SCIENCE CHINA
Physics, Mechanics & Astronomy

• Letter to the Editor •

June 2016 Vol. 59 No. 6: 664201
doi: 10.1007/s11433-016-5792-x

Characterizing the oil and water distribution in low permeability core by reconstruction of terahertz images

RiMa Bao[1††], XinYang Miao[1††], ChengJing Feng[1], YingZhi Zhang[2], HongLei Zhan[1], Kun Zhao[1*], MaoRong Wang[3], and JianQuan Yao[3]

[1] *Beijing Key Laboratory of Optical Detection Technology for Oil and Gas, China University of Petroleum, Beijing 102249, China;*
[2] *Qingxin Oil Field Development Company Limited, Anda 151400, China;*
[3] *College of Precision Instrument and Opto-electronics Engineering, Tianjin University, Tianjin 300072, China*

Received December 4, 2015; accepted January 20, 2016; published online March 30, 2016

Citation: R. M. Bao, X. Y. Miao, C. J. Feng, Y. Z. Zhang, H. L. Zhan, K. Zhao, M. R. Wang, and J. Q. Yao, Characterizing the oil and water distribution in low permeability core by reconstruction of terahertz images, Sci. China-Phys. Mech. Astron. **59**, 664201 (2016), doi: 10.1007/s11433-016-5792-x

Dear Editors,

Exploitation of low permeability oilfield has become an interest of the world due to the decline of conventional oil reserves. Flooding has been observed to be able to enhance oil recovery in tight sandstone reservoir. The pore throat diameter of the sandstone described above is in nano/micro scale, and remaining oil and irreducible water exist simultaneously. Therefore, better understanding of reservoir behavior is essential to predict future performance of water flooding process [1,2]. Terahertz (THz) radiation (wavelengths from 30 μm to 3 mm) has recently emerged as an efficient tool in many fields such as oil and gas characterization, cultural heritage investigation, air pollution detection and design of metamaterials [3-6]. Applications of THz techniques are promising such as time domain spectroscopy (TDS) in solid-state physics and aqueous chemistry [7]. Response of THz wave is intrinsically associated with low energy events such as molecular torsion or vibration as well as inter and intramolecular hydrogen-bonding, causing the strong attenuation of THz waves by water [8]. Therefore, THz spectroscopy was considered as an effective means for detection of water content and distribution [9]. In this letter, we investigated the distribution of oil and water in low permeability core via reconstruction of THz images.

The argillaceous sandstone reservoir cores with low porosity (from 12% to 14%) and low permeability (1.0 mD) were employed as the object in this study. The core has a diameter of 25 mm. Before each measurement, cores were firstly deoiled and saturated with water, then flooded with kerosene to an irreducible water state. All the cores were immersed into the solution blended by kerosene and water to simulate a real situation underground. One of the cores was sliced into 10 pieces. The thickness of each wafer was about 2 mm, and all of them were numbered from 1 to 10 according to the original positions.

The THz spectroscopy was measured with a reflection THz-TDS. The THz wave source was introduced by the Cherenkov type phase matching and optical rectification in a non-linear optical crystal ($LiNbO_3$). The effective frequency range was 0.1-4 THz and the minimum spatial resolution of the system was below 0.3 mm. Scanning was achieved via mechanical motion of object so as to obtain information to characterize the entire slice. Parameters such as peak amplitude and delay time were extracted directly from the spectrum for imaging. The center of the wafer was selected as the starting point of scanning. The sweep range referred to an 8 mm radius circle, and the step interval was 0.4 mm.

The reflective spectra of a selected region (2 mm×2 mm) on the first slice (numbered 1) was shown in Figure 1(a). The amplitudes of the spectra were different from each other

*Corresponding author (email: zhk@cup.edu.cn)
††These authors contributed equally to this work.

© Science China Press and Springer-Verlag Berlin Heidelberg 2016

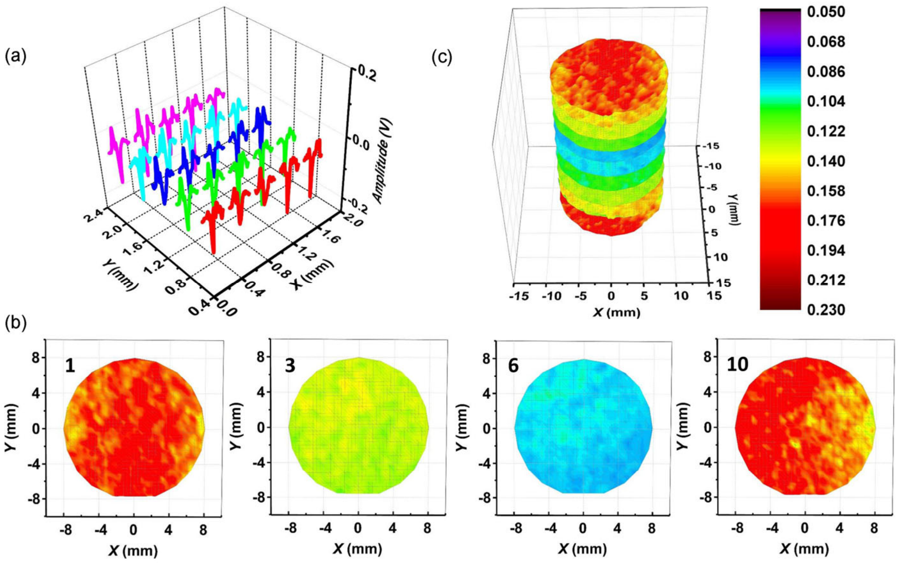

Figure 1 (a) THz spectra at the selected regions of the sample 1; (b) THz images of the samples numbered 1, 3, 6 and 10 obtained by exacting the peak amplitude of each point, and mixed colors were selected to represent the level of intensity visually; (c) reconstruction of all the 10 samples by order.

due to the component changes of the rock at different positions. Since water had a much stronger interaction with THz waves compared with oil and kerosene [10], the attenuation of the radiation can be related to the water content in the porous media. In order to display more clearly, the peak amplitude of the THz spectrum at each position was selected for imaging, and the levels of the intensity were represented by various colors. Figure 1(b) presents the THz amplitude images of the samples numbered 1, 3, 6 and 10, respectively. Since the oil and water distribution was not absolutely homogenous, regions with different compositions were identified in the spatial distribution map. Colors of the images displayed in Figure 1(b) varied gradually from red to azure, and changed back to red at last among these images, indicating that the content of water rose first and then declined. As shown in Figure 1(c) the THz images of all the pieces were rebuilt according to the original position in order to figure out the oil and water distribution within the core. On the basis of analysis above, we could predict the oil-water distribution via the reconstructed diagram. By the changes of the colors, kerosene mainly existed in the upper area, and remaining oil failed to be flooded and occupied the lower regions of the core while the irreducible and free water was distributed in the center of the core. This result is consistent with the flooding processes in low-permeability cores. It is noteworthy that the color changed suddenly at various positions due to a few number of slices, and the accurate evaluation of water content will be studied with the achievement of thinner slices in the future.

In this letter, THz imaging technology was used to predict the occurrence state of oil and water in handled sandstone cores. THz amplitude images were performed to characterize the distribution of oil and water in each piece. The existence of kerosene, water and remaining oil could be clearly identified by THz three-dimension (THz-3D) reconstruction. The results prove THz to be a promising means for detecting reservoir properties. Furthermore, the image reconstruction method used in this letter may provide a new idea for THz tomography technique and application.

This work was supported by the National Key Basic Research Program of China (Grant No. 2014CB744302), the Specially Funded Program on National Key Scientific Instruments and Equipment Development (Grant No. 2012YQ140005) and the National Natural Science Foundation of China (Grant Nos. 61405259 and 11574401). The authors also thank the testing service provided from the Advantest Corporation.

1 D. Yuan, J. Hou, Z. Song, Y. Wang, M. Luo, and Z. Zheng, J. Petrol. Sci. Eng. **129**, 15 (2015).
2 F. Torabi, N. Mosavat, and O. Zarivnyy, Fuel **163**, 196 (2016).
3 Z. W. Zhang, K. J. Wang, Y. Lei, Z. Y. Zhang, Y. M. Zhao, C. Y. Li, A. Gu, N. C. Shi, K. Zhao, H. L. Zhan, and C. L. Zhang, Sci. China-Phys. Mech. Astron. **58**, 124202 (2015).
4 Q. Li, K. Zhao, L. W. Zhang, L. Chuang, Z. W. Zhang, C. L. Zhang, and D. H. Han, Sci. China-Phys. Mech. Astron. **57**, 2354 (2014).
5 R. M. Bao, Y. Z. Li, H. L. Zhan, K. Zhao, W. Wang, Y. Ma, J. X. Wu, S. H. Liu, S. Y. Li, and L. Z. Xiao, Sci. China-Phys. Mech. Astron. **58**, 114211 (2015).
6 D. C. Wang, Q. Huang, C. W. Qiu, and M. H. Hong, Sci. China-Phys. Mech. Astron. **58**, 084201 (2015).
7 P. U. Jepsen, D. G. Cooke, and M. Koch, Laser Photon. Rev. **5**, 124 (2011).
8 H. L. Zhan, S. X. Wu, R. M. Bao, K. Zhao, L. Z. Xiao, L. N. Ge, and H. J. Shi, RSC Adv. **5**(19), 14389 (2015).
9 W. J. Jin, K. Zhao, C. Yang, C. H. Xu, H. Ni, and S. H. Chen, Appl. Geophys. **10**, 506 (2013).
10 Y. S. Jin, G. J. Kim, C. H. Shon, S. G. Jeon, and J. I. Kim, J. Korean Phys. Soc. **53**, 1879 (2008).