SCA2003-61: FACTORS AFFECTING RELATIVE PERMEABILITY MEASUREMENTS FOR THE MIOCENE AND THE ROTLIEGEND POORLY CONSOLIDATED SANDSTONES

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ABSTRACT
Measurements of the relative permeability to water and gas were performed for the Rotliegend and the Miocene sandstones. Poorly consolidated sandstones were a great part of investigated rocks. The base relative permeability to gas and water, as well as residual water saturations were measured. The results were validated with the use of mercury injection capillary pressure investigations. More than 50% of investigated rocks showed pore space damages. It was found that processes such as web effect of hairy illite, swelling of illite/smectite and mechanical damage are responsible for relative permeability changes. Relative permeability results were correlated with distribution of grain diameters, a content of cements and mineralogical composition of investigated rocks. Every investigated process affected relative permeability parameters specifically.

INTRODUCTION
The Upper Rotliegend sandstones from the Forsudetian Monocline of the Polish Lowland and the Miocene sediments from The Carpathian Foredeep are main reservoir rocks for gas reservoirs [6,7]. Additionally, several underground storages of gas are placed in the Rotliegend sandstones. Those facts determined a necessity of multi-phase permeability investigations of those rocks. Unfortunately, the both types of reservoir rocks exhibit a complicate structure issuing from its sedimentary and diagenetic history. Contact with reservoir water damages a pore space of great part of investigated rocks. That has to be taken into account during exploitation.

INVESTIGATIONS
Procedures
Poorly consolidated rocks were chosen from the Rotliegend and the Miocene sandstones. Parallel and vertical plug type samples were cut and coated by thermo-shrinkage sleeves. Porosity, permeability to nitrogen and mercury injection capillary pressure investigations were carried out.

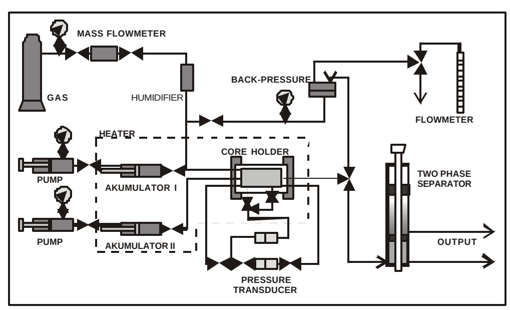

Fig.1 Reservoir condition relative permeabilty apparatus

Macroscopic observations of full dimension cores, geological analyses of sedimentary processes, anisotropy of permeability to air and analyses of capillary pressure curves allowed to extract three groups of rocks for subsequent analyses. The

groups consisted of: (i) good sorted, high permeable homogenous rocks with very small content of cement, (ii) porous, permeable microporous homogenous sandstones with large content of cements and (iii) permeable samples showing high anisotropy.

Additionally, the type of pore space and heterogeneity of investigated sample were verified by microscopic analysis of thin sections. Then, prepared plug type samples, covered by thermo shrink sleeves were placed into the core holder of the steady state relative permeability apparatus (Fig.1) [3,4]. The apparatus allowed for monitoring on-line such parameters as outlet pressure (p), pressure gradient (Δp), confining pressure (p_c), backpressure (p_b) flow volumes (V_g, V_w) and temperature (T) in core holder. After establishing reservoir conditions and confining pressure equal to 500-psi permeability to nitrogen was measured. Subsequently, a flow of water was established until a steady state condition was obtained and base permeability to water could be calculated. The third step of the experiment consisted of saturation of investigated sample by water and then water displacement with the use of gas (nitroge n), until steady state flow was reached. That allowed for base permeability to gas calculation. The sample was weighted three times during the experiment as a dry sample, a water-saturated sample and residually water-saturated sample. It made it possible to calculate residual water saturation. Only the end-points of relative permeability curves (base permeabilities) were measured.

Types of Rocks

Typical reservoir rocks were chosen from 23 investigated boreholes for the Rotliegend sandstones and from 8 bore holes for the Miocene sediments. In total, 68 samples of the Rotliegend and 45 samples of the Miocene were investigated (Tab.1.). As parameters, the sample permeability, value of threshold pressure and fractal dimension [8] were taking into account.

Tab.1. Investigated samples

	The Rotliegend sandstones	The Miocene sandstones
Number of samples	68	45
Number of boreholes	23	8
Depth (m)	1647-4219	257-2490
Permeability:		
Lower than 10 mD	26	4
10-50 mD	18	12
50-200 mD	14	17
Greater than 200	10	12

Additionally 6 samples of good sorted, permeable, rigid sandstones neither of the Rotliegend nor the Miocene sandstones were used for method validation.

RESULTS

The main goal of the first part of the experiment was to recognize if it was possible to apply steady state relative permeability investigations to water - gas system, particularly to

check the reliability of residual water saturation evaluation. Quartz, good sorted, permeable sandstones were used. Residual water saturation was measured as a function of reservoir pressure in the range between 0 and 2500 psi. The results showed statistical dispersion and no significant dependence could be observed. The accuracy of measurement of residual water saturation was “one droplet accuracy” and could be estimated to $\pm$ 2%.
The results of relative permeability investigations are presented in Fig.2A (relative-base permeability to water) and 2B (relative- base permeability to gas) as a frequency diagrams. Base permeability to water covered the range from 0 to 0.35 for the Miocene and from zero to 0.42 for the Rotliegend samples. Base permeability to gas covered the ranges from 0 to 0.9 and from 0 to 0.86, respectively. Even though that the maximal values of base permeability to gas were high, a great part of samples exhibited rather low values of that parameter. The pore space of 13 analyzed samples was completely closed during flow of water (including the sample characterized by porosity 18% and permeability to gas greater than 60 mD). The correlation between relative permeability, effective permeability and pore diameter distributions gave no significant dependence. Therefore, it is clear that the values of base permeability are controlled by a degree of pore space damage.

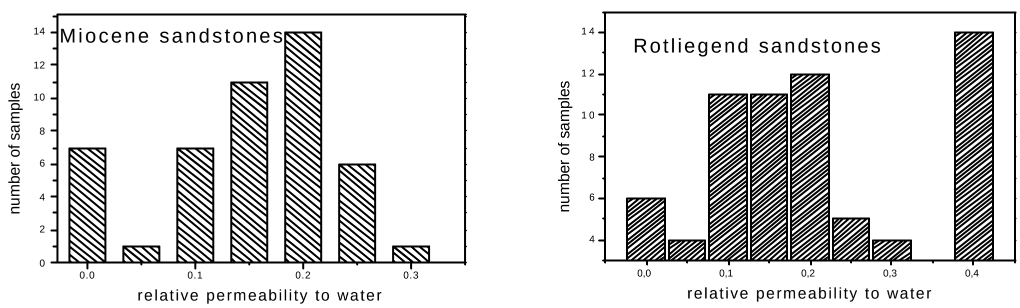

Fig. 2A. Frequency diagram of base permeability to water

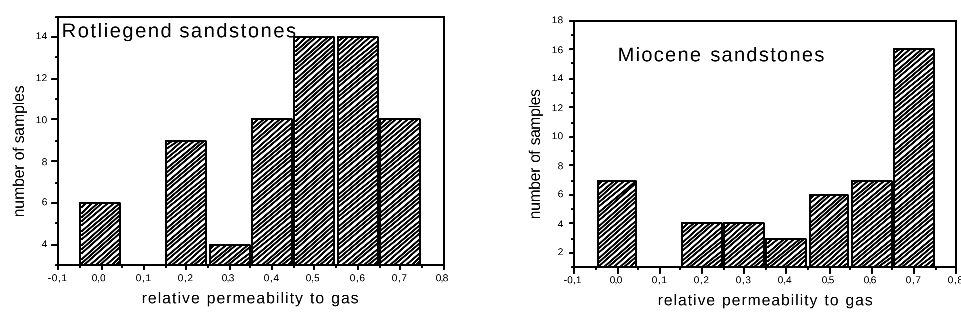

Fig. 2B. Frequency diagram of base permeability to gas

Mercury injection capillary pressure investigations were performed for entire set of samples. Pore size diameter cumulative curves were recalculated to obtain log (V) – log (p) curves [1] and fractal dimensions were obtained from the slope of straight-line part of log-log curves. The correlation between residual water saturation and fractal dimension was

done [8]. The results are presented in Fig.3 and Fig.4. The samples were divided with respect to the values of their relative permeability to gas.
The first group for both the Rotliegend and the Miocene included samples exhibiting values of relative permeability to gas greater than 0.6. The line dependence between relative permeability and fractal dimension for this group gave the base trend lines. For the Miocene the trend line is given by:

$$S_r(g) = -301.4D + 920.6\,, \quad /1/$$

whereas for the Rotliegend

$$S_r(g) = -283.3D + 871.4\ . \quad /2/$$

The second group (black triangles in fig.3 and 4.) consisted of the samples characterized by a value of relative permeability to gas between 0.45 and 0.6 and, at the same time values to water comparable with the base group. Those samples satisfied trend lines or showed small deviation from it.

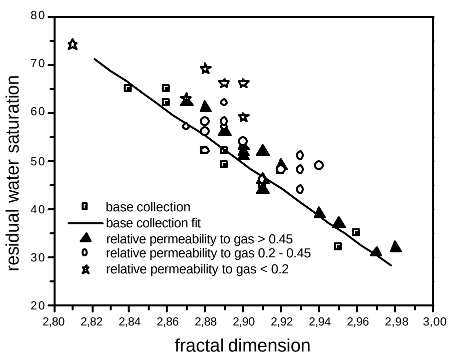

Fig.3. Residual water saturation versus fractal dimension for The Rotliegend

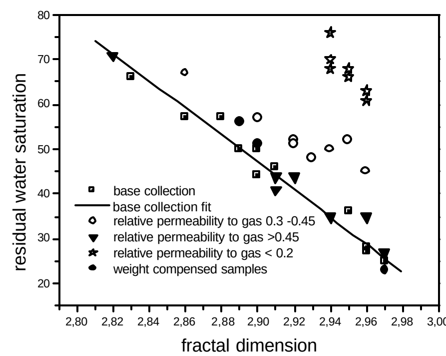

Fig.4. Residual water saturation versus fractal dimension for the Miocene

The third and the fourth group covered the range of relative permeability to gas from 0.3 to 0.45 (medium damaged pore space) and below 0.2 (nearly destroyed pore space) respectively.
Petrography analyses allowed for characterizing which type of sandstones could be defined as poorly consolidated [6,7]. There were either porous sandstones with very small content of cements or sandstones with large content of specific type of cements: contact clay cement for the Miocene and contact cement with high content of plate illite and chlorite for the Rotliegend. The presence of illite/smectite packets and the presence of hairy illite formed additional factors affecting relative permeability in the Rotliegend [5]. Several measurements were performed into the dependence permeability to gas and to water on overburden pressure (500-1500 psi)[2]. The results showed change of these parameters up to 30% for some types of Miocene sandstones

DISCUSSION

The research showed quite different behavior of the Rotliegend and the Miocene sandstones during flow of water through their pore space. The Rotliegend cements (quartz, calcite, dolomite, anhydrite) were not damaged by flow of reservoir waters. The most important factor affecting relative permeability in those rocks were presence of clay minerals[7]. Three effects were observed during relative permeability measurements: (i) the web effect of hairy illite caused relatively small reduction of relative permeability to gas and significant reductions for relative permeability to water (capillary trap), (ii) chlorite and illite plates could be extracted during flow of water and plugs pore throats (clay type cements could be completely destroyed), (iii) swelling of mixed layer clay minerals and squeezing of channels and pore throats. That process could be extracted by a speed of reaction (measured 20-35min). Reduction of permeability by physical extraction of plates and grains was slower (several hours)

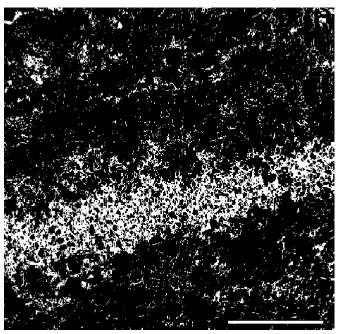

Fig.5. Heterogeneous Miocene sandstone (mark 1mm, white – pore space)

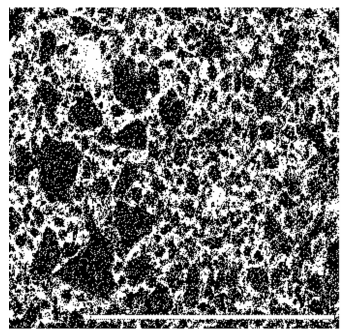

Fig.6. Miocene sandstone (low cement content, mark 1 mm, white - pore space)

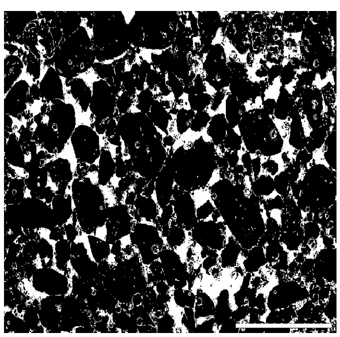

Fig.7. Rotliegend sandstone (low cement content, mark 1 mm, white – pore space)

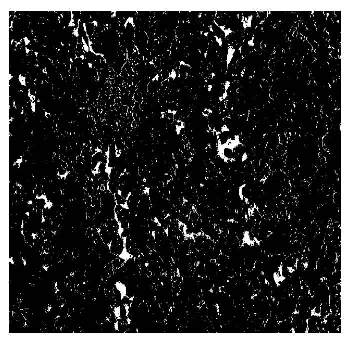

Fig.8. Rotliegend sandstone (high cement content, mark 1 mm, white – pore space)

In the Miocene, two types (Fig 5, 6) of sandstones were damaged by flow of water: microporous sandstones with high content of cement and rocks with very small content of cement (often laminated)[5]. The cement content in the Miocene sandstones was up to 40.4%. It consisted of carbonates (calcite, dolomite), quartz, clay minerals and mixture of clay-carbonate and quartz-carbonate. Destruction of the pore space was realized either by extraction of clay cement in sandstones with high content of cement or destroying all kinds of cements in sandstones characterized by very small content of cement. In the Miocene sediments sand grains are mainly cube-packed and cements take part in building of pore space. As the result, apart from plugging pore throats destruction of cement caused collapse of sand grains. That enlarged degree of pore space damage and gave dramatic increase of residual water saturation (Fig.4). Due to rhombohedral packing of sand grains in the Rotliegend, relatively small changes in the residual water saturation were observed (Fig.7, 8).

CONCLUSION

1. Relative permeability to gas for undamaged samples are greater than 0.6, relative permeability to water is controlled by wettability of reservoir rocks (Fig.2A)
2. Type and content of cement, presence of mixed layer and hairy illite and space distribution of sand grains affect phase flow parameters.
3. All observed processes give characteristic changes in relative permeability parameters.
4. All observed phenomena are present in the Rotliegend deposits, in the Miocene sediments dominate mechanical extraction of cement and collapse of sand grains. Pore space damage in the Miocene is connected to a great increase of residual water saturation

NOMENCLATURE

S (w) – water saturation (%)
S_r (W) – residual (irreducible) water saturation (%)
D – fractal dimension

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