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Estimation of the width of microfractures in shale rocks

Anomalous results of permeability for rock samples from shale formations have been analysed. It has been concluded that the microfracture systems present in the examined rocks are the reason of the anomalous values of permeability. 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.

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

Szacowanie rozwartości mikroszczelin w skałach łupkowych

Przeanalizowano anomalne wyniki przepuszczalności dla próbek skał z formacji łupkowych. Stwierdzono, że przyczyną anomalnej wartości przepuszczalności są systemy mikroszczelin obecne w badanych skałach. Przebadano zależności przepuszczalności szczelinowej od ciśnienia nadkładu. Badania symulacyjne pozwoliły powiązać, dla próbek w formie rdzeników, przepuszczalność z rozwartością szczelin.

Słowa kluczowe: anomalna przepuszczalność, skały łupkowe, rozwartość szczeliny.

Introduction

Measurements of reservoir rock permeability have been conducted 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 are observed in all unconventional reservoirs with varying shares of either type. Natural microfracture systems increasing the permeability of the rock matrix are also recorded in shale rocks. The issue is to determine the actual width of the microfractures used for calculations. In conventional reservoirs the width of microfractures can be evaluated based on a comparison between the permeability obtained from a borehole test and the results for the rock matrix and microfracturing. Analyses of microfractures on core material have been conducted in the Oil and Gas Institute – National Research Institute since the beginning of the 1970s. They were calibrated multiple times based on the results of borehole tests as part of the work conducted for PGNiG SA [5, 6, 7, 14], reservoirs in the Main Dolomite, as well as the Devonian, the Permian and the Cretaceous limestones. The developed methodology has been used in the present paper to evaluate the width of microfractures in shale rocks.

The values of shale gas pearmeability, presented in the literature range between several and several hundred nanoDarcy (for the rock matrix) [2, 3]. The dispersion of results is associated with the mineral composition and the petrographic type of shale rocks (mudstones, claystones, siltstones). For typical claystone rocks, the assumed value of permeability ranges between several and over a dozen nD, and for siltstones it may reach values up to several hundred nD. In practice, petrographically pure rock types are very rare encountered. Usually, they are constitute a variety mixtures of rocks, like clayey mudstones, silty mudstones or clayey rocks with mudstone or siltstone-sized grains dispersed in the rock matrix.

The anomalously high values of permeability obtained for a considerable number of examined rocks from shale formations, not reflected in the pore space parameters of these rocks, have triggered explanation for anomalous permeability values occurrence.

Conducted studies

The most frequent problem encountered during the preparation of shale rock samples for measurements of permeability is cutting a cylindrical sample 2.54 cm in diameter and approximately 4 cm in length, which is sometimes virtually impossible. This is related for shales fissisility and the presence of microfractures in the rocks. Observations with the use of a 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).

The research programme involved:

- collection of core samples,
- cutting cylindrical samples 2.54 cm in diameter and 7÷8 cm in length,
- securing the samples in heat-shrink tubing (protects against damaging samples when conducting various measurements),
- 3D imaging using the X-ray microtomography method (CT),
- 2D imaging in an X-ray apparatus (RTG),
- permeability measurements using the PulsDecay method (PDP-250), according to the methodology presented in paper [13],
- on the base 3D and 2D imaging – the selection of fractured samples (in which the permeability is related to microfractures),
- calculation of the width of microfractures based on the permeability measurements.

40 drill core samples from the Baltic Basin were selected for the analyses. The obtained results are presented in Table 1 and in Figure 1.

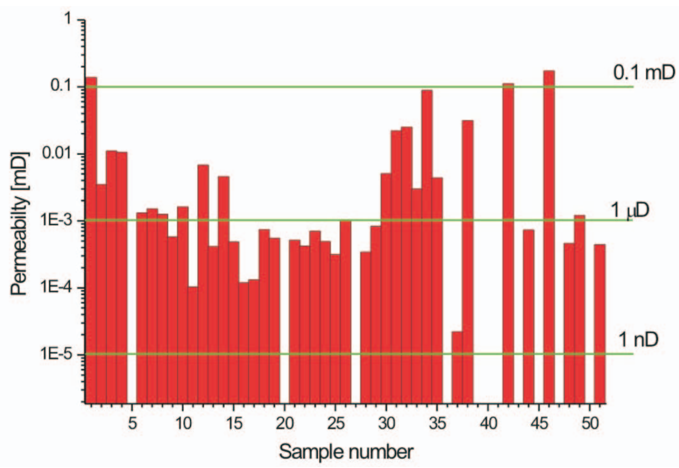

Fig. 1. Permeability distribution histogram (empty spaces – no sample)

Table 1. Results of permeability analyses

Sample no.	Permeability [µD]
1	138.160
2	3.495
3	11.018
4	10.522
6	1.309
7	1.511
8	1.253
9	0.580
10	1.619
11	0.103
12	6.789
13	0.415
14	4.569
15	0.483
16	0.119
17	0.131
18	0.741
19	0.554
21	0.515
22	0.420
23	0.702
24	0.493
25	0.314
26	1.005
28	0.342
29	0.832
30	5.065
31	22.036
32	24.898
33	2.991
34	88.423
35	4.363
37	0.022
38	31.156
42	111.287
44	0.727
46	173.012
48	0.458
49	1.202
51	0.4411

The dispersion of the obtained results ranges between 0.17 mD and 22 nD (meaning four orders of magnitude). The base question is: are measured permeability values reflect to intergranular or fracture permeability? Assuming that the 22 nD is the lowest value of rock matrix permeability, and considering that rock matrix permeability (according to the available published materials) [2, 3, 12] can reach to up to 1.3 μD, it should be assumed that all samples with permeability values greater than 0.0013 mD (1.3 μD) are associated with the system of microfractures.

Analyses of microfracture permeability are conducted with the use a polarisation microscope and thin sections by means of the so-called "random traverse" method. The method involves the random superimposing of segments with the length L over the examined thin sections, and the examination of the number of intersections of this segment with the microfractures [9, 10, 11]. The significant value determined during the microscopic measurements is the width of microfractures. It is one of the values adopted for the calculation of permeability and fracture porosity. The measurement of width is performed for each observed microfracture. It involves the measurement of microfracture width in several to over a dozen points. The value of width is assumed as an average value from all measurements for the given thin section. It should, however, be taken into account that these measurements are performed on decompressed samples. In previous studies for shale rocks, a value between 0.005 and 0.008 mm was used for calculations.

In this case, it has been decided to reverse the issue and, based on the measured permeability, to calculate the actual width of microfractures.

The formula for the calculation of microfracture permeability has the following form [1, 6, 8]:

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

where:
k – microfracture permeability,
m_l – the number of fields of vision superimposed over the thin section with the number l,
n – the number of intersections of fracture traces with m_l segments, each with the width of L,
b – the width of microfracture,
k_l – the number of measurement segments superimposed over a sample,
C – the chaotic system coefficient, resulting from the conversion of units (mm to cm).

After conversion of the microfracture permeability formula in order to calculate the width (b), the result is as follows:

$$b = \sqrt[3]{\frac{k \times k_l \times 2L}{\pi \times C \times \sum_{i=1}^{m_l} n_i}} \qquad (2)$$

During the measurements of microfracturing, the obtained results represent only the permeability for a network of microfractures. During measurements of permeability for "plug" type samples, the permeability of both the rock matrix as well as of permeability of microfractures network present in the sample is measured. For this reason, when calculating the value of microfracture width, the rock matrix permeability should be subtracted from the sample permeability. In order to correctly estimate the rock matrix permeability, it has been assumed that microfractures are not responsible for the magnitude of permeability in samples with permeability values below 1.3 μD [2, 3, 12]. A permeability value distribution histogram has been prepared for those samples (Figure 2).

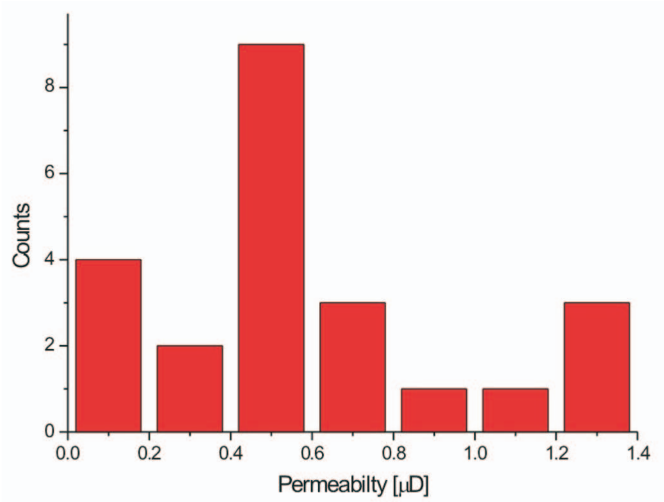

Fig. 2. Permeability distribution histogram for rocks exhibiting the value of this parameter lower than 1.3 μD

Based on the results of all the analyses, the value of 0.6 μD has been arbitrarily assumed as the maximum value of the rock matrix permeability. The results of 3D CT imaging of samples as well as 2D X-ray imaging were also helpful when adopting this value. For samples used to determine the rock matrix permeability in both types of imaging (2D and 3D), no system of microfractures, following the whole length of the sample, has been observed. In his paper, Heller [4] claims the results of rock matrix permeability for shales to be of several to several dozen nD, and of several to about a dozen μD. The matrix permeability in the μD range is explained by presence of the carbonate lamination/layers. In the samples analysed by Heller, the sum of clay mineral content ranges between 5 and 52%. The results of permeability in the μD range were obtained for samples with the total clay mineral content below 25%. In the samples analysed in the present paper, the average total clay mineral content ranges between 44 and 64%. Much lower quartz content is also observed in those samples. It can be therefore assumed that the real value of rock matrix permeability would certainly be lower than 1 µD. In the works performed for the shale gas prospecting in Poland, the assumed shale matrix permeability values ranged between 200 and several hundred nD. A value of 600 nD for the performed calculations seems to be a safe option at the present stage of study.

The calculations of microfracture width were performed in two variants. For each sample, the calculations of microfracture width were conducted for the total value of permeability (column 3) and for the value of permeability diminished by the rock matrix permeability (column 5). Table 2 presents the results for 1 microfracture in a sample, while Table 3 shows the width calculations for 2 microfractures in a sample. Based on the observations of 3D CT imaging and 2D X-ray imaging, it has been concluded that in the analysed samples we are definitely dealing with one microfracture extending along the whole sample. Sometimes it linked into a system of two microfractures. With the 3D CT imaging resolution of approximately 4÷6 µm, it is difficult to arbitrarily conclude whether we are dealing with a microfracture or with a change in density caused by a change in mineralogical composition, which is why the calculations have been presented both for 1 and 2 microfractures, considering the second case to be a system of microfractures.

The calculations assumed:

- one field of vision with the value L equall to the diameter of the sample (a cylinder 2.54 cm in diameter),
- one intersection with a microfracture,
- two intersections with microfractures,
- permeability for the given sample,
- the C coefficient (chaotic system) – 171 000 – resulting from the conversions of units (mm to cm).

The obtained values of microfracture width (for 1 microfracture, Table 2) range between 0.939 and 5.478 µm. They can be compared to the average size of pores in conventional sandstones reservoir. For two microfractures in a sample, these values range between 0.745 and 4.348 µm. It should be noted that a twofold change in the number of microfractures in a sample does not alter the calculated width of microfractures in the same manner.

Also, the differences in the width of microfractures when skipping the value of rock matrix permeability do not change drastically. For low values of permeability up to 3 µD, the change in microfracture width amounts to approx. 15%; for the permeability greater than 20 µD the change is smaller than 1%.

Table 2. The results of calculation of the microfracture width (for 1 microfracture in a sample)

Sample number	Permeability [µD]	Fracture width [µm]	Permeability – matrix permeability [µD]	Fracture width [µm]
1	2	3	4	5
7	1.511	1.112	0.911	0.939
10	1.619	1.137	1.019	0.975
33	2.991	1.399	2.391	1.299
2	3.495	1.472	2.895	1.382
35	4.363	1.598	3.763	1.521
14	4.569	1.607	3.969	1.534
12	6.789	1.861	6.189	1.805
4	10.522	2.134	9.922	2.093
3	11.018	2.161	10.418	2.121
31	22.036	2.727	21.436	2.702
32	24.898	2.863	24.298	2.840
38	31.156	3.065	30.556	3.045
34	88.423	4.356	87.823	4.346
42	111.287	4.734	110.687	4.726
1	138.160	5.021	137.560	5.014
46	173.012	5.485	172.412	5.478

Table 3. The results of calculation of the microfracture width (for 2 microfractures in a sample)

Sample number	Permeability [µD]	Fracture width [µm]	Permeability – matrix permeability [µD]	Fracture width [µm]
1	2	3	4	5
7	1.511	0.882	0.911	0.745
10	1.619	0.903	1.019	0.774
33	2.991	1.111	2.391	1.031
2	3.495	1.168	2.895	1.097
35	4.363	1.268	3.763	1.207
14	4.569	1.276	3.969	1.217
12	6.789	1.477	6.189	1.432
4	10.522	1.694	9.922	1.661
3	11.018	1.715	10.418	1.684
31	22.036	2.164	21.436	2.144
32	24.898	2.272	24.298	2.254
38	31.156	2.432	30.556	2.417
34	88.423	3.458	87.823	3.450
42	111.287	3.758	110.687	3.751
1	138.160	3.985	137.560	3.980
46	173.012	4.353	172.412	4.348

Simulation of microfracture width changes

The simulative research has been conducted in order to ascertain the impact of confining pressure on the change in fracture width and the change in permeability. During preparation of the cylindrical samples, sample no. 30 split along the existing lamination/microfracture (the splitting took place during the stage of ends cutting of the stabilised sample). Because matching the two fragments together did not cause any problems, the sample was secured in heat-shrink tubing, guaranteeing precise fitting of the two parts. The measurements of permeability were conducted for this sample with different confining pressures. Performing permeability measurements with different confining pressures reflects the change in the microfracture width, and enables the calculation of its real width depending on the overburden pressure.

2D X-ray imaging of sample no. 30 with an indicated microfracture (yellow arrow) is presented in Figure 3. It is visible in darker shades of grey (due to lower density) than the remaining part of the rock.

The performed study enabled us to ascertain the very high vulnerability of the obtained results of permeability, depending on the overburden pressure. This result is quite obvious because of the fracture closing effect caused by overburden pressure is known quite well, and the permeability depends on the width of the fracture [5, 9, 10, 11]. The scale of this effect is shown in Figure 4.

The unique possibility of examining the plug-type sample with well defined fracture geometry enabled the presentation of the dependence of permeability on the width of the fracture. In all the measurements geometry is the same, the temperature is constant, with the only varying factor is the overburden pressure. In other words, for this experiment the changes in permeability depend only on the width of the fracture.

Based on 3D CT imaging as well as 2D X-ray imaging, sample no. 35, where the presence of microfractures had also been recorded, was selected for the next analysis. For this sample, measurements of permeability were performed

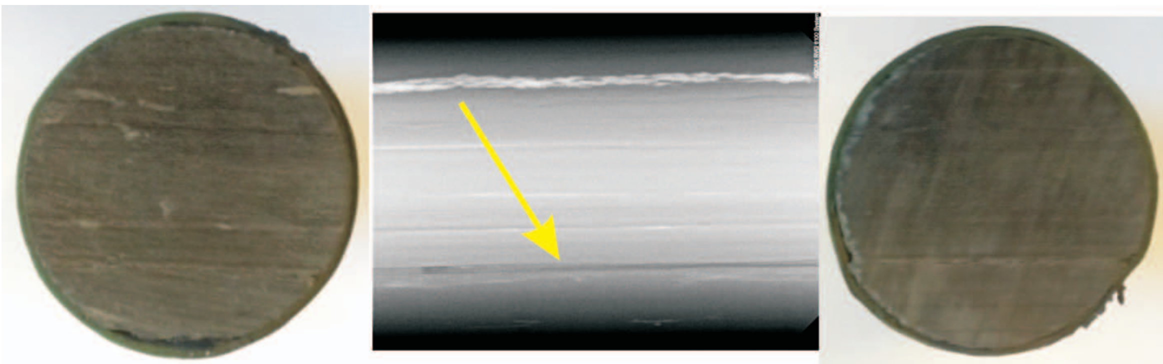

Fig. 3. Picture of sample no. 30 in 2D X-ray imaging. Side images show the upper and lower surfaces.

Table 4. The results of permeability measurements the microfracture width calculated for various confining pressures (sample 35)

Confining pressure [psi]	Permeability [μD]	Width of microfracture [μm]
900	174.615	5.459
1125	118.762	4.798
1225	79.109	4.187
1400	60.083	3.817
1600	43.847	3.432
1800	30.474	3.034
2000	18.084	2.538
2500	7.765	1.885
3000	5.030	1.606

in the PDP250 apparatus with nine confining pressures. For each measurement of permeability the corresponding width of the microfracture has been calculated. The obtained results are presented in Table 4 and in Figures 5 and 6.

Figure 7 shows the results of permeability changes in the function of the confining pressure for samples 12, 14, 33 and 7, in which the presence of microfractures was also suspected based on 3D CT imaging. The changes in permeability based on the overburden pressure confirm the presence of microfractures in these samples.

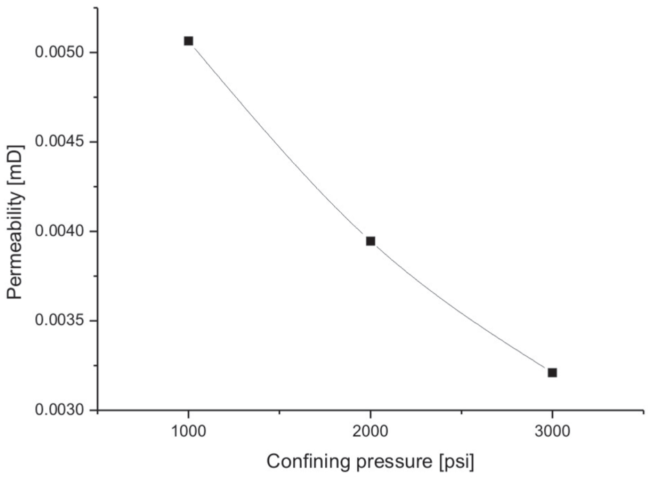

Fig. 4. The change in the value of permeability depending on the confining pressure

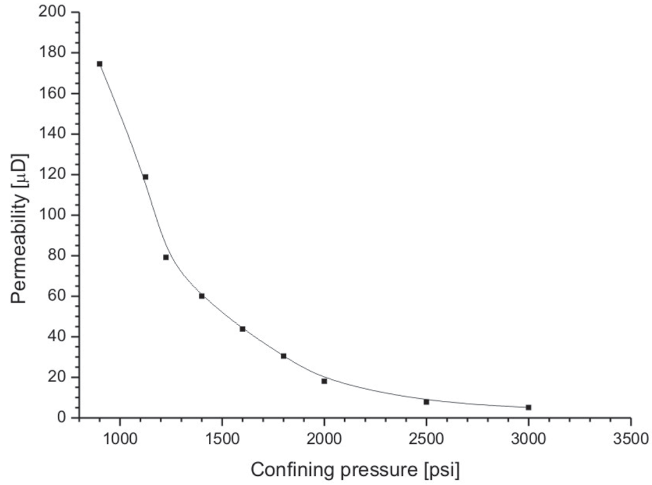

Fig. 5. The change in the value of permeability depending on the confining pressure

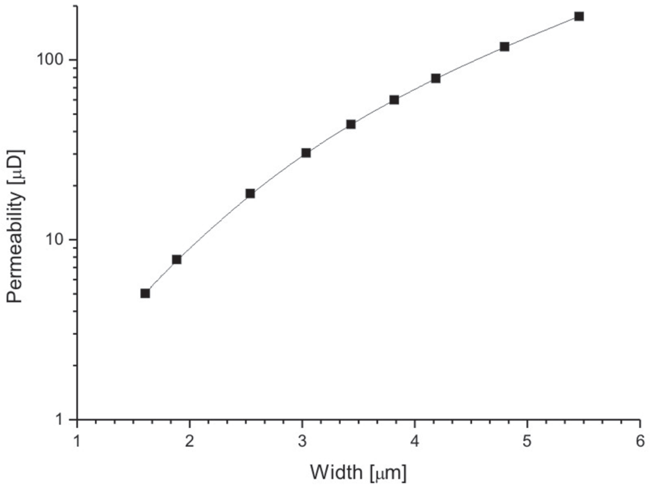

Fig. 6. Relation of permeability to the width of the microfracture

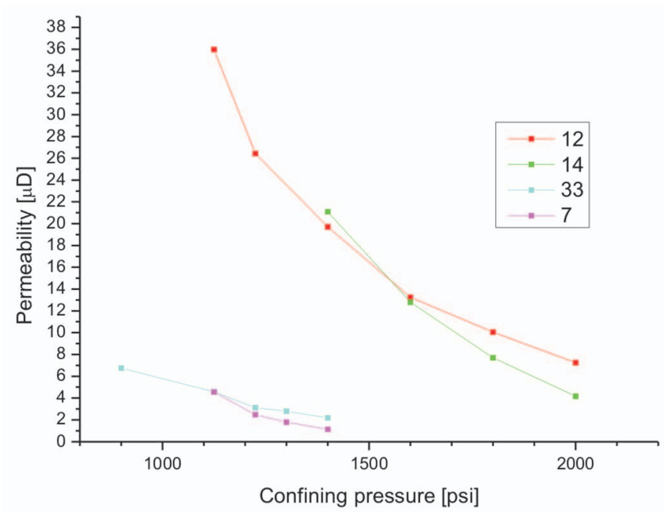

Fig. 7. The change in the value of permeability depending on the confining pressure

Summary

1. The conducted research confirmed that microfracture systems are responsible for the "anomalous" values of permeability in shale rocks. For this reason, more emphasis should be put on the proper evaluation of rock matrix permeability (without microfractures).
2. The limits of permeability, above which microfractures in the examined shale rock samples are to be expected, have been estimated.
3. The impact of microfracture parameters on shale rock permeability in depositional conditions has been analysed, and the base role of the existing fractures has been presented.

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