Journal of Applied Geophysics 119 (2015) 16–24

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A dielectric logging tool with insulated collar for formation fluid detection around borehole

Bin Wang, Kang Li *, Fan-Min Kong, Jia Zhao

School of Information Science and Engineering, Shandong University, No. 27, Shanda South Road, Jinan, Shandong Province 250100, PR China

ARTICLE INFO

Article history:
Received 14 August 2014
Received in revised form 16 March 2015
Accepted 1 May 2015
Available online 7 May 2015

Keywords:
Surface wave
Metal collar
Dielectric tools
UWB antennas

ABSTRACT

A dielectric tool with insulated collar for analyzing fluid saturation outside a borehole was introduced. The UWB (ultra-wideband) antenna mounted on the tool was optimized to launch a transient pulse. The broadband evaluation method provided more advantages when compared with traditional dielectric tools. The EM (electromagnetic) power distribution outside the borehole was studied, and it was shown that energy was propagated in two modes. Furthermore, the mechanism of the modes was discussed. In order to increase this tools' investigation depth, a novel insulated collar was introduced. In addition, operation in difference formations was discussed and this tool proved to be able to efficiently launch lateral EM waves. Response voltages indicated that the proposed scheme was able to evaluate the fluid saturation of reservoir formations and dielectric dispersion properties. It may be used as an alternative tool for imaging logging applications.

1. Introduction

Dielectric measurements have been used in different kinds of reservoirs to determine dielectric properties of the zone near boreholes since 1970s. Recent research on complex permittivity surveys was prompted by an increasing interest in the fluid saturation of formations, particularly in residual oil and heavier reservoirs. Since the 1980s electromagnetic propagation tools (EPT) have been added to the standard logging suite to aid in the effort of locating reservoirs and quantifying the fluid saturation (Chew and Gianzero, 1981). EPT operating at a single frequency of 1.1 GHz, and from measured phase shift and attenuation of wave traveling through the formation have determined petro-physical properties including dielectric permittivity and porosity.

After introduction of the EPT, other dielectric tools based on a single frequency and slot antennas were developed. Logging data recorded at different frequencies often yielded different results. Comparing the fluid saturation and porosity output from EPT with other tools was often a problem. Those differences were attributed to the frequency dispersion of the dielectric properties. The concept of complex permittivity was proposed in order to combine materials' dielectric and conductive properties (Von Hippel, 1954). Although the complex permittivity of a dry formation is constant over a wide range, in practice reservoir formations are filled with fluids. Complex permittivity of invaded zone and virgin formation are frequency dispersive because of several polarizations in a fluid saturated formation at the microwave range (Von Hippel, 1954). For the dispersion of dielectric properties, a single frequency method has serious limitation in evaluating the complex permittivity of the formation. Furthermore, the tool's mandrel design makes it quite easy to limit energy along the metal collar as a non-radiating wave (Wait, 1987), but it seriously decreases the detection depth of EPT, which will be explained in this paper.

The dielectric scanner was developed to quantify complex permittivity at different frequencies (Hizem et al., 2008). Transmitters and receivers are mounted on a pad in contact with the borehole and raw measurement of attenuation and phase shift are obtained at four frequency points between 20 MHz to 1 GHz. Because great differences exist between permittivity dispersion properties of the water saturated zone and the reservoir zone, dielectric information at wide band provides competitive advantages for carbonate reservoir interpretation, shaly sand analysis, and heavy-oil reservoir evaluation (Little et al., 2010). The dielectric scanner offers extra logging information, but it would be better to have a swept frequency dielectric measurement in the broadband. Moreover, dipole antennas mounted in the tool cannot supply efficient high emission for each operating frequency. Thus, there are still possible improvements to be made in the evolution of dielectric logging tools.

This study demonstrates a new logging tool as an improvement to traditional dielectric tools for formation complex permittivity and fluid saturation evaluation. First, the design of the proposed dielectric tool based on UWB antennas is described, and detailed geometrical parameters are presented. A monopole slot antenna was optimized for the pulse emission with an operating band from 750 MHz to 2.5 GHz. Then EM energy distribution around the tool was studied by both numerical simulation and theoretical analysis, and the design of the drilling collar was modified in order to improve the lateral wave launching efficiency. The proposed tool was tested in formations with different fluid saturations, and response voltages were presented and analyzed in both the

* Corresponding author.
E-mail address: kangli@sdu.edu.cn (K. Li).

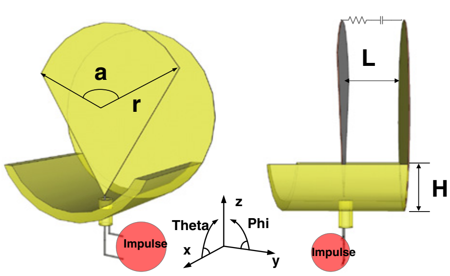
http://dx.doi.org/10.1016/j.jappgeo.2015.05.007

time domain and frequency domain. The simulation results were obtained from finite-difference time-domain (FDTD) codes.

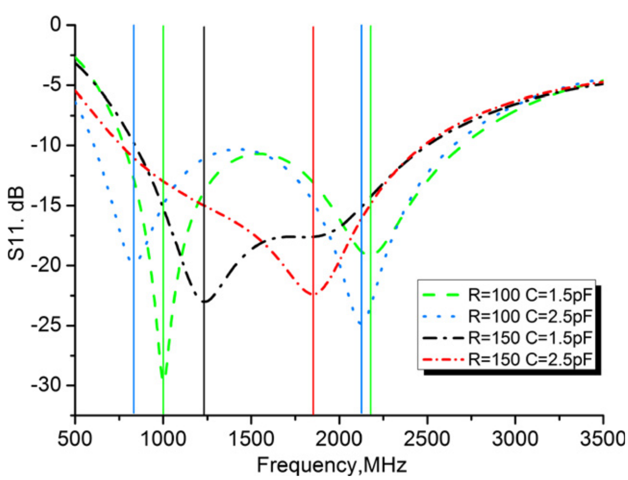
2. Design of the dielectric tool

UWB monopole antennas as originally described by Li (Li et al., 2011) are used as transmitters and receivers of the proposed dielectric tool. The model shape and size of the monopole antenna are shown in Fig. 1(a): r = 20 mm, α = 120°, L = 12.5 mm, and H = 10 mm, with the monopole installed at the middle point of the cavity, a resistor R = 150 Ω and capacitor C = 2.5 pF are loaded between the tops of the monopole, while the disk and the antenna are fed by a coaxial line from the bottom. The load is used to reduce terminal reflection and ensure the broadband characteristics. Simulated S_{11} parameters of the proposed UWB antenna with different terminal loads obtained in air are shown in Fig. 1(b). The increase from 100 to 150 for the loaded resistor has combined the two very sharp resonance points into one. Then, the resonance point shifted to a range between 1.5 and 2 GHz, when the capacitor was raised to 2.5 pF. When the load was set as 150 Ω and 2.5 pF, we obtained a −10 dB operating band covering 750 MHz to 2.5 GHz, and the resonance point matched the center frequency of the excitation pulse.

The tool's geometrical parameters are shown in a lateral view in Fig. 2(a): The transmitter and receiver are mounted along the metal drilling collar, the length of slots opened on the collar for the antennas is D^*_1 = 45 mm, the cylindrical part between the two antennas is made of PVC with length D^*_2 = 230 mm which is widely used in borehole radar and antennas, and reflecting plates are stuck to the two terminals of the PVC cylinder. The monopole and parasitic disk of the antennas and reflecting plates are made of 0.2 mm thick copper sheets while the cambered cavity is made of a 2 mm thick copper sheet. The 3D schematic diagram of this system is shown in Fig. 2(b) and the size

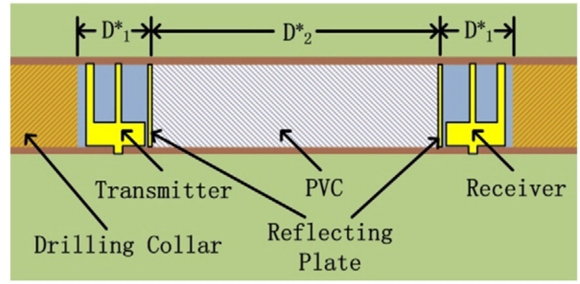


(a)

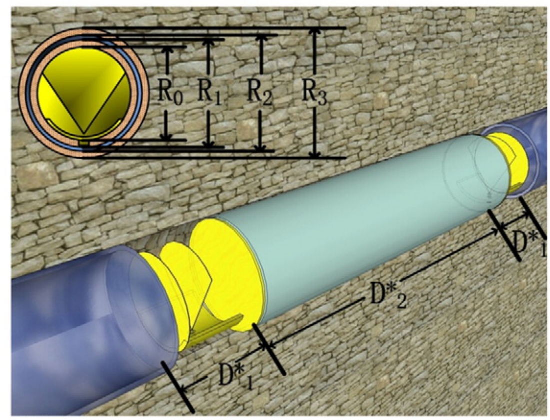


(b)

Fig. 1. Diagram and electrical properties of the UWB antenna: (a) 3D plot and physical dimension of the antenna and (b) simulated S_{11} of UWB antenna in broadband with different loadings.



(a)



(b)

Fig. 2. Diagram of the dielectric tool: (a) lateral view of the dielectric tool and (b) 3D view of the dielectric tool.

of the tool is shown in an axial view in the inset. The outer diameter of the antennas is R_0 = 40 mm, and the transmitting and receiving antennas were mounted along the metal drill collar with an outer diameter R_2 = 46 mm and inner diameter R_1 = 40 mm in a single-borehole whose diameter is R_3 = 50 mm. Oil-based mud is used as a borehole fluid in practice. The dielectric properties of the oil-based mud depend on the brine volumetric fraction and weighting material volumetric fraction, and its complex permittivity changes over a wide range (Jannin et al., 2014). In the application of dielectric logging, drilling mud with a smaller loss factor increases the depth of penetration of the tool. Therefore, we set the oil-based mud at $\varepsilon^* = 3 + 0.05j$ in all the following calculation models.

The antenna's directivity assembling in the tool was studied at its operation frequency band. The simulated directional patterns at 1, 1.5 and 2 GHz were selected as examples as shown in Fig. 3. The coordinate axis is the same as that shown in Fig. 1(a) and the Phi and Theta of polar coordinate system in Fig. 3(d) are also shown in Fig. 1(a). From patterns in Fig. 3, it can be observed that the proposed antenna launches EM energy unidirectionally towards the receiving antenna, and its directivity remains roughly the same among the broadband. The unsymmetrical reflecting shield shown in Fig. 1(a) was designed to obtain unidirectional radiation. Fig. 3(d) shows the contour map at 1.7 GHz, which was the center frequency of the operation band, and the radiation pattern is bilaterally symmetrical about the xz-plane. Strong unidirectivity allows the antenna to have a good focusing ability.

3. Results and analysis

3.1. Dielectric tool with metal collar

The transmitter and receiver are mounted on the drilling collar, and excitation signals are fed into the transmitter by coaxial line with impedance of 50 Ω. When the pulse reaches the transmitter, it generates EM wave propagating out of the slot antenna. EM energy going through