities k_{GM} and k_{IG} given by equations (6) and (16) are obtained taking into account the permeability measured at laboratory, that is, $k = k_{Lab}$.

According to the data in Table 1, the FZI_{AM} that provides the best fit line are collected in the following DRT_{AM}= 6, 7, and 10, with slopes and correlation coefficients given by ($a = 1.0989, R^2 = 0.8947$), ($a = 1.0088, R^2 = 0.8382$) and ($a = 1.0456, R^2 = 0.9474$), respectively. Figure 1 presents these DRT_{AM}.

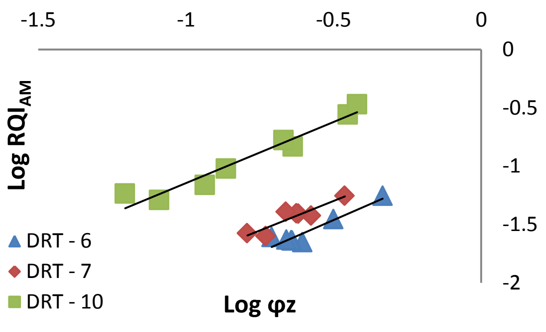

Figure 1. The set of FZI_{AM} and DRT_{AM} that forms the *HFUs* for the AM model.

The constants α and β in equation (5) were found by curve fitting the data of each DRT_{AM} through the linearized transformation,

$$\log(k_{Lab}) = PS \times \beta + \log(\alpha), \tag{19}$$

where $PS = \varphi_z \times \frac{1-S_{wi}}{S_{wi}}$. Table 2 presents the coefficients, for each set of DRT_{AM}, the number of rock samples and the correlation coefficients.

Table 1. Laboratory, Amaefule, GM and IG data

φ_e	k_{Lab}	RQI_{AM}	FZI_{AM}	DRT_{AM}	k_{GM}	RQI_{GM}	FZI_{GM}	DRT_{GM}	k_{IG}	RQI_{IG}	FZI_{IG}	DRT_{IG}
0.022660	0.2	0.0933	4.0235	13	0.3480	0.1230	5.3071	14	0.2753	0.1094	4.7202	14
0.029430	0.7	0.1531	5.0503	14	0.6573	0.1484	4.8939	14	0.9634	0.1797	5.9249	14
0.030188	0.8	0.1616	5.1929	14	0.7062	0.1519	4.8791	14	1.1011	0.1896	6.0922	14
0.044863	7.8	0.4140	8.8148	15	2.8980	0.2524	5.3730	14	10.7353	0.4857	10.3412	15
0.053854	7	0.3580	6.2894	14	7.0334	0.3588	6.3044	14	9.6343	0.4200	7.3785	15
0.058607	0.2	0.0580	0.9317	10	0.2311	0.0624	1.0016	11	0.2753	0.0681	1.0931	11
0.059543	6.7	0.3331	5.2609	14	12.4341	0.4538	7.1669	15	9.2214	0.3908	6.1719	14
0.075122	0.2	0.0512	0.6308	10	0.3141	0.0642	0.7904	10	0.2753	0.0601	0.7400	10
0.077244	0.1	0.0357	0.4268	9	0.1209	0.0393	0.4693	9	0.1376	0.0419	0.5007	9
0.081652	0.1	0.0347	0.3908	9	0.1368	0.0406	0.4572	9	0.1376	0.0408	0.4585	9
0.088661	0.2	0.0472	0.4848	9	0.1669	0.0431	0.4428	9	0.2753	0.0553	0.5687	9
0.099717	0.1	0.0314	0.2839	8	0.1000	0.0314	0.2839	8	0.1376	0.0369	0.3331	8
0.103890	0.5	0.0689	0.5942	10	0.5504	0.0723	0.6234	10	0.6882	0.0808	0.6971	10
0.106818	0.3	0.0526	0.4400	9	0.2834	0.0511	0.4277	9	0.4129	0.0617	0.5162	9
0.108561	0.5	0.0674	0.5533	9	0.2985	0.0521	0.4275	9	0.6882	0.0791	0.6492	10
0.120349	1.1	0.0949	0.6939	10	0.7714	0.0795	0.5810	10	1.5140	0.1114	0.8140	10
0.136791	0.6	0.0658	0.4150	9	0.7129	0.0717	0.4524	9	0.8258	0.0772	0.4869	9
0.138965	0.1	0.0266	0.1650	7	0.1065	0.0275	0.1703	7	0.1376	0.0312	0.1936	7
0.153670	0.5	0.0566	0.3119	8	0.5001	0.0566	0.3120	8	0.6882	0.0664	0.3660	9
0.157051	0.1	0.0251	0.1345	7	0.1420	0.0299	0.1602	7	0.1376	0.0294	0.1578	7
0.163354	0.1	0.0246	0.1258	6	0.0789	0.0218	0.1118	6	0.1376	0.0288	0.1476	7
0.171686	2.1	0.1098	0.5298	9	2.2701	0.1142	0.5509	9	2.8903	0.1288	0.6216	10
0.176512	5	0.1671	0.7797	10	2.7012	0.1228	0.5731	9	6.8816	0.1961	0.9147	10
0.178911	0.3	0.0407	0.1866	7	0.2043	0.0336	0.1540	7	0.4129	0.0477	0.2189	8
0.179605	0.1	0.0234	0.1070	6	0.0988	0.0233	0.1064	6	0.1376	0.0275	0.1256	6
0.185382	0.1	0.0231	0.1013	6	0.1073	0.0239	0.1050	6	0.1376	0.0271	0.1189	6
0.186430	0.1	0.0230	0.1004	6	0.1089	0.0240	0.1047	6	0.1376	0.0270	0.1177	6
0.187177	4.1	0.1470	0.6382	10	3.4947	0.1357	0.5892	10	5.6429	0.1724	0.7487	10
0.191568	0.3	0.0393	0.1658	7	0.2544	0.0362	0.1527	7	0.4129	0.0461	0.1945	7
0.193591	0.3	0.0391	0.1628	7	0.2637	0.0366	0.1527	7	0.4129	0.0459	0.1910	7
0.198857	0.1	0.0223	0.0897	6	0.1305	0.0254	0.1025	6	0.1376	0.0261	0.1052	6
0.209653	0.3	0.0376	0.1416	7	0.3525	0.0407	0.1535	7	0.4129	0.0441	0.1661	7
0.240123	0.3	0.0351	0.1111	6	0.2485	0.0319	0.1011	6	0.4129	0.0412	0.1303	7
0.256637	0.8	0.0554	0.1606	7	0.8857	0.0583	0.1690	7	1.1011	0.0650	0.1884	7
0.261207	20.3	0.2768	0.7829	10	25.6365	0.3111	0.8798	10	27.9394	0.3247	0.9185	10
0.275373	32	0.3385	0.8907	10	39.3209	0.3752	0.9874	11	44.0424	0.3971	1.0450	11
0.316982	1	0.0558	0.1202	6	1.0137	0.0562	0.1210	6	1.3763	0.0654	0.1410	7

Table 2. Values of the curve fitting constants α and β.

DRTs	#Samples	α	β	R^2
6	7	0.0124	0.4633	0.9640
7	7	0.0166	0.5621	0.8879
9	7	0.0166	1.1579	0.9331
10	8	0.0845	0.7887	0.9684
13,14 e 15	6	0.0441	4.3482	0.8604

The case $DRT_{AM} = 8$ has to be discharged due to the fact that is has two points only. From Table 2, the k_{GM} permeability were computed and then by equations (6) and (7) the respective FZI_{GM} and DRT_{GM} were obtained, the values are given in Table 1. The Figure 2 presents the HFUs corresponding to the GM model.

The best fit lines for the FZI_{GM} correspond to the following $DRT_{GM} = 7$ e 10/11, with slopes and correlation coefficients given by $(a = 0.979, R^2 = 0.9614)$ and $(a = 1.0229, R^2 = 0.9013)$, respectively.

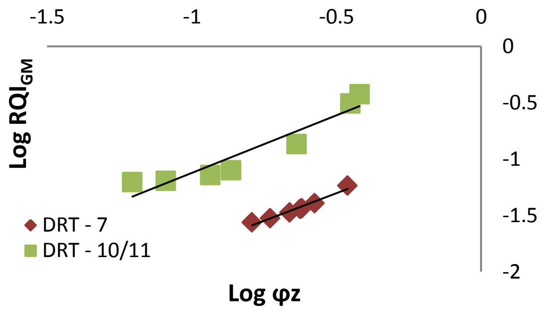

Figure 2. The set of FZI_{GM} and DRT_{GM} that forms the HFUs for the GM model.

Figure 3 presents the HFUs corresponding to the IG model. The best fit line for the FZI_{IG} correspond to the following $DRT_{IG} = 10/11$, with slope and correlation coefficients given by ($a = 1.0451, R^2 = 0.9129$). The Table 3 summarizes the HFUs for the three models.

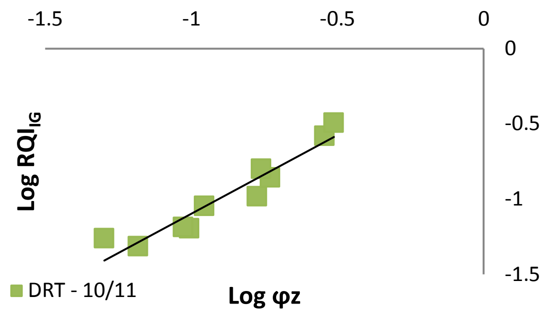

Figure 3. The set of FZI_{IG} and DRT_{IG} that forms the HFUs for the IG model.

Table 3. Best HFUs for the three models. The shades show the HFUs refinement sequence.

AM Model			GM Model			IG Model		
#Samples	DRTs	Slope	#Samples	DRTs	Slope	#Samples	DRTs	Slope
7	6	1.0989	**7**	6	1.107	**4**	6	-0.4051
7	7	1.0088	**7**	7	0.979	**9**	7	0.8255
8	10	1.0456	**7**	10/11	1.0229	**10**	10/11	1.0451

Discussions and Conclusion

The Amaefule model, based on Lab data, provided three main distinct HFUs whose DRTs are 6, 7 and 10. As the AM model does not take into account the contribution of irreducible water saturation, two alternative models including irreducible water saturation have been discussed, namely the Gholinezhad and Masihi (GM) model and the Izadi and Ghalambor (IG) model.

To identify the main HFUs for the GM and IG models, the FZIs for each one were computed and then the DRTs. It has been shown that the main HFUs for the GM model are those ones with DRT_{GM} 7 and 10/11. The DRT_{GM} 10/11 is a merge of 10 and 11, as only two FZI_{GM} correspond to $DRT_{GM} = 11$ and the inclusion of them improved the slope of best fit line. The main HFU for the IG model was identified as having DRT_{GM} 10/11, which is also a merge of the FZI_{IG} providing a better slope for best fit line.

To be able to compare HFUs for the three models the Bland-Altman plot is analysed to see the limits of agreement between them. Figure 4 shows the Bland-Altman plots comparing AM and GM models, and GM and IG models. Although none of the models is considered as the standard model, it can be seen that within 95% limit of agreement, when the best FZIs are compared, anyone of the models can indistinguishably be applied to find out the best HFUs. Nevertheless, when looking at each individual model, it can be seen that AM model provides a large number HFUs; the GM model, which includes irreducible water saturation, shows a refinement to AM model. Finally, the IG model, which extend AM model to include irreducible water saturation, provided an even better refinement for the HFU over the previous two models. In other words, the IG model would select the HFU more accurately than the others.

Of course, the results above cannot be extended straightforwardly to any reservoir, deserving further investigation to be more conclusive.

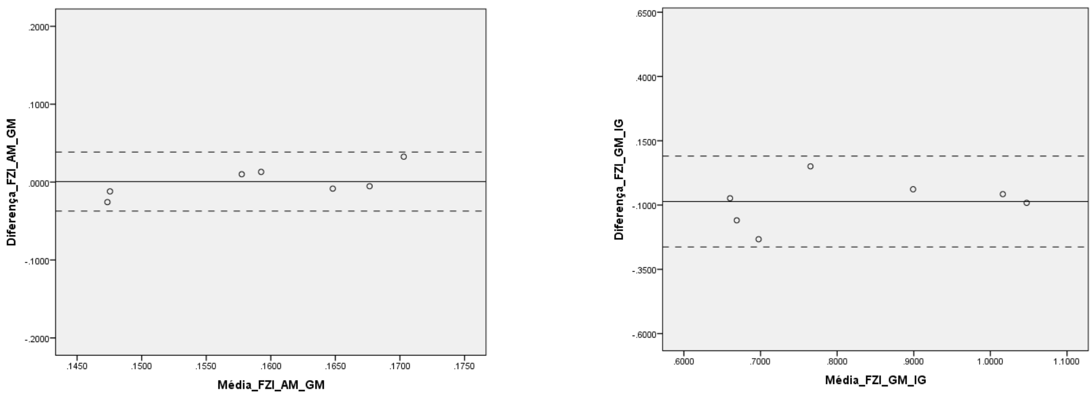

Figure 4. Bland-Altman plots. On the left, AM and GM models for DRT 7; on the right, GM and IG models for equivalent DRT 10/11 only found in both models.

References

[1] Amaefule J.O., Altunbay M., Tiab D., Kersey D. G., and Keelan D.K.: Enhanced Reservoir Description: Using Core and Log Data to Identify Hydraulic (Flow) Units and Predict Permeability in Uncored Intervals/Wells, SPE 26436, presented at the 1993 SPE Annual Technical Conference and Exhibition in Houston, Texas, 3-6 October 1993.

[2] M. Izadi and A. Ghalambor, A New Permeability and Hydraulic-Flow-Unit Determination. SPE 151576 Reservoir Evaluation & Engineering, August, pp. 257-264, 2013.

[3] S. Gholinezhad and M. Masihi, A Physical-based Model of Permeability/Porosity Relationship for a Rock Data of Iran Southern Carbonate Reservoir. Iranian Journal of oil & Gas Science and Technology, vol. 1, pp. 25-33, 2012.

[4] G. Guo, M. A. Diaz, F. Paz, J. Smalley and E. A. Waninger, Rock Typing as an Effective Tool for Permeability and Water Saturation Modeling: A Case Study in a Clastic Reservoir in the Orient Basin, SPE 97033 presented at annual technical conference and exhibition in Dallas, Texas, 2005.

[5] T. Babadagli and S. Al-Salmi, A Review of Permeability-Prediction Methods for Carbonate Reservoirs Using Well-Log Data. SPE 87824 Reservoir Evaluation & Engineering, April, pp. 75-88, 2004.