Available online at www.sciencedirect.com
ScienceDirect
Russian Geology and Geophysics 56 (2015) 782–792
RUSSIAN GEOLOGY AND GEOPHYSICS
www.elsevier.com/locate/rgg

X-ray tomography in petrophysical studies of core samples from oil and gas fields

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Received 4 September 2013; received in revised form, 29 May 2014; accepted 21 October 2014

Abstract

The porosity and permeability of core rocks were studied by X-ray tomography. This method has a high potential for studying petrophysical properties of rocks, because it permits not only a general quantitative estimation of the void volume but also visualization of the rock texture, including pores, cavities, cracks, and zones of different densities in the matrix. X-ray tomography permits detailed studies of rock inhomogeneity, which are necessary for the elaboration of reliable porosity–permeability models for hydrocarbon pools. The investigations at Perm State National Research Polytechnic University have shown that X-ray tomography of core samples has a wide spectrum of applications in petroleum geology. Nikon Metrology XT H 225 X-ray computed tomography makes it possible to examine samples with a standard diameter (30 mm) and whole core samples (100 mm). The structure of voids in carbonate and terrigenous rocks was studied on samples with standard and full diameters; the results of hydrochloric acid treatment of carbonate reservoir rocks were visualized; and the mechanical properties of rock salts were studied. Three-dimensional models for the structure of voids and mineral matrix of the core samples have been constructed with the use of the Avizo Fire software.

Keywords: X-ray tomography; core samples; petrophysical studies; reservoir; porosity; inhomogeneity

Introduction

The selection of the optimum systems of development for hydrocarbon pools depends on the study of issues related to the porosity and permeability of reservoir rocks (first and foremost, with regard to the estimated inhomogeneity of the reservoir properties in the bulk of the pool). This is particularly important for reservoirs which are heterogeneous geologic bodies with a complicated structure, often characterized by high facies variability. However, the variability of the structure of voids in geologic objects is not taken into account to the full extent in the modeling of development of hydrocarbon pools. For example, the structure of pools is very much simplified in geological–hydrodynamic modeling, and the underestimation of the effect of inhomogeneity in the structure of developed objects violates the succession of development of the pool and reduces the final recovery of reserves.

A new direction with good prospects in studies of the porosity and permeability of reservoir rocks is X-ray tomography. X-ray studies of core rocks are based on difference in the density of rock, mineral inclusions, voids, fractures, and the formation fluids which fill them. When passing through rock, X-rays become weaker. The attenuation of X-rays depends exponentially on the thickness of "X-rayed" rock and the "attenuation exponent" coefficients depend on the physical properties of rock. Note that, as the rock density increases, the damping coefficients increase after the passage of rock, forming a pixel image.

The obtained halftone images, whose brightness characterizes the degree of X-ray absorption, are used to reconstruct a 3D model for the sample. Thus, the result of X-ray tomography is the 3D distribution of "X-ray density" in the bulk, which makes it possible to judge about the structure of the rock matrix and the distribution of pore channels.

Application of the X-ray tomography of core samples in the solution of problems in the petroleum industry

X-ray tomography has been used in petroleum geology since the late 1980s (Wellington and Vinegar, 1987). The early

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1068-7971/$ - see front matter
http://dx.doi.org/10.1016/j.rgg.2015.04.009

studies were carried out only abroad (Australia, United States, Great Britain, Germany, Norway, and Poland); the Russian X-ray tomography studies of core samples began in the 2000s (Yakushina et al., 2003). The main centers of these studies in Russia are Moscow State Univesity, named after M.V. Lomonosov (Moscow); All-Russia Petroleum Research Exploration Institute (VNIGRI) (St. Petersburg); SIBKOR (Tyumen'); TomskNIPIneft' VNK (Tomsk); and Perm National Research Polytechnic University.

The sizes of the samples under study are determined by the technical characteristics of tomographs (power of the X-ray gun, distance from the receiver, dimensions of the detector). When equipment is used, the size of the focal spot increases as the penetrating power of X-rays increases, which has a negative effect on the results of scanning of objects. Therefore, a tomograph with a certain range of the main characteristics of X-rays (working potential difference and maximum power) should be used for core samples of the given size.

Based on the experience of application of the method, the aspects of X-ray tomography studies with the best prospects can be distinguished:

for full-size core samples (100 mm in diameter);

for standard core samples (26 and 40 mm in diameter);

for core samples up to 30 mm in diameter (5–15 mm).

Full-size core samples ($d = 100$ mm, $h = 1000$ mm) are studied to detect lithologic inhomogeneities, fractured zones, and cavernous zones. The results of tomographic studies of full-size core samples can be used as an express analysis for determination of the type of the reservoir, calculation of the volumes of fractures and cavities, and correlation of data obtained from geophysical studies of wells and laboratory petrophysical studies. Tomography of full-size samples is also used as a method for study of fractured rocks, which are unsuitable for making standard samples ($d = 30$ mm) (Zhukovskaya and Lopushnyak, 2006, 2008). The experience of studies of full-size core samples was summarized in the presentation "The Experience of Application of the X-ray Tomography of Full-Size Core Samples" by D.A. Bezhentsev and I.V. Fedortsov at the International Conference and Exhibition (Tyumen', 2009). According to the authors, the good prospects of tomographic studies of full-size core samples are related to the systematic detection of commercial reserves in fractured reservoirs.

The tomography of standard petrophysical samples ($d = 30$ mm) makes it possible to study structure–morphologic features and the geometry of voids (pores, cavities, and fractures) and to control the quality of production of samples, i.e., to check whether the orientation of their stratification corresponds to parallel or perpendicular (Arns et al., 2005; Peters and Afzal, 1992; Saadat et al., 2011). Also, X-ray tomography studies of standard petrophysical samples make it possible to assess the effect of microinhomogeneities and stratification of core samples on the distribution of liquid and the electric and acoustic properties of reservoir rocks (Alemu et al., 2012).

The tomography of core samples <30 mm in diameter (usually 15 or 9 mm) permits study of the composition of mineral components and their spatial relationship, bulk and surface characteristics, type of cement, and structure of voids. The high resolution obtained owing to the small size of the samples under study makes it possible to assess saturation with fluid, the distribution of the front of movement of the fluid in the determination of phase permeabilities, and the distribution of residual water in the samples during the plotting of the curve of capillary pressure (Korost et al., 2010). X-ray tomography studies of small core samples can be carried out when it is impossible to make standard samples (sludge, chipping, etc.) (Eremenko and Murav'eva, 2012; Ketcham and Carlson, 2001; Zhuravlev and Vevel', 2012).

Note that the tomographic equipment available in Russian centers permits studies of only one of the above-mentioned aspects. For example, in West Siberia (TomskNIPIneft' VNK and SIBKOR), Russian tomographs are used, whose design, owing to the fixed distance from the source of radiation to the receiver, permits study of core samples 100 mm in diameter and 1000 mm high. On the contrary, SkyScan (the most widespread tomographic systems in Russia), which have a voltage limitation to 100 kV, do not permit efficient study of samples >30 mm in diameter. Therefore, the technical characteristics of SkyScan tomographs do not permit studying full-size core samples.

Analysis of both the Russian and non-Russian experience of X-ray tomography of core samples shows that the optimum tomograph must have a working potential difference with a maximum value of at least 210 kV and a design which permits changing the distance from the X-ray tube to the receiver. Tomographs with the above-mentioned characteristics permit qualitative study of samples from several millimeters across to full-size ones, including standard samples 30 mm in diameter.

Studies of core rocks using Nikon Metrology XT H 225 X-ray computed tomography (Fig. 1) have been carried out at Perm National Research Polytechnic University since 2011; this system was used successfully in studies of core rocks abroad.

The working potential difference of the apparatus is from 30 to 225 kV; power of the X-ray tube, 225 W; size of the focal spot, 0.003 mm; dimensions of the detector, 200 to 250 mm; and distance from the source to the receiver, 1000 mm. Owing to its technical characteristics, this system permits studies of core samples from several millimeters in diamater to full-size ones. For example, the smallest resolvable elements for samples 100 mm in size are 0.07 mm in size; for samples 30 mm in size, 0.02 mm; and for samples 10 mm in size, 0.007 mm.

In 2012–2013 the authors carried out X-ray tomography studies of core samples from the pools of the Perm and Krasnoyarsk Territories, Iraq, and Uzbekistan. Note that the analysis of projections and the subsequent visualization of the 3D model were carried out using the Avizo Fire software. In all the cases, the tomographic studies were controlled by standard petrophysical studies of core samples. Petrophysical studies permit a quantitative estimation of the main reservoir properties averaged for the bulk of the sample, whereas