EFFECT OF MICROFRACTURE ON ULTRATIGHT MATRIX PERMEABILITY

G. Leśniak, P. Such, R. Cicha-Szot
Instytut Nafty i Gazu - Państwowy Instytut Badawczy, Kraków, Poland

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Vienna, Austria, 27 August – 1 September 2017

ABSTRACT

Measurements of reservoir rock permeability have been executed in the oil industry for several decades. Depending on the type of permeability, oil and gas reservoirs can be divided into those with pore reservoirs, pore – fracture reservoirs and fracture reservoirs. In practice, pore and fracture permeability is observed in all unconventional reservoirs with varying proportions of either type. Natural microfracture systems increasing the permeability of the rock matrix are also recorded in shale rocks. In this paper anomalous results of permeability for rock samples from shale formations have been analysed. Observations with the use of SEM and petrographic microscope allow us to distinguish microfractures generated as a result of decompression of rocks (change of stress) and natural ones. The fractures generated as a result of core decompression are usually associated with very fine laminations with a material of different grain size composition comparing with rock matrix (smaller or larger grains), or with clay laminations within mudstones (author's microscopic observations). It has been concluded that the microfracture systems present in the examined rocks are the reason for anomalous values of permeability measured by the Pulse-Decay method. Dependences of overburden pressure on fracture permeability have been analysed. Simulative research performed for plug-type core samples allowed us to obtain permeability values in a function of the microfractures width. Finally, dependence of reservoir conditions on fracture width as well as on porosity was examined.

Key words: anomalous permeability, shale rocks, microfracture width.

INTRODUCTION

Measurements of permeability of reservoir rocks have been performed in the oil industry for over 100 years. At that time, the measurement methodology was changed, and in addition to steady state measurement (flow measurement), measurements were made in unsteady state (Pulse Decay method).

All natural reservoirs of crude oil and natural gas, taking into account the type of permeability, can be divided in porous reservoirs, porous-fracture reservoirs and fracture ones. In practice, all unconventional fields are dominated by porous-fracture permeability (with variable proportions of both types). Also in the shale complexes, natural fracture systems and microfracture are observed. These fracture systems aid a permeability of the rock matrix. The problem is to determine the real width of the microfractures under the reservoir conditions. It is necessary to perform flow simulation. In conventional reservoir, width of microfracture can be evaluated on the basis of comparison of the permeability obtained from the well test and the results obtained for the rock matrix as well as the descriptions of fractures and microfracture distribution. The methodology developed for a conventional reservoir [5,6,7,15] was applied to calculate the width of microfractures in the shale.

In the literature on shale gas permeability measurements, the values of gas permeability ranges from a few to several hundred nano Darcy for the rock matrix (the rock matrix is understood as a skeleton and cements) [2, 3]. The distribution of results is connected with the mineral composition and the petrographic type of shale (mudstones, claystone's, siltstones). For typical claystones, permeability value level covers the range from several to twenty nD, for siltstones it may reach the level of several hundred nD. In fact, we rarely deal with pure petrographic types of rocks. Generally they are mixtures of claystones mudstones, siltstones or claystones with a thicker detritical fraction scattered in the rock matrix.

The permeability (regardless of the applied method) is related to the system of connected pores. If this system is built from the pores of a small number of connections, then even a large number of pores will not bring about high permeability (eg pumice). The matrix permeability values for shale rock should be related to the porosity types present in the analyzed samples. In the case of pores occurring exclusively in organic matter (in most samples pores are insulated), the matrix permeability value should be relatively low (several nD). If there are mixed pores (OM-Pores, InterP Pores, ItraP Pores, Fig.1) in the sample, then we can expect the matrix permeability to be much higher (up to several hundred nD).

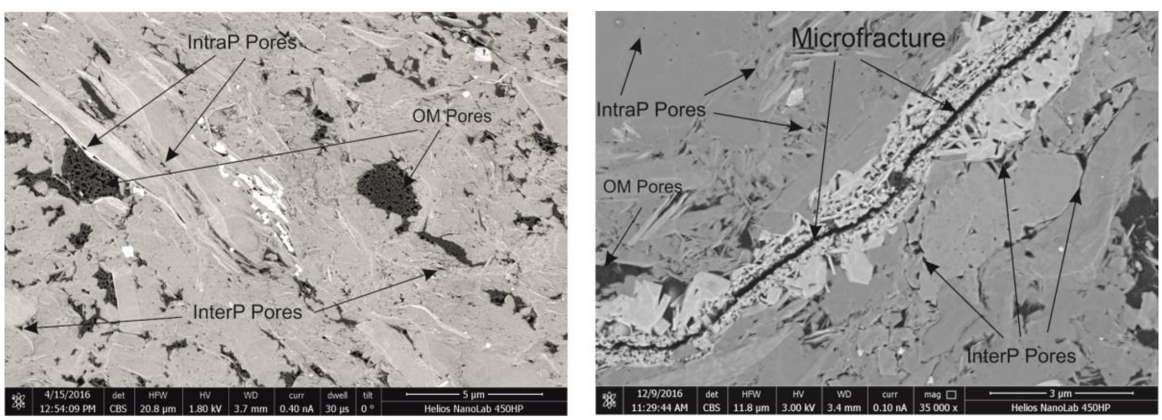

Figure 1 Typical pore space in shale from Baltic Basin

Silurian and Ordovician shales from the Baltic basin have a different mineral composition compared to the most famous and most commonly described shales (Barnet, Marcellus, etc.). Mineral composition of the Baltic basin shales is dominated by clay minerals (from 40 to 60%) from the illite and chlorite groups. The mineral composition is complemented by quartz, feldspars, carbonates (calcite, dolomite, ankerite) and muscovite, biotite and iron sulphides (pyrite and marcasite). It seems that for such a high content of minerals developed in the form of plaques, the compaction should lead to a creation of numerous pores (InterP Pores, IntraP Pores) as a result of a bending of mineral plaques or their delamination. Of course, this leads to the creation of numerous relatively well- linked pores. It should be assumed that the permeability of the rock matrix of the analyzed shales may be higher than the values reported for US shales. The anomalous high permeability values obtained for a large number of investigated shale samples stimulated the search for the causes of this situation.

RESEARCH STUDY

The problem encountered during the selection of shale samples for permeability measurements is that the sample is cut in the form of a cylinder of 2.54 cm in diameter and 4 cm in length, which is often unfeasible. This is caused by typically shale cleavage and the presence of microfractures. Observations in the petrographic microscope allows us to divide the microfractures resulting from the expansion of the rock after pulling to the surface (change of stress) and the system of natural microfractures (Fig. 2). The fracture resulting from the expansion of the core are associated with very fine laminations with different granulometric material from the rock matrix (smaller or larger grains) or clay laminates within the mudstones.

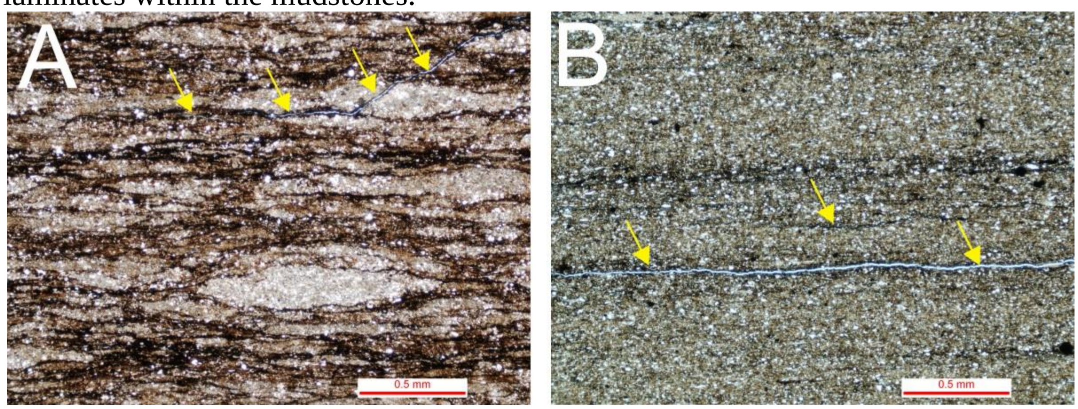

Figure 2 Foto A – natural microfractures, B - microfractures generated by decompression

The research procedure was as follows:

- preparation of plug samples,
- permeability measurement - Pulse Decay (PDP-250) ,
- 3D imaging - X-ray microtomography (CT) – resolution 10-12 μm,
- 2D X-ray imaging (RTG)
- selection of samples in which we deal with the microfracture permeability (based on permeability measurements and 3D and 2D imaging),
- calculation of width of microfractures based on permeability measurements

48 samples of the Baltic basin shale cores were selected for the study. The results are shown in Figure 3 and 4.

The range of obtained permeability researches cover the range from 3.8 mD to 0.4 nD (that is, six orders of magnitude). Samples with permeability above 1 mD (no 19 and 29) were recognized as the samples with fractures formed during their preparation. For the rest of samples the base question is: are the obtained permeability values only connected with rock matrix or also with microfractures? Assuming that the value of 0.4 nD is the lowest permeability of the rock matrix, and taking into account permeability of the rock matrix (according to available publications) [2,3,14] can be up to 1.3 μD, we should accept that all measurements of permeability values greater than 0.0013 mD (1.3 μD) should be connected with the existence of the microfracture system present in the samples.

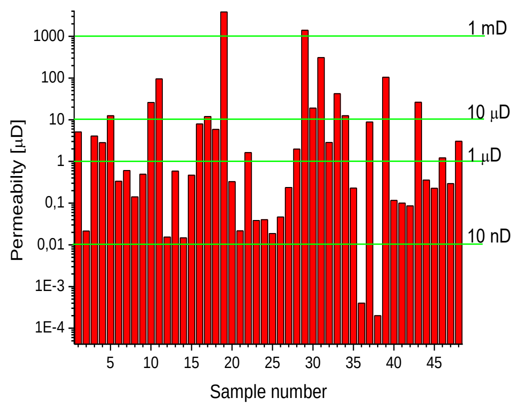

Fig.3 Histogram of permeability distribution

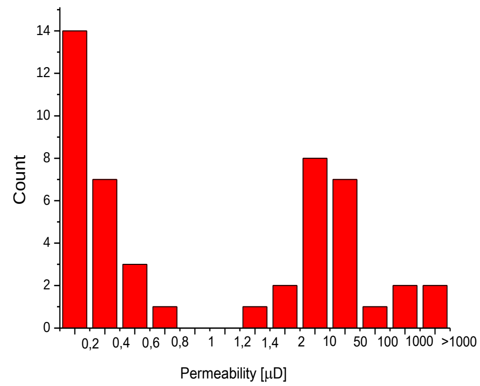

Fig. 4 Frequency diagram distribution of permeability

In order to examine the effect of effective stress on permeability and microfracture width for samples with macroscopically visible microfractures permeability measurements at different confining pressure were performed [16]. The results are shown in Figure 5 and Table 1.

Table 1 Measurement of permeability in different confining pressure for fractures sample

Confining pressure [psi]	Permeability [μD]	With of fracture [μm]
2000	0.0688	2.496
3000	0.0364	2.017
4000	0.0286	1.860
5000	0.0236	1.744
6000	0.0225	1.715
7000	0.0221	1.705

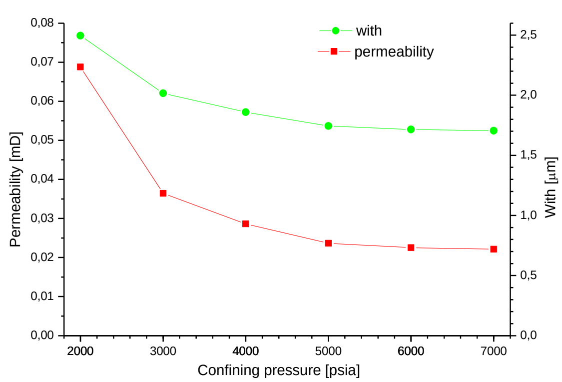

Figure 5 Relationship between confining pressure permeability and with of fracture

CALCULATIONS OF WIDTH OF MICROFRATURES

Analyses of microfracture permeability for classical reservoir rocks (dolomites, sandstones) are performed by the “random traverses” method with the use of a polarization microscope and polished thin section. This method consists in random placing of segments of the length L on a tested thin section and counting the number of intersections of each

segment with microfractures [9,10,13]. The width of the microfracture is an important value determined during microscopic measurements. It is one of the values used to calculate the fracture permeability and porosity values. Measurement of the width is carried out for each observed microfracture. It is based on the measurement of the width of the microfracture at several points. The value of the width of microfracture is assumed to be the average of all measurements for a given thin section. However, we should bear in mind that these measurements are performed on expanded samples. In the previous studies for shale rock, values ranging from 0.005 to 0.008 mm were accepted for calculations.
In our analysis, it was decided to reverse the problem and, calculate the actual width of the microfracture on the basis of measured permeability.
A formula for calculating the microfracture permeability is (1) [1,7,8]:

$$k = \frac{C\pi}{2L}\frac{b_l^3}{k_l}\sum_{i=1}^{m_l} n_i \tag{1}$$

where:
k - microfracture permeability
ml - the number of field of view applied to the thin section number l,
n - number of intersection fractures with section ml, each length L,
b - width of the microfracture
kl - number of test section applied to the sample
C - factor of random system, resulting from unit conversions (mm per cm)
After transforming the formula for microfracture permeability in order to calculate width (b) we obtain (2)

$$b = \sqrt[3]{\frac{k \times k_l \times 2L}{\pi \times C \times \sum_{i=1}^{m_i} n_i}} \tag{2}$$

The obtained results represent only permeability of the microfracure network.
The permeability measurements using plugs, give theoretically both permeabilities: that of the rock matrix and the microfracture network permeability. Of course, if there are microfracure passing through the whole sample, practically only microfracture permeability is measured (the gas always flows through the places with the smallest possible flow resistance).
Therefore, two cases should be considered. Case 1: microfracture system are present in the sample, but fractures are not connected to each other and do not pass through the entire sample. For this reason, the permeability value of the rock matrix should be subtracted from the permeability of the sample when calculating the width of the microfractures.
The second case - there are microfracture networks in the sample and they pass through the whole sample, so it can be assumed that the value of the measured permeability depends only on microfracture permeability (we do not measure the permeability of the matrix during the measurement).
In order to correctly estimate the permeability of the rock matrix, it was assumed that the micro fractures were not responsible for the permeability value below 0.6 μD [2,3,14]. For all measurements, the permeability frequency distribution was computed (Figure 4). In

Figure 4, we clearly see the frequency distribution of permeability values into two sets from 0.3 to 604 nD and above 1.2 μD. Based on the results of all analyzes the value of 0.6 μD was arbitrarily assumed as the maximum permeability of the rock matrix.
For all samples, 3D imaging in X-ray tomography (CT) and X-ray imaging (2D), in multiple planes were performed [11,12]. On this basis, samples with potential micro fractures or laminations forming from detrital material as pseudo fracture (both methods allow capture areas / laminas with reduced density) were selected (Fig. 6).
The samples with values of permeability greater than 1.2 μD include micro fractures or fine laminations forming pseudo microfracure rocks. In the samples with a permeability lower than 600 nD also fine microfractures or lamination occur but they do not cross the entire sample (based on data shown on Fig. 3 two groups of sample can be distinguished – one with microfractures which goes through whole length of the sample, the second with microfractures which goes through a part of the sample).

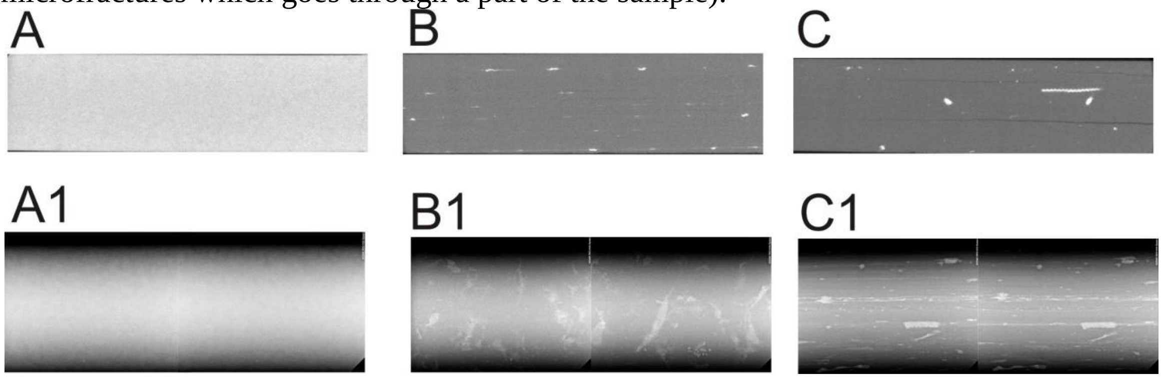

Fig. 6 Imaging in CT (A, B, C) and RTG (A1, A2, A3) A, A1 – sample without microfractures and lamination; B, B1 – sample with microfracture and lamination (do not cross the entire sample);
C, C1 – sample with microfracture (crossed the sample)

There were only five in the whole set of analyzed samples, which can be described as having no microfractures or lamination in them. It can be assumed that for these samples only the permeability of the rock matrix was measured. The maximum permeability value is 295.3 nD. On this basis, the permeability of the rock matrix for further calculations was accepted as 300 nD.
In his work Heller [4] reports the results of permeability of the rock matrix for shale on the level of several to several dozen nD and on the level of several up to several dozen μD.
The permeability of the matrix at μD level is explained by lamination / stratification of carbonates. In the samples analyzed by Heller the sum of clay minerals varied from 5 to 52%. The permeability results at μD level were obtained for samples with the total clay mineral content of less than 25%.
In the samples analyzed in this article, the average content of clay minerals is 44 to 64%. These samples also exhibit significantly lower quartz content. It should be assumed that the real permeability of the rock matrix will be less than 1 μD.

In the studies executed for shale gas prospecting in Poland, the matrix permeability of the shale was accepted from 200 to several hundred nD. Adopting the 300 nD value for the calculation is a safe variant at this stage of the study.

Table 2 Results of calculations of width of microfracure

Sample number	k-measured [mD]	k-km [mD]	number of microfratures	width of microfracture [μm]	number of microfratures	width of microfracture [μm]
sample of permeability > 1.2 μD						
49	0.0012184	0.0012184	1	1.035	4	0.652
23	0.0016281	0.0016281	1	1.140	4	0.718
29	0.0019714	0.0019714	1	1.215	4	0.765
4	0.0028218	0.0028218	1	1.369	4	0.862
33	0.0028655	0.0028655	1	1.376	4	0.867
52	0.0030537	0.0030537	1	1.409	4	0.888
3	0.0040748	0.0040748	1	1.549	4	0.976
1	0.0051350	0.0051350	1	1.687	4	1.063
17	0.0079767	0.0079767	1	1.935	4	1.219
38	0.0088810	0.0088810	1	2.028	4	1.277
18	0.0120271	0.0120271	1	2.252	4	1.419
6	0.0124535	0.0124535	1	2.257	4	1.422
35	0.0125460	0.0125460	1	2.257	4	1.422
31	0.0189670	0.0189670	1	2.594	4	1.634
11	0.0259657	0.0259657	1	2.903	4	1.829
46	0.0262357	0.0262357	1	2.894	4	1.823
32	0.0310969	0.0310969	1	3.054	4	1.924
34	0.0422202	0.0422202	1	3.405	4	2.145
12	0.0960610	0.0960610	1	4.508	4	2.840
42	0.1045971	0.1045971	1	4.638	4	2.921
30	1.3920000	1.3920000	1	10.990	4	6.923
20	3.8649000	3.8649000	1	15.201	4	9.576
sample of permeability > 300 nD						
21	0.0003270	0.0000270	1	0.291	4	0.183
7	0.0003350	0.0000350	1	0.317	4	0.200
47	0.0003578	0.0000578	1	0.375	4	0.236
16	0.0004657	0.0001657	1	0.532	4	0.335
10	0.0004935	0.0001935	1	0.560	4	0.353
14	0.0005838	0.0002838	1	0.637	4	0.401
8	0.0006048	0.0003048	1	0.652	4	0.411

Calculation of width of microfracture was carried out in two variants. For the samples with permeability greater than 1.2 μD, the width of microfracture was calculated for the full permeability value for one and four microfractures in the sample.

For these samples it was assumed that the flow from which the permeability is calculated is related only to the microfracture permeability while the permeability of the rock matrix is negligible. For the samples with permeability lower than 600 nD, calculation of the width of microfracture was made for the permeability value reduced by the permeability of the rock matrix. The results are shown in Table 2.

Based on observations of 3D imaging in CT and 2D in RTG, it was found that in the analyzed samples we can certainly deal with one microfracture passing through the entire sample [11]. Sometimes it develops into a system of two or more connected microfractures. Therefore, the calculations are presented for 1 and 4 microfractures, treating the second case as a microfracture system. The calculations assume:

- one field of view with an L value equal to the sample diameter (2.54 cm diameter)
- one intersection with a microfracture,
- four intersections with microfractures,
- permeability for a particular sample,
- C-factor (random system) -171000- resulting from unit conversions (mm per cm).

The obtained results of the width of microfractures (for one microfracture, Tab.2) range from 1.035 to 15.201 μm. This width can be compared with the average pore size in classic sandstone reservoirs. For the four microfractures in the sample, these values range from 0.652 to 9.576 μm. In the case of the samples with permeability of less than 600 nD for one microfracture, the width is from 0.291 to 0.652 μm, and for 4 microfractures from 0.183 to 0.411 μm.

It should be noted that the change in the number of microfractures in a sample does not alter the calculated of width of microfractures in the same way. Also, the differences of the width of microfractures – if we ignore the permeability values of the rock matrix - do not change drastically. The variation in the width of microfractures is approximately 40%.

CONCLUSION

Studies have shown that the "anomalous" values of permeability in shale rocks correspond to microfracture systems. Therefore, it is important to put more emphasis on the correct determination of permeability of the rock matrix (without microfractures).

The impact of microfracture parameters on the permeability of shale under reservoir conditions was analyzed. The width existing microfractures was calculated..

The permeability value over which microfracture samples (matrix permeability) should be expected in the specimen samples of shale rock was estimated.

ACKNOWLEDGEMENTS

This article is the result of research conducted in connection with a project: *Methodology of determining sweet spots on the basis of geochemical, petrophysical, and geomechanical properties, based on the correlation of the results of laboratory examinations with the geophysical measurements and the 3D generation model*, co-funded by the National Centre for Research and Development as part of programme BLUE GAS – POLISH SHALE GAS. Contract no. BG1/MWSSSG/13.

REFERENCES

1. Aguilera R., 1980. Naturally Fractured Reservoirs. PennWell Publ. Comp., Tulsa, 1–703
2. Apaydin O., 2012. New coupling considerations between matrix and multiscale natural fractures in unconventional resource reservoirs. PhD thesis, Colorado School of Mines

3. Cho Y., Apaydin O.G., Ozkan E., 2013. Pressure-dependent natural fracture permeability in shale and its effect on shale-gas well production. SPE Reservoir Evaluation & Engineering (216-228)
4. Heller R., Vermylen J., Zoback M., 2014 Experimental investigation of matrix permeability of gas shales" AAPG Bulletin v. 98 no 5, (975-995)
5. Leśniak G., 1992, "Mikroszczelinowatość wapieni wizenu z otworu Nosówka 2"Nafta-Gaz, nr.7-8 (165-168)
6. Leśniak G., Darłak B., 1995, Laboratory investigation of petrophysical properties of fractured and vugged rocks" Modern exploration and improved oil and gas recovery methods. Kraków, 12-15 wrzesień 1995, (203-204)
7. Leśniak G., Darłak B.,1994, Próba kompleksowego przedstawienia parametrów fizycznych złóż szczelinowych na przykładzie wapieni wizenu z odwiertu Nosówka-8. Nafta-Gaz nr. 8 (277-283)
8. Nelson R.A., 1985. Geologic Analysis of Naturally Fractured Reservoirs. Gulf Publ. Comp., Houston, 1–320.
9. Paduszyński J., 1965 Szacowanie gęstości mikroszczelin metodą trawersów losowych, Nafta, 8.
10. Romm E.S., 1970 Usowierszeństwowanie metoda szlifów dla opriedielienia paramietrow trieścinowatości. Tr. WNIGRI, 290.
11. Rydzy M. B., Patino J., Elmenti N., Appel M., 2016. Stressed permeability in shales: effect of matrix compressibility and fractures – a step towards measuring matrix permeability in fractured shale samples. SCA2016-027
12. Chhatre S. S., Braun E. M., Sinha S., Determan M. D., Passey Q. R., Zirkle T. E., Wood A. C., Boros J. A., Berry D. W., Leonardi S. A., Kudva R. A., 2014. Steady state stress dependent permeability measurements of tight oil bearing rock. SCA2014-012
13. Smechov J.M. (red): Treščinovatost' gornych porod i treščinnovye kollektory. Trudy WNIGRI, 193, 1-120, Leningrad 1962
14. Subrata Roy, Reni Raju, Chuang H.F., Cruden B.A., Meyyappan M. 2003: Modeling gas flow through microchannels and nanopores", Journ of Applied Physics, vol 93, no8 (4870 - 4879)
15. Such P., Leśniak G., 2003, Complex Correlation for Chracterisation of Transport System in Fracture Rocks Proceedings of 12 th. Improved Oil Recovery Symposium, Kazań 2002 (502-505)
16. Such P., Dudek L., Mroczkowska – Szerszeń M,, Cicha-Szot R., 2015 The influence of reservoir conditions on filtration parameters of shale rocks. Nafta-Gaz no 11 (25-29)