The influence of the scale effect on the connected porosity in Bashkirian limestones

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Abstract. The concepts of the representative elementary volume and the scale effect for terrigenous and carbonaceous reservoirs have been considered. Various approaches of representative elementary volume calculations have been investigated. The whole core segment connected porosity is evaluated in two ways using the 7.3 cm diameter core samples in the first approach and the core samples 10 cm long by 3 cm in diameter in the second way. Logging porosity data and core samples values have been studied to identify optimal core sizes for the estimation of the relationship between core and well log data.

1. Introduction

The relevance of the topic is that results of laboratory porosity measurements depend largely on sample sizes. This phenomena is known as scale effect. Another term known as upscaling is used in modeling of rock pore structure. It is the process of scale increase from detailed geological model to the model of reservoir properties [1]. The scale effect has also a great influence on the results of STOIIP since the value of the core porosity is used in the STOIIP formula.

The goal of the research work is to investigate fluctuations of core connected porosity values depending on the sizes of samples extracted from the Bashkirian whole core segment 1 m long by 13.1 cm in diameter. The objectives are to evaluate connected porosity values of core samples 10 cm long by 3 cm in diameter, other core samples including 7.3 diameter cores using the buoyancy method and compare the results obtained with the data of the neutron porosity log. Next we plot the connected porosity versus sample volume in order to calculate the whole core segment representative elementary volume. The article presents the analysis of Russian, American, English and some other researches on the representative elementary volume and the size effect.

2. Object of investigations

The whole core segment 1 m long by 13.1 cm in diameter was recovered from the borehole # 4993 of the Ivinskoye heavy oil field located in the Republic of Tatarstan, the Russian Federation. Carboniferous sedimentary rocks were drilled-in in the depth interval of 935.0-1008.0 m. The investigated whole core segment 1 m long by 13.1 cm in diameter was extracted from depths of 974.0-975.0 m. The extracted rocks appeared to be the Bashkirian limestones (grainstones and packstones) having porosity varying from 9.8 до 19.3 % according to the neutron porosity log.
3. Literature review

J. Bear and B. Prilous investigated the porous medium representative elementary volume using the continuum approach [2], [3]. The spherical porous medium was analysed by shrinking its volume around the center point to identify the minimum fluctuations of porosity values. Porous medium volumes characterised by minimum porosity fluctuations appeared to be representative.

H. Sun et al. analysed the core samples using the X-ray computed tomography to make 3D rock images [4]. As a result of experiments the sub-volume selections of these images were done to calculate porosity values of various subsamples.

S. Serag El Din et al. and M. Kalam et al. did researches of core samples having different sizes with the use of laboratory methods to analyse the relationship between connected porosity and core volume [5], [6].

4. Methodology

In the first step macroscopic and microscopic researches of core samples drilled out of the whole core segment were done. In the second step core sample connected porosity values were estimated using the buoyancy method.

Core samples have been saturated with the distilled water using the special equipment for the saturation known as “Napor-RM” according to the approach described in the “Petrophysics MC Course Notes” [7].

The seven 7.3 cm diameter core samples were drilled out of the whole core segment 1 m long perpendicular to its axis. Then four core samples 10 cm long by 3 cm in diameter were taken at 0.2-0.3 cm intervals (Figure 1). Seven core samples are numbered as 1, 2...7 while four core samples 10 cm long by 3 cm in diameter are numbered as I, II, III, IV. These samples have been cleaned using the chloroform and then cut into smaller samples. The core sample II 10 cm long was damaged so the core sample II only 3 cm long is used.

![Figure 1. Core samples 10 cm long by 3 cm in diameter numbered with Roman numerals and 7.3 cm diameter core samples.](image-url)
After porosity measurements have been made the connected porosity value of the whole core segment 1 m long by 13.1 cm in diameter is calculated in two different ways to compare results. Using the first way we average core sample porosity values having the diameter of 7.3 cm. The first result is the true value of the whole core segment. The second way is the averaging of core sample porosity values having the length of 10 cm and the diameter of 3 cm. After that the ratio of the second result to the first one has been calculated to establish the difference between them.

5. Results and Discussions

The results of initial core sample porosity measurements have been grouped in two selections and presented in the Table 1. The values of the whole core segment connected porosity have been estimated in each selection. Porosity values of all investigated core samples are shown in Figure 2. The analysis of the graph allows to make some conclusions. It is obvious that all the core samples shown in the graph can be divided into two groups. In the first group volumes of core samples are less than 100 cm$^3$ while in the second one core volumes are more than 100 cm$^3$.

| The number of selection | The number of core | Core volume, cm$^3$ | $\phi_{con}, \%$ | The whole core segment porosity, % | The whole core segment volume, cm$^3$ |
|------------------------|--------------------|---------------------|----------------|----------------------------------|------------------------------------|
| 1                      | 1                  | 197.236             | 14.39          |                                  | 13.88                              |
|                        | 2                  | 245.286             | 16.01          |                                  | 13478.22                           |
|                        | 3                  | 77.326              | 11.55          |                                  |                                    |
|                        | 4                  | 157.922             | 14.95          |                                  |                                    |
|                        | 5                  | 255.615             | 15.50          |                                  |                                    |
|                        | 6                  | 231.003             | 12.78          |                                  |                                    |
|                        | 7                  | 204.473             | 11.96          |                                  |                                    |
| 2                      | I                  | 69.653              | 10.08          |                                  | 9.59                               |
|                        | II                 | 22.261              | 10.83          |                                  |                                    |
|                        | III                | 70.456              | 10.26          |                                  |                                    |
|                        | IV                 | 70.179              | 7.58           |                                  |                                    |

Porosity values of the first group of core samples are mostly less than core porosity values from the second group. This phenomenon is due to the fact that core samples in the first group have mostly intergranular porosity while the core samples of the second group have mostly fracture porosity. This fact was proved during macroscopic and microscopic investigations of core samples. Fractures 2-3 cm long with width of 1 mm are identified in core samples in the second group (Figure 3). Thus, the whole core segment connected porosity consists of the intergranular porosity and the fracture porosity.
Figure 2. Investigated core sample porosity values in function of the core volume.

Figure 3. 2-3 cm long fractures in large core samples.

In each group of core samples the maximum deviation of connected porosity from the average value is calculated for every core volume. Results of calculations are presented in Figure 4 and Figure 5. Porosity values of some large whole core segment fragments calculated using the known experimental porosity data are also shown in Figure 5. Values of the increments of the maximum deviations demonstrated in graphs are estimated to identify the stable intervals of the connected porosity.

As a result of graph analysis it is concluded that the representative volume of core samples having the volume less than 100 cm$^3$ varies from to 54.02 to 72.43 cm$^3$ (Figure 4). Investigations of core samples having these volumes allow to calculate intergranular porosity values. The representative elementary volume of the whole core segment is 3056.25 cm$^3$. Representative core sizes are presented in Table 2.
Figure 4. Maximum deviations of the connected porosity from the average value in function of the core volume less than 100 cm³.

Figure 5. Maximum deviations of the connected porosity from the average value in function of the core volume.
Table 2. Representative core sizes.

| Representative elementary volume, cm³ | Height of core sample, cm | Diameter of core sample, cm |
|--------------------------------------|---------------------------|-----------------------------|
| 54.02                                | 7.5                       | 3                           |
| 3056.25                              | 23                        | 13.1                        |

The comparison of the data of neutron porosity log and porosity values of core samples are shown in Figure 6. In depths of 974.64-975.0 m there is a high correlation between porosity log and porosity values of core samples 10 cm long and 3 cm long by 3 cm in diameter while in the depth interval of 974.0-974.64 m there is a high correlation between porosity log and porosity values of 7.3 cm diameter core samples.

Figure 6. The comparison of porosity log and porosity values of core samples. In the lithology column grainstones and packstones are marked in orange and green colours. The interval of lithology change is marked in purple.
The analysis allows to make a conclusion that 7.3 cm diameter core samples or full-diameter core samples should be used to accurately compare core porosity data with the neutron porosity log in this case. This is explained by the fact that the trend of the core porosity curve constructed with the use of the porosity data of large core samples is mostly similar to the trend of the porosity log. Moreover, analysis of core and log data allows to make a conclusion that macro-fractures in limestones occurring in depths of 974.64-975.0 m are less widely spread than fractures in limestones extracted from the depth interval of 974.0-974.64 m.

In depth intervals of 974.0-974.1 m and 974.64-975.0 m values of porosity log are constant and equal to 19.15 % and 10 %. As a result of investigations of core samples and several well logs (Figure 6) it is estimated that grainstones occur at depths of 974.0-974.1 m, packstones occur at depths of 974.8-975.0 m, consequently, in the depth interval of 974.1-974.64 m the porosity decrease results from the changes of rock lithology.

6. Conclusions

The influence of core sample sizes on connected porosity has been studied. Various approaches and methods for estimation core samples representative elementary volumes including the X-ray computed tomography, the buoyancy method and the method of helium porosimetry have been analysed in the article. The concept of the representative elementary volume is also discussed and analysed for the investigated 1 m long Bashkirian whole core segment.

The results of experimental investigations demonstrate that the scale effect has a great influence on porosity measurements of Bashkirian samples. This phenomenon is due to intergranular pores occurring in core samples having the volume less than 100 cm$^3$ and 2-3 cm long macro-fractures that are widely spread in bigger core samples having the volume more than 100 cm$^3$. The representative elementary volume of the whole core segment is equal to 3056.25 cm$^3$. As a result of graph analysis it is proved that connected porosity estimated for representative core sample 23 cm long by 13.1 cm in diameter is maximally similar and representative to the whole core segment connected porosity. It means that there is no need to cut the 1 m long whole core segment into several full-diameter cores as representative 23 cm long core sample can be cleaned using the Soxhlet distillation extractor without additional core segmentation. Application of the approach including representative core investigation allows to get more accurate connected porosity value and use less volume of solvent for core cleaning than for several full-diameter cores cleaning.

The difference between the whole core segment connected porosity evaluated by averaging porosity values of 7.3 cm diameter core samples (true porosity value) and the whole core segment connected porosity calculated by averaging porosity values of core samples 10 cm long by 3 cm in diameter is equal to 4.29. The given approach for the estimation of the whole core segment connected porosity including application of 10 cm long core samples does not allow to get reliable results for Bashkirian limestones investigated.

Comparison of core porosity values and data of the neutron porosity log makes it possible to conclude that the precise porosity correlation of extracted Bashkirian core samples to the geophysical borehole log can be defined only using full-diameter cores or core samples having large diameters and extracted from the whole core segment perpendicular to its axis.

References

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