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Development of an NMR system for down-hole porous rocks

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ABSTRACT

Nuclear magnetic resonance (NMR) has been widely employed in the petroleum industry, as oil and gas reservoirs are typical complex porous media. Down-hole NMR measurements (thousands of meters below the surface) face the challenges of high temperature, high pressure, strictly limited size of instruments and high speed tool movement. All these challenges make the probe design, spectrometer manufacture, data acquisition, data processing and interpretation quite different from desktop NMR measurements in the laboratory. In this paper, we present our recent development on the key technologies and implementation of an NMR system for down-hole porous rock applications. The techniques used in developing the down-hole NMR tool have not only been used in oil and gas exploration, but also can be adapted to physics, chemistry, materials, agricultural, food science non-destructive analysis.

1. Introduction

Nuclear magnetic resonance (NMR) has been widely employed in physics, chemistry, biology, medicine, agriculture, earth science and other scientific fields. The unique information provided by NMR is very important for the discovery of new phenomena of science. In the exploration of oil and gas, as well as water resources, NMR has been a special research focusing on porous rock because of its unique response features. With the development of NMR instruments using the geomagnetic field [1] and the inside-out design of Jasper Jackson [2], the down-hole NMR idea was developed and commercialized in the 1990s [3–8].

Compared with electrical, acoustic, and nuclear radiation methods, NMR signals directly come from the fluid-saturated pores of the formation, thus providing rich information on petrophysics and fluid types. Such information can be used to estimate porosity, bound water, permeability, pore size distribution, as well as fluid type and concentrations. During oil and gas development, NMR can provide necessary data for the prediction of production, such as remaining oil and gas, enhanced oil recovery and improving production. In shale and other unconventional oil and gas exploration and production, NMR, along with elemental capture spectroscopy logging, formation micro-imager, and dipole sonic logs, are combined to evaluate geological and engineering sweet-spots. Over the last 20 years, the development of NMR methods, applications and instrument have always been at the frontier of petroleum exploration. Several oilfield service corporations have developed NMR wireline logging, NMR logging while drilling, and down-hole NMR fluid analysis instruments.

Since 1982, we have carried out relevant research in NMR theory in porous media, NMR logging methods, as well as the instruments and data applications to complex oil and gas reservoirs. In China, NMR measurements have been performed in thousands of oil and gas wells. Data application becomes more and more significant, when it is difficult to evaluate the formation with conventional technology, such as in reservoirs with special or complex lithology, low porosity/low permeability/low oil saturation, and tight sandstone gas. Meanwhile, numerous fundamental and theoretical problems have been encountered. These problems include depth of investigation, SNR, vertical resolution, stratum inhomogeneity and internal magnetic field gradients. Based on these problems, we have launched a systematic investigation of NMR in porous rocks. Meanwhile, we developed NMR systems that can satisfy the geological conditions of land and/or deep-water reservoirs in China [9–11].

2. Petrophysical information from down-hole NMR

Porous rocks in oil and gas reservoirs usually consist of matrix solids, clay mineral, and pore fluids. Such fluids include oil and gas, free water, capillary-bound water and clay-bound water. With

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the measurements of longitudinal relaxation time (T_1), transverse relaxation time (T_2) and diffusion coefficient (D), NMR is commonly employed to determine petrophysical information, fluids typing and quantitative evaluation.

Laboratory results prove that short and long relaxation time components corresponds to clay-bound, capillary-bound and free water in water-saturated porous rocks. Furthermore, the behavior of the relaxation and the diffusion coefficients are related to the viscosity of fluids. Higher viscosity results from stronger intermolecular forces. Therefore, the differences of T_1, T_2, and D can be used to distinguish clay and capillary-bound water, free water, heavy oil, light oil and gas.

Borehole NMR detection includes multiple stages. The probe is along the well bore and moving up/down to acquire NMR data. The data acquisition and processing system is installed in a truck on the surface. The control commands are sent to the down-hole probe and NMR data are sent back to the surface truck through wire line cable. Inversion methods are then used to process the acquired data to determine the properties of pore fluid and pore structure.

3. Composition and structure of down-hole NMR system

A down-hole system to accomplish the NMR measurements includes probe, spectrometer, as well as pulse sequence for data acquisition and inversion software for data processing, as shown in Fig. 1.

3.1. Probe

The design of an NMR probe is an issue of electromagnetic fields and includes optimization of both structure and material. The signal detected in down-hole NMR probe is from hydrogen nuclei of pore fluids, which are located several kilometers underground. This is a harsh environment with high temperature and high pressure, restriction of the instrument size, motion effect of probe, which requires high reliability and efficiency of the instrument.

The structure design, optimization of material and probe size enables the probe to fulfill the basic requirements of NMR measurement, such as the magnetic field match and transmit power demand. Moreover, the probe possesses good detection characteristics, including high signal strength, high SNR, large depth of investigation, as well as multi-frequency and multi-dimensional capability.

For different well bore environments, we have developed eccentric and centered probes that satisfy the requirements of on land and offshore wire line logging, respectively. As shown in Fig. 1a, each probe includes a magnet, antenna, and frame. The design of the magnet and antenna should consider the orthogonal matching of the static magnetic and radio frequency fields, enlargement of sensitive volume, overall mechanical properties of the probe, and assembly process requirements. Owing to well bore restrictions, the outer diameter of the probe should not exceed borehole size. The details of the probes designed can be found in Ref. [9].

3.2. Spectrometer and electronics

NMR measurement under harsh down-hole condition requires a quality spectrometer. The functional block and signal flow diagram is shown in Fig. 1b. The electronic components comprise a power amplifier, storage, Q-switch, isolation, receiver, main controller, antenna tuner, relay driver, and power circuits. During the detection process, power transmission affects probing depth. The weak echo signal is amplified by the preamplifier, and analog-to-digital conversion components are close to the full range to ensure high SNR. Proper pulse sequence has to be used to address the diversity and complexity of the detected object and will restrict the time of antenna energy discharge. Thus, optimizing the circuit design is a feasible solution for effectively improving the antenna power discharge rates. To solve the practical problems confronting a down-hole NMR spectrometer, the difficulties in spectrometer design include: large power (kW grade) transmission, weak signal (nV grade) detection, pulse sequence alteration and the rapid energy discharge on antenna.

In the work flow of a spectrometer system, the main control circuit receives the ground system command, decodes the corresponding signals, and creates the instruction timing and all control signals, including the transmission control, Q-switch control, isolation control, sampling clock, sampling clock gating, and calibration signals. The specific frequency pulse transmission control signal is generated by the main control circuit with the pulse sequence requirements. The pulse is converted into a large current drive control signal by the power amplifier drive circuit to open the power MOSFET of the amplifying circuit quickly. A dc voltage of 600 V is processed into a peak value of 2400 V for a high-power RF pulse. The high-power RF pulse is transmitted to the antenna. Through the Q-switching circuit, the quality factor of the antenna is reduced after the completion of pulse firing. Thus, the energy stored in the antenna discharges quickly. After the completion of discharge energy, the echo signal is ready to be received. The isolating circuit enables the echo signal to enter the receiving circuit. The amplified echo signal is processed by the main control circuit for data acquisition and digital processing. The amplitude and phase information is extracted by using a digital phase sensitive detection algorithm, and data are transferred to the remote transmission system through the CAN bus. The data are then sent to the ground system through the remote transmission system. The details of the spectrometer and electronics designed can be found in Ref. [10].

3.3. Pulse sequence

In down-hole environments, detection objects usually contain complex components with different physical properties that cannot be distinguished effectively with a single NMR parameter. The advent of low-field two-dimensional (2D) NMR facilitated the development of multi-dimensional NMR, which gave rise to significant interest and expectations. Multi-dimensional NMR measurement is based on the need to realize the joint distribution of two or more dimensions from the distribution of T_1, T_2, D, and internal magnetic field gradient (G). The joint distribution of multi-parameter measurements can provide a richer pore size of porous media, fluid type, fluid migration, and other information that can be used to identify the components of complex samples more efficiently. The traditional multi-dimensional NMR measurements possess some drawbacks, such as long measurement time, large data set, and big data processing error, unsuitable for down-hole environments that impose higher requirements on measuring efficiency. Based on actual measurements and down-hole environmental demands, in addition to the conventional CPMG/Dual waiting-time/Dual echo-spacing activation, a rapid 2D NMR relaxation time measurement pulse sequence DEFSR was employed [12]. The 2D relation between the ratio of transverse relaxation time to longitudinal relaxation time of fluid (T_1/T_2) and T_1 distribution were obtained by using DEFSR with only two one-dimensional measurements. The rapid measurement of relaxation characteristics was thus achieved. The details of the pulse sequence designed and tested can be found in Ref. [12].

3.4. Inversion and data processing software

NMR data processing for porous rocks is based on the Laplace transform inversion [13–14]. Taking one-dimensional (1D) CPMG