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Computed X-ray microtomography as the useful tool in petrophysics: A case study of tight carbonates Modryn formation from Poland

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ABSTRACT

Detailed qualitative and quantitative studies using the X-ray computed microtomography proved to be a reliable source of information about the pore space properties of clastic and carbonate reservoir rocks. X-ray computed tomography with higher resolution (nano) allows improving and completion of porous rocks analysis in aspects of new parameters determination. In this paper, results of the X-ray computed microtomography analysis were presented for core samples probed from the Palaeozoic carbonate intervals (Modryn formation) from the selected wells located in the Central-Eastern Poland. Several parameters were calculated on the basis of microtomographic images (total porosity, tortuosity, homogeneity parameter, mean chord length, Euler number), which allowed to parameterize pore space structure of tight carbonates. In the case of rock hydrocarbon potential determination, e.g. filtration properties, computed X-ray microtomography turned out as an alternative method in rock characterization. It appeared that the Modryn formation consists of rocks with poorly developed pore space with limited filtration abilities.

1. Introduction

Tight, low porosity and low permeability reservoirs are now under careful investigations to expand the potentially reservoir formations prospection onto new areas of rocks deeply sited and not only clastic but also carbonate rocks. Limestones and dolomites are still the subject of interest as hydrocarbon-bearing formations (Montaron, 2009). Also, tight carbonates are considered as potentially unconventional reservoir rocks. Incessantly, new laboratory methods are developed to gain more precise information for the rock complexity description. Qualitative and quantitative interpretation of microtomographic (micro-CT) images provided the answer about the physical properties of the analysed rocks: reservoir and filtration properties (Cai et al., 2010). Such description of the pore space structure is important in detailed reservoir analysis (Li et al., 2012; Guo et al., 2015; Berge et al., 2005).

Computed X-ray microtomography (micro-CT) is one of the most modern, non-invasive techniques in the petrophysical analysis (Wellington and Vinegar, 1987; Stock, 2008). Applying the micro-CT method to rock sample investigations makes possible obtaining a three-dimensional image of the rock consisted of skeleton and pore space. X-ray tomography provides information on porosity, i.e. free space between mineral grains and cement, pores distribution in this free space, as well as geometrical information about the tortuosity of the pore channels (Kayser et al., 2006; Zalewska et al., 2009; Bielecki et al., 2009, 2013). Porous volume and structure allows describing the rock ability to fluid flow (Arns et al., 2005; Krakowska et al., 2014; Trykozko et al., 2015).

2. Materials

The research material consisted of 10 samples of low porosity and low permeability, tight Palaeozoic carbonates (Table 1). Core samples were probed from wells located on Lublin Basin (Krzywiec, 2009), south-eastern Poland (Fig. 1). All samples belong to the Modryn formation, which now is considered as potentially perspective, gas-bearing, tight formation in Poland. Modryn formation occurs on the whole area on the Lublin Basin. It is built of characteristic, mainly carbonate complex, bordered on the top and bottom to deposits with the terrigenic admixture. Complicated depositional architecture of the Modryn formation responds to

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Table 1
Research material from the Modryn formation carbonates (Devonian, Frasnian). Symbols: H – coring depth, Q – quartz, C – calcite, D – dolomite, Ha – halite, P – pyrite, An – ankerite, A – anhydrite, M– micas, K–F – alkali feldspars, Cl – sum of clay minerals; mineral content from X-ray diffraction analysis.

Sample	Well	H	Lithology	Lithostratigraphic member	Q	C	D	Ha	P	An	A	M	K–F	Cl
		[m]			%	%	%	%	%	%	%	%	%	%
882	K-IG2	3239	limestone	Werbkowice	1	71					28			
884	R-IG1	3045	limestone	Zubowiec	2	98								
131	M-6k	3926	limestone	Zubowiec	4.5	85.6	1	0.9	0.6			7.4		7.4
133	M-7k	4170	dolomite	Werbkowice	4.2	8.6	74.5	0.7	1.7	5.5	0.9	3.9		3.9
134	P-1	3998	limestone	Zubowiec	1.4	95.4	1.8		0.7	0.7				
135	K-1	4001	dolomite	Werbkowice	1.5	1.2	88.1	0.7	1.3	1.2	0.6	5.4		5.4
136	M-9	4044	dolomite	Werbkowice	2.2	1.4	94					2.4		2.4
138	M-5	4024	dolomite	Werbkowice	1.3	1.4	89.8	0.8	0.7		2.4	3.6		3.6
140	C-9	3839	dolomite	Lipowiec	1.1	0.4	65.8		2.3	3.4		25.4	1.6	25.4
142	M-2	4196	dolomite	Werbkowice	0.7	1.3	75.1			19.8		3.1		3.1

main facies of carbonate platform system (Narkiewicz, 2007, 2011).

Werbkowice member consist mainly of dolomites, often with the anhydrite and clay minerals admixture, while the Zubowiec – of quite pure limestones (Table 1). Lipowiec member is represented by shaly dolomite with micas admixture. Werbkowice member is informally vuggy dolimites complex, considered to be one of the best Devonian reservoir rocks in the Lublin Basin (Darłak et al., 1998).

Average total porosity from helium pycnometer of the group of samples in research was below 1.5% and absolute permeability mostly reached the permeameter lower limit – 0.01 mD.

3. Method

X-ray computed tomography (CT) is a unique source of information about the complexity of pore space (Ketcham and Carlson, 2001).

X-ray computed tomography measurement starts on the X-ray beam emission by the X-ray tube. Exposed sample casts a shadow on the detector, creating a 2D projection. The radiation passing through the sample is absorbed and attenuated. Larger attenuation of the beam is the result of increased sample density related to the mineral composition and porosity. Beer law defines the basic quantity measured in X-ray tomography, linear attenuation coefficient μ_t (Haken and Wolf, 2004; Cnudde, 2005):

$$\frac{I}{I_0} = \exp(-\mu_t * h) \quad (1)$$

where: I_0 [W/m2] – intensity of incident radiation, I [W/m2] – intensity of transmitted radiation, h [m] – sample thickness, μ_t [1/m] – linear attenuation coefficient.

Used in the micro-CT X-ray beams emit the energy from the energetic range of X-ray, not the energy of monochromatic radiation, that is why it is used integral of linear attenuation coefficient with respect to sample thickness *h*. In this way the changes of linear attenuation coefficient are taken into account, along the X-ray path:

$$I = I_0 e^{-\int \mu_t(h)dh} \quad (2)$$

Scanning of the sample with X-rays of low and high energy, and solving the Equation (2) for each pixel of the image separately allows for obtaining the one image which is proportional to the bulk density and the other – to the atomic number (dependence on chemical composition).

The measuring principle is based on storing successive X-rays projections (sample projection image on the detector plane), with different angular position in the range of 0–360°. The smaller rotation angle of the sample, the greater image accuracy, but also a longer measurement time. As the sample is rotated during the measurement, 2D projections are collected. Finally the reconstructed 3D (consisting of 2D cross sections) image may be created.

For the sample tomographic cross-sections, that is a cutting of complex shape (projection cross-sections), there must be the back-projection algorithm used, which allows to obtain a picture of the linear absorption coefficient variation. Back-projection algorithm is a reconstruction algorithm that is mathematical process enabling the reconstruction of a acquired image (Feldkamp et al., 1984). With the X-ray computed tomography a complete 3D image of the rock sample pore space is obtained. Depending on the scanner resolution there are micrometer-sized (micro-tomography) or nanometer-sized (nano-tomography) (Madonna et al., 2013).

The detailed analysis was made to determine the size and type of pore space. X-ray microtomograph Benchtop CT160 was the scanning device, with the source emitting a conical beam of X-ray photons with energy in the range 40–160 kV and a resolution up to 3 microns. Micro-CT images of 10 samples were interpreted qualitatively and quantitatively (Cnudde and Boone, 2013; Krakowska and Puskarczyk, 2015). Image processing was performed in the ImageJ and Avizo software and quantitative analyzes in the MAVI software. Obtained resolution of the micro-CT images reached 5.8 × 5.8 × .5.8 μm^3. Initial spherical samples have 3 mm in diameter and total scanned volume 1550 × 1550 × 400 voxels (1 voxel = 5.8 × 5.8 × .5.8 μm^3).

3.1. Total porosity

Total porosity was calculated for the whole sample and two subsamples (Fig. 2, Table 2) by dividing the volume of pores to the whole sample volume, i.e. sum of pore and skeleton volume (Zalewska et al., 2011, 2013). Analysed carbonates from the Modryn formation showed average total porosity equal to 0.63% at the range of 0.1–1.5% and standard deviation – 0.5%. The 10% of samples revealed total porosity below 0.14% and 90% in the range of 0.14–1.5%. Considerable difference between total porosity for the subsample A and B evidenced pore space heterogeneity. Samples 133 and 135 represent heterogeneous formations. Relative error of total porosity, estimated as the ratio of difference between total porosity of subsample B and A to the total porosity of subsample A (in percentage), was equal to 67 and 82%, respectively. Significant difference between total porosity of subsamples was often caused by fractures and microfractures evidenced in the macroscopic and microscopic description enclosed in reports on wells.

Total porosity obtained from the micro-CT interpretation in comparison to total porosity from the helium pycnometer (Table 3) assumed different values. This observation can be the result of micro-CT and helium pycnometer difference in resolution. Micro-