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TECHNICAL NOTE

THE CONCEPT OF A COMPUTER SYSTEM FOR INTERPRETATION OF TIGHT ROCKS USING X-RAY COMPUTED TOMOGRAPHY RESULTS

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Abstract: The article presents the concept of a computer system for interpreting unconventional oil and gas deposits with the use of X-ray computed tomography results. The functional principles of the solution proposed are presented in the article. The main goal is to design a product which is a complex and useful tool in a form of a specialist computer software for qualitative and quantitative interpretation of images obtained from X-ray computed tomography. It is devoted to the issues of prospecting and identification of unconventional hydrocarbon deposits. The article focuses on the idea of X-ray computed tomography use as a basis for the analysis of tight rocks, considering especially functional principles of the system, which will be developed by the authors. The functional principles include the issues of graphical visualization of rock structure, qualitative and quantitative interpretation of model for visualizing rock samples, interpretation and a description of the parameters within realizing the module of quantitative interpretation.

Key words: *tight gas, shale gas, X-ray computed tomography, tight rocks, computer system for rock analysis*

1. INTRODUCTION

The unconventional gas deposits accumulated in sedimentary rocks (tight gas, shale gas) are currently the topic of interest of an oil and gas industry and research and development centers, which take into consideration the prospection and exploration of hydrocarbons in the amount that would be economically viable (Poprawa and Kiersnowski 2008, Poprawa 2010, Such et al. 2010, Porębski et al. 2013, Bieleń and Matyasik 2013, Jarzyna et al. 2013, Zorski et al. 2011). Tight gas or shale gas deposits require an extra work expenditure, especially when it comes to deposit recognition, due to the necessity to create a geochemical analysis (the presence of organic carbon), mineral composition (clay minerals that build shale and the assessment of their mechanical properties), as well as the analysis of significantly weaker, as compared to conventional deposits, reservoir parameters, such as porosity and permeability. Exploration of this kind of deposits includes performing additional technical practices such as hydraulic fracturing, which are contrary to conventional deposits, which also requires a suitable preparation. An X-ray computed tomography (CT) is a new method for rock analysis, which is a unique source of information on complexity of pore space (Wellington and Vinegar 1987). Based on the detailed qualitative and quantitative analyses performed the CT scanning is being recommended as a basic tool while doing research on pore space and a skeleton of rock samples (Krakowska et al. 2016). Commercial software, which is currently available and offers the possibility to analyze tomographic images, use the modules for quantitative parametrization of tomographic image elements, however they process images in a universal form and are not devoted to issues which are strictly petrophysical or geological. For this reason, it was decided to engage in the topic of designing a computer application that would be dedicated for the purposes which are strictly petrophysical and geological as well as for general purposes in terms of the analysis of porous materials presented in a two- or three-dimensional form.

2. X-RAY COMPUTED TOMOGRAPHY FOR THE TIGHT ROCKS ANALYSIS

Sedimentary rocks of Precambrian and Paleozoic era can be analyzed in terms of reservoir and elastic properties, which are used in the prospecting for hydrocarbons, drinking water and geothermal waters and the assessment of the usefulness of rocks to CO2 sequestration (Jaworowski and Mikołajewski 2007, Kotarba 2010, Semyrka et al. 2010, Kotarba and Lewan 2013). A modern approach to integration of diverse laboratory measurement results on cores and a detailed profile of pore space is possible thanks to the new techniques of testing solid substances. Those techniques enable broadening of the concept of reservoir rocks to a greater extent than criteria set so far and including to this category tight gas and shale gas deposits. The results obtained can be useful for further research and identification works. The key to understand the specification of reservoir rocks of Precambrian and Paleozoic era is a detailed analysis of pore space, where hydrocarbons are accumulated. Only recently an X-ray computed tomography has been included in the rock analysis and considered as a modern, noninvasive method (Dohnalik and Zalewska 2013). Tight gas is a natural gas, which is accumulated in the isolated rock pores (empty spaces between the solid phase of a rock). Rocks with low porosity and low permeability that store tight gas, for example, sandstones or limestones, have typically poorly developed pore space, with nanopores mainly present. Shale gas is a natural gas which is present in shale rocks (claystones, mudstones). Bedrock for shale gas deposits is also a reservoir rock, therefore generation, migration and accumulation of hydrocarbons occur within the same formation. Tomographic analyses turned out to be a significant technique of qualitative and quantitative research on pore space of rocks. Because of this kind of analyses, it is possible to assess the total porosity of rocks, the complexity of the structure of pore space, which is crucial, for example, when assessing rocks for the hydraulic fracturing process, as well as generating three-dimensional image of pore space in order to conduct the simulation of fluid flow and to estimate absolute permeability. Information contained in tomographic images is crucial in quantitative description of rock pore structure. For this reason, a solution should be found in order to obtain numerical characteristics of pore space and grains that build rock skeleton based on the computed tomography results. In the world literature, there are several articles on tomographic analysis of shale gas (Watson and Mudra 1991, Xiao-Chun et al. 1992, Lenoir et al. 2007, Ciechanowska et al. 2012, Josh et al. 2012, Panahi et al. 2013), tight gas reservoirs (Jarzyna et al. 2012, Krakowska and Puskarczyk 2015) as well as conventional reservoirs (Lindquist and Venkatarangan 2000, Van Geet et al. 2000, Dvorkin et al. 2008, Karpyn et al. 2003, Siddiqui et al. 2006, Youssef et al. 2006, Madonna et al. 2012, Renard 2012, Madonna et al. 2013).

X-ray computed tomography relies on overexposing a rock sample with an X-ray radiation (Kayser et al. 2006). Information on porosity, spatial distribution of pores, as well as information about pore channels tortuosity can be obtained by applying image processing methods on the CT results, in order to segment images. It is crucial regarding evaluation of capacity of the rock for media flow (Arns et al. 2005). X-ray computed tomography measurement begins when X radiation beam is emitted by X-ray tube. X-rayed sample casts a shadow on detector creating 2D projection. Radiation which goes through the sample is absorbed, so depending on a test object it would be weakened variably. The 011 greater weakening of a beam stems then greater density of a sample. The principle of measurement is based on saving subsequent projections (the view of an image of a sample to a surface of a detector), which differs in an angular position in the scope from 0 to 360 degrees. The smaller the rotation angle is, the bigger the precision of an image, but also the time of the measurement. In order to obtain sample cross-sections, it is necessary to use a back-projection algorithm (Feldkamp 1984), which in effect makes it possible to obtain an images' variability of linear absorbance coefficient. An algorithm of back-projection makes a group of algorithms for reconstruction, i.e., mathematical process, which allows converted image to be obtained. Thanks to computed X-ray tomography it is possible to obtain the full image of pore space of a test rock sample. Visualization of pores in micrometers (microtomography) or nanometers (nanotomography) can be provided by tomography resolution. The results of X-ray computed tomography can be presented in a form of two-dimensional images (Fig. 1) or three-dimensional visualization of pore space (Figs. 2, 3). 2D and 3D visualizations enable the qualitative interpretation of tomographic results. From qualitative interpretations, it is necessary to pass to quantitative interpretation, which encompasses appointing 011 numerical values of petrophysical parameters, i.e., porosity values, tortuosity coefficients as well as estimating selected statistical parameters.

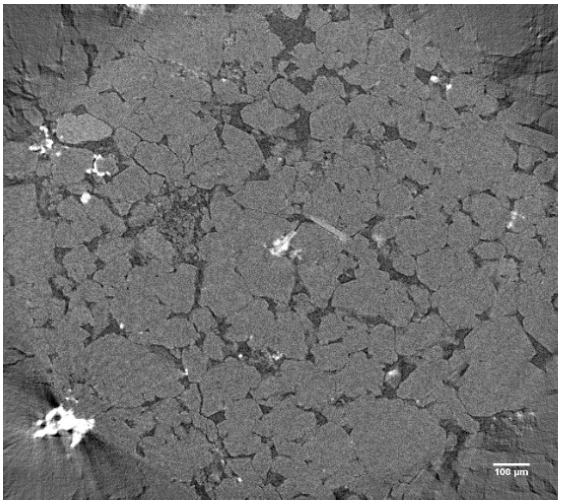

Fig. 1. 2D tomographic image of Carboniferous sandstone, nanotomograph at FPACS AGH in Cracow; light grey area – grains, dark grey – pore space

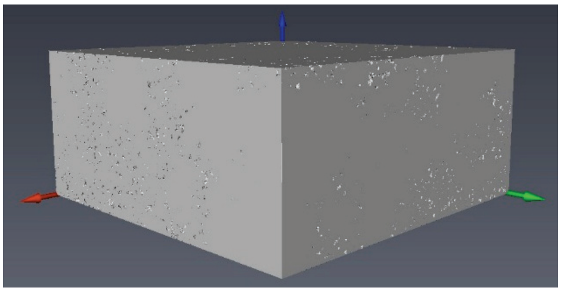

Fig. 2. Visualization of the sandstone (Carboniferous) skeleton, Avizo software, OGI-NRI in Cracow

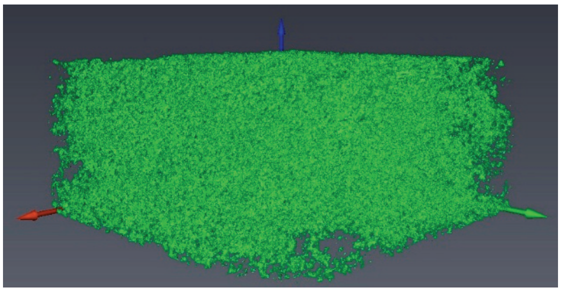

Fig. 3. Visualization of pore space of the sandstone (Carboniferous) skeleton, Avizo software, OGI-NRI in Cracow

3. THE CONCEPT OF A COMPUTER SYSTEM FOR TIGHT ROCKS ANALYSIS

In Polish and international research centers, commercial programs are used for processing and visualization of 2D and 3D images named Avizo (FEI company), ScanIP (Simpleware) and the following ones for quantitative interpretation of images: MAVI (Fraunhofer). A free software which enables processing tomographic images is ImageJ. During simulations of liquid flow through the pore space a commercial software is being used, including Comsol (Comsol company), Star CCM + (CD-adapco) company or non-commercial software, for example, Palabos or Open-FOAM. Limitations that occur during the process of analysis are connected with the cost of purchasing a software license and heterogeneity of the solution, which generates the need to use various programs. Furthermore, it generates some issues with data exporting and various file formats – very often strictly dedicated to a given solution. Available, non-commercial software that offers an opportunity to analyze tomographic images, uses modules for quantitative parameterization of tomographic images' elements, but such software converts images in a universal form and is not devoted to issues which are strictly petrophysical, geological or geotechnical. It became a basis to work on one, useful and homogeneous solution, which allows an analysis to be conducted within one software. The necessity of obtaining reliable information on the pore space and mineral skeleton of a rock retrieved from the results of X-ray computed tomography, especially in the case of difficult formations such as tight gas and shale gas, proves that there is a need for a software to be used by petrophysicists, geologists and geoscientists and other groups of researchers that deal with material structure in different aspects in a detailed way (for example, ceramic, medical materials, etc.). Thus, the authors began the software development process of such a solution. In this paper, a preliminary analysis of the proposed system requirements is presented, to submit it to the public discussion. The authors hope to obtain feedback regarding the usefulness of selected requirements, and it is welcome to hear some functional suggestions from the readers.

3.1. THE PRODUCT FUNCTIONALITY

The functionality of the product is treated as a set of attributes that define a set of functions of a proposed software, and it refers to a complex, usable analysis of images obtained during X-ray computed tomography. The set of functionalities included in the software provided is dedicated to qualitative and quantitative analysis of issues dealing with research of unconventional deposits. It is assumed that the software will enable the following actions:

- importing a three-dimensional tomographic data saved in a defined format (the module of data loading);
- visualization of the results from image obtained from X-ray computed tomography in two different ways: presented as two-dimensional images or three-dimensional visualizations of pore space (the module of data visualization);
- supporting qualitative interpretation of tomographic results based on the module of data visualization, thanks to defined facilitation, e.g., in a form of dedicated navigating system, the possibility to export and save selected view, etc. (the module of qualitative interpretation);
- supporting quantitative image interpretation through enabling calculation of numerical petrophysical, geological parameters, such as porosity values, tortuosity coefficient as well as calculation of selected statistical parameters (the module of quantitative analysis);
- applying custom algorithms for image processing, based on a set of applied methods of computer analysis and digital image processing, e.g., non-standard algorithms for porosity detection of an analyzed rock sample (the module of image processing).

3.2. THE MODULE OF IMPORT AND EXPORT OF ROCK STRUCTURE

Characteristics of the module for importing and saving the model for rock visualization covers the functionalities in the scope of managing data that are the input of the system. The authors plan to create a functionality for loading and saving tomographic data in two and three-dimensional form that would be saved in predefined format and would include the following features:

(a) import a model of a sample/file into the system in selected formats (e.g., RAW, VOL);
(b) import a single cross-sectional image, which presents a selected section of a rock sample into the system (e.g., jpg, tiff, bmp, png formats);
(c) select a file from the drive with the use of a dialogue window/the possibility of selecting a file from the drive with the use of drag and drop method/ the possibility of selecting an input file with a fly-over help of recently used localization to save files;
(d) save the actual view (visualization) of a model with the use of a window;
(e) export a set of calculated (in other modules) parameters of a given model and save it in a selected format.

3.3. THE MODULE OF GRAPHICAL VISUALIZATION OF ROCK STRUCTURE

The characteristic of the visualization module of the model for rock depiction includes functionalities in data visualization. It is permissible to visualize the result of X-ray computed tomography of an image in two ways:

- presented as a set of two-dimensional cross-sections (Fig. 4);
- presented in a form of three-dimensional visualization of CT data model (Fig. 5).

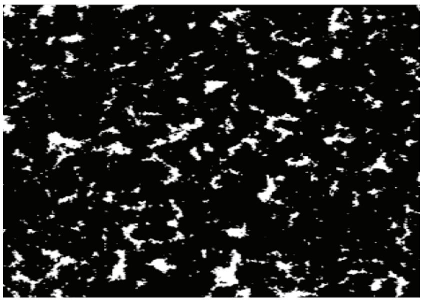

Fig. 4. An example of cross-section of a rock sample, binarized in order to detect pore space (claystone) in the new computer system

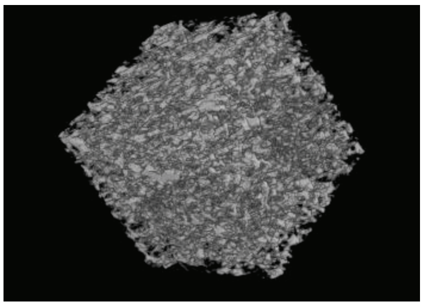

Fig. 5. An example of three-dimensional visualization of pore space of rock model (claystone) in the new computer system

It is assumed that the visualization model will be singled out to a form of the application window and it will provide the defined functionalities on the naviga-

tion and browsing of the model based on the work stages, for example:
(a) enable the software user to browse through data as loaded original image sequence – through the use of defined browsing bar, scroll bar through entering the number of an image to preview and the possibility to increment or decrement the number of an image;
(b) ensure operation of a model, which is loaded as an image after segmentation;
(c) enable the user to control rotating along the Cartesian axis coordinate system, that is, *X*, *Y*, *Z* axis;
(d) enable the user to control zooming in and zooming out the model;
(e) enable control of the tapering of displayed view of a model to the selected fragment;
(f) enable changing colouring (according to fixed, acceptable colour sets) of a binary object.

3.4. THE MODULE OF QUALITATIVE INTERPRETATION

Designation of the module of rock visualization model is to support qualitative interpretation of tomographic results. It is assumed also for qualitative assessment of pore space and mineral skeleton. The analysis of homogeneity and development of pore space and granulation can be evaluated. The quantitative analysis of image leads to proving heterogeneity in pore space, which should be supported by the functionality to visually separate selected objects to predefined groups of objects. The possibility to group and index objects in detected pore space is being considered (labelling) (Figs. 6, 7). During processing the microtomographic results, the pore space of each sample can be divided into subgroups that would make up a set of pores connected with each other, however not being connected with other subgroups. The subgroups can be classified as far as their volume.

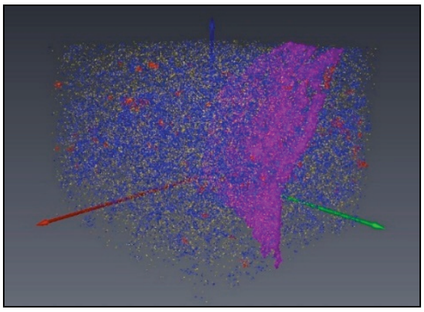

Fig. 6. Microtomographic image of Devonian sandstone pore space (subsample A); Avizo application, OGI-NRI in Cracow

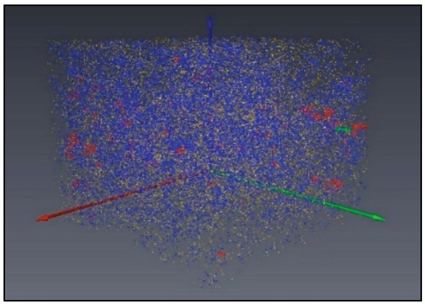

Fig. 7. Microtomographic image of Devonian sandstone pore space (subsample B); Avizo application, OGI-NRI in Cracow

For example, during a research on Devonian sandstones (Krakowska et al. 2014), it was possible to single out the volume classes (expressed in voxels – volumetric picture element) of pore space subgroups, marked in an microtomographic image with relevant colours: Class I: 1–9 voxels, yellow; Class II: 10–99 voxels, red; Class IV: 1000–9999 voxels, green, Class V: >100000 voxels, violet (Figs. 6, 7).

3.5. THE MODULE OF QUANTITATIVE INTERPRETATION

The characteristics of quantitative interpretation module of a rock visualization model covers enabling the calculation of numerical value of petrophysical parameters of an analyzed rock sample, considering 3D model. It is assumed that the process of quantitative tomographic image interpretation concerns establishing the values of significant petrophysical, geological parameters, including the following:

- the total porosity of a sample;
- the effective porosity of a sample;
- the tortuosity of pore channels of a sample;
- the number of subgroups of pores within a given class of volume;
- a relative standard deviation being homogeneity parameter of pore structure of a sample;
- the average length of a chord lead through the pore layer in a sample;
- the characteristic of Euler number as a parameter reflecting the quality of pore connections;
- the granulometric characteristic of distribution of pore diameters of a sample.

Execution of the above requirements will enable a detailed analysis of pore space and mineral skeleton based on tomographic images that are input data for the software. Since those parameters are elements of rock characteristics, the functionality will enable to calculate parameters, which from the perspective of further evaluation of a reservoir potential of a sample are crucial.

3.6. THE MODULE OF CUSTOM IMAGE PROCESSING

Computer tomographic analysis of digital images is a complicated task due to its exceptionally irregular characteristic of input data. Applying the standard algorithms for image analysis, which give effective results in, for example, medical sciences (in the area of medical diagnostics), does not guarantee the effectiveness in Earth sciences, which are a separate issue for research. The goal of the module for digital image processing is enabling the user to apply own algorithms for image processing in order to detect pore space of a given sample. The actual concept of the software assures model operation, imported as a gray image as well as binary image. In the case of importing grey/binary image it is meant to enable the user to apply selected methods from computer processing and analysis of digital images in order to detect or modify the pore space of an image. It is anticipated to implement selected algorithms for converting and context filtering of digital images, morphological conversion elements and/or in the area of frequency.

4. SUMMARY

The article focuses on the specification of issues connected with the analysis of images retrieved from the X-ray computed tomography, devoted to research of hydrocarbon-bearing reservoirs. The concept of designing a software that would allow the reservoir potential to be assessed based on the possibilities of qualitative and quantitative analysis of a rock sample. The system requirements (functional) were presented and grouped into modules: data import/export data visualization, qualitative analysis (grouping and classification of objects), quantitative analysis (calculating parameters which are typical of rock skeleton and detected pore space) and a module of applying own algorithms for detecting pore space (as based on methods of analysis and processing digital images) are a modern solution and useful in terms of the assessment of reservoir potential of rocks. Presented solution (financed by the National Centre for Research and Development, LIDER programme) is in the developmental stage and this is a conceptual and discussion article. The authors believe that due to the costs of obtaining and maintaining commercial software for processing and qualitative and quantitative interpretation of tomographic images being very high (cost of annual or monthly license), industrial centers, scientific-research centers very often cannot afford such tools, giving up the detailed interpretation of tomographic images, which carry the key information on pore space and skeleton of rocks. The authors hope that the proposed concept and future execution of a plan will be appraised by researchers' community and will be a useful specialist tool.

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