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Design and Optimization of NMR Logging Probe Magnet

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Abstract

As an effective technical means of oil and gas reservoir analysis, nuclear magnetic resonance logging has attracted more and more attention from academic and industrial circles at home and abroad. The probe is the core component of NMR logging products, which is used to establish the NMR environment and receive signals. The technical characteristics of the probe largely determine the overall performance of the instrument. Firstly, this paper briefly introduces the development history of nuclear magnetic resonance logging. Then, based on the discussion of the probe structure and parameters of nuclear magnetic resonance logging products of several major companies, combined with the finite element analysis method, the mathematical model of the static magnetic field of the typical nuclear magnetic resonance logging tool is established by ANSYS software. Then, a new type of nuclear magnetic resonance logging tool probe magnet structure is designed, and the optimization modeling of the magnet is completed from three aspects : magnet material, magnet shape and magnet distance.

Keywords

Nuclear Magnetic Resonance Logging Probe; Finite Element Analysis; ANSYS; Gradient Distribution; Magnet Optimization.

1. Introduction

Nuclear magnetic resonance logging is a downhole oil geophysical exploration method proposed in the 1950 s and developed in the 1980 s. It is a new technology involving physics, electronics, geology and computer technology. Unlike conventional logging methods, NMR logging signals are directly derived from formation pore fluid, and the measurement results are not affected by rock skeleton minerals. NMR logging signal contains the whole formation information, which can be used to quantitatively determine the effective porosity, free fluid porosity, total porosity[1,2,3], irreducible water porosity[4,5], oil saturation[6,7], pore size distribution and permeability[8]. In the exploration stage, nuclear magnetic resonance logging can provide reliable information for solving formation evaluation problems such as liquid production properties, reservoir properties and recoverable reserves. In the development stage, it can provide quantitative data for the evaluation and analysis of strong water flooding, oil displacement efficiency, residual oil saturation and oil recovery [9,10,11,12]. Therefore, the development of nuclear magnetic resonance instrument and the application of nuclear magnetic resonance logging instrument has become a hot spot in the field of logging research, and has become an important index to measure the logging technology level of a company and a country. Compared with other logging tools, the nuclear magnetic resonance logging tool has the advantages of shallow detection depth and poor signal-to-noise ratio. The probe structure is the core of the NMR logging tool. The probe structure determines the measurement method, the position and size of the resonance region, the design of the electronic circuit, and ultimately affects the signal-to-noise ratio of the NMR signal. The probe consists of a magnet and an antenna. The design of the magnet in the probe is an important part of the design of the NMR logging probe. Its function is to polarize and excite the protons in the formation pore fluid and excite the NMR signal.

2. Simulation Analysis of Typical NMR Logging Probe

Chevron began to use the geomagnetic field to establish an NMR environment for downhole exploration in the 1950 s. In the 1980 s, Schlumberger introduced nuclear magnetic exploration equipment based on geomagnetic field. However, due to the large power required by the geomagnetic field, the system has a long dead time and cannot observe the bound fluid information. Subsequently, Jackson broke the previous application limit by using the magnetic resonance model of the permanent magnet, and all products since then are based on the structure of the permanent magnet. At the end of the 1990s, Halliburton and Schlumberger launched a new generation of nuclear magnetic logging tools. The former is MRIL-Prime, which increased the observation frequency to 9, and designed a pre-polarized magnet. The latter is CMR-Plus, which also adds a pre-polarized magnet. In 2002, Baker launched the MREx nuclear magnetic resonance logging tool, claiming to take into account the advantages and disadvantages of previous instruments. Schlumberger introduced MR Scanner in 2003, which can easily perform multi-parameter measurements with high and low vertical resolutions. This chapter will briefly introduce the structure and performance of several typical NMR logging probes.

2.1 Structure and Performance of Several Typical NMR Logging Probes

2.1.1 Structure and performance of CMR probe

CMR (Combinable CMR) was published by Schlumberger in 1995, slightly later than MRIL-B. CMR-Plus is based on the improvement of CMR-200 (1999), adding pre-polarized magnets and improved sequences, so the speed can be increased by 3 to 5 times. Compared with other nuclear magnetic logging products, CMR-Plus has unique advantages in small size and light weight. As shown in Fig.1, in CMR, two flat magnets are placed in parallel with the same polarization direction. A shimming zone is established in the area extending outward between the two magnets. A third small magnet is placed between the two magnets to extend the shimming area to the detection direction. The coil is located between the two main magnets and is close to the outer wall of the instrument, forming a semi-circular structure with an open side facing the sensitive area. The sensitive area is unilateral, and the main signal comes from a cylindrical area of 15 cm long and 2.5 cm thick. This can achieve high spatial resolution and signal-to-noise ratio.

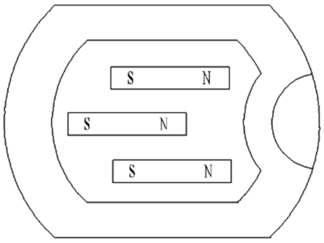


Fig 1. Structure of CMR NMR logging tool probe

2.1.2 Structure and Performance of MR Scanner Probe

Schlumberger 's latest nuclear magnetic resonance logging tool MR Scanner was put into the market in 2003.MR Scanner uses a gradient magnetic field to measure shells at different depths by switching frequencies. As shown in Fig. 2, MR Scanner has a main antenna and two high-resolution antennas. The main antenna has three operating frequencies, and the detection depth range is 1.5 ~ 4.0 in, which is mainly used for fluid evaluation. The other two high-resolution antennas use single-frequency operation, and the detection depth is about 1.25 in, which is mainly used to provide lithological parameters. The MR Scanner probe magnet is a cylindrical, radially polarized. Up to 6 inches vertical resolution. In addition, MR Scanner can change the working state of the probe according to the actual needs, flexibly adjust the speed and measurement accuracy, and has good market adaptability.

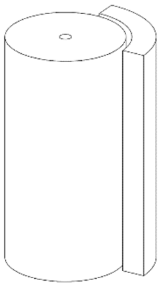


Fig 2. Structure of probe of MR Scanner NMR logging tool probe

2.1.3 Structure and Performance of MREx Probe

MREx was launched by Baker in 2002. Using gradient magnetic field, unilateral measurement is adopted. The detection depth is 6.1~11.2cm, slightly deeper than MR Scanner. The MREx probe is composed of a main magnet and an auxiliary small magnet, which have the same polarization direction, as shown in Fig. 3. The auxiliary magnet has two functions. One is to enhance the magnetic field strength outside the probe and increase the signal strength. The second is to reduce the field strength inside the probe and avoid magnetic core saturation. The magnetic core is to increase the efficiency of the antenna. The polarization direction of the MREx probe magnet is towards both sides of the probe sensitive area. Compared with the polarization direction of the CMR probe scheme magnet, this design can reduce the influence of the magnetic core in the antenna on the static magnetic field, and can obtain the maximum azimuth resonance region. Magnets generally use materials with high magnetic energy product, such as samarium cobalt materials.

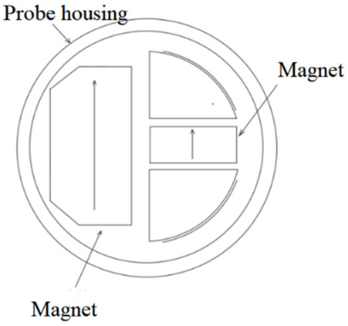


Fig 3. Structure of probe of MREx NMR logging tool probe

Table 1 lists the technical characteristics and parameters of these typical nuclear magnetic probes. The following will use ANSYS software to simulate the probe according to the following technical characteristics, and then analyze the gradient distribution in the resonance region of different NMR logging instruments.

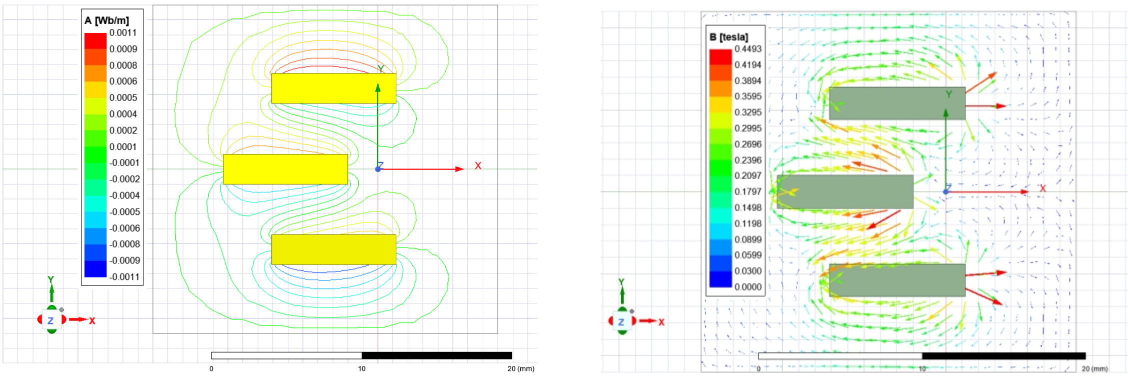
Table 1. NMR logging probe parameters

Product	CMR	MR scanner	MREx
Resonance region	unilateral	Unilateral~80°	Unilateral~120°
Magnetic field type	Uniform field	Gradient field	Gradient field
Operating frequency	2200	500-1000	500-900
Applicable diameter	14.9+	14.9+	15.2-35.6
Depth of detection	1.3-3.8	3.2-10.2	6.1-11.2
Resonance length	15.2	19.1/45.7	61

2.2 Typical NMR Logging Probe Simulation

2.2.1 Simulation Analysis of CMR Probe

The material used in this magnet is samarium cobalt material, with a relative permeability of 1.03 and a coercivity of -732100 A/m. The relative permeability of the formation medium is 1. Because the detection area of nuclear magnetic resonance logging is in the formation far away from the magnet, its boundary conditions are different from other boundary value problems in the field of electrical engineering. The outer boundary of the air is generally 10~15 times the outer diameter of the magnet. Considering the upper and lower symmetry of the magnet model, in order to improve the computational efficiency, a 1/2 simulation model is established in this paper. The magnet and air boundaries in this paper are divided by tetrahedral elements. The maximum subdivision boundary for the magnet is 3 mm, and the maximum subdivision boundary for the air boundary is 10 mm. Because it is necessary to analyze the magnetic field in the stratum far away from the magnet, it is also necessary to encrypt the air area near the resonance region while encrypting the permanent magnet mesh, so as to obtain more accurate magnetic field distribution and magnetic field value. The magnetic induction line distribution and magnetic induction intensity vector distribution of CMR magnet are obtained by finite element calculation, as shown in Fig. 4.

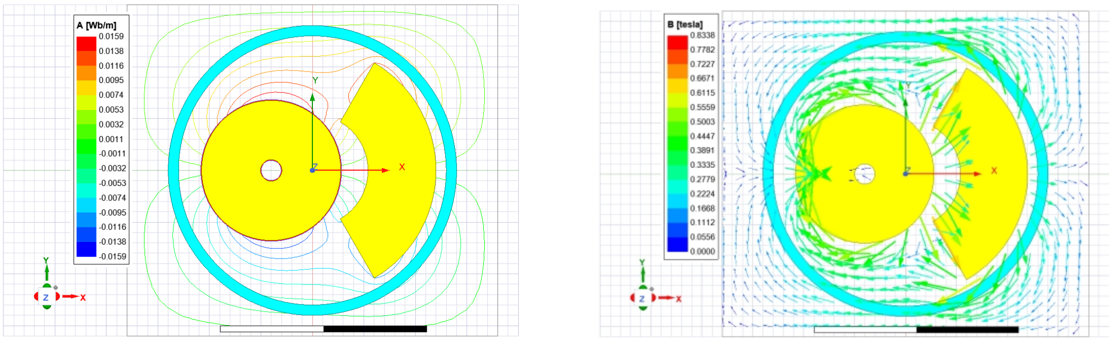


(a) The distribution of magnetic induction line of CMR magnet (b) magnetic induction intensity vector of CMR magnet

Fig 4. Magnetic field of CMR magnet

2.2.2 Simulation Analysis of MR Scanner Probe

The MR Scanner magnet still uses samarium cobalt material, with a relative permeability of 1.03 and a coercivity of-732100 A/m. The relative permeability of the formation medium is 1. The magnetic induction line distribution and magnetic induction intensity vector distribution of MR Scanner magnet are obtained by finite element calculation, as shown in Fig. 5.



(a) The distribution of magnetic induction line of MR Scanner magnet (b) magnetic induction intensity vector of MR Scanner magnet

Fig 5. Magnetic field of MR Scanner magnet

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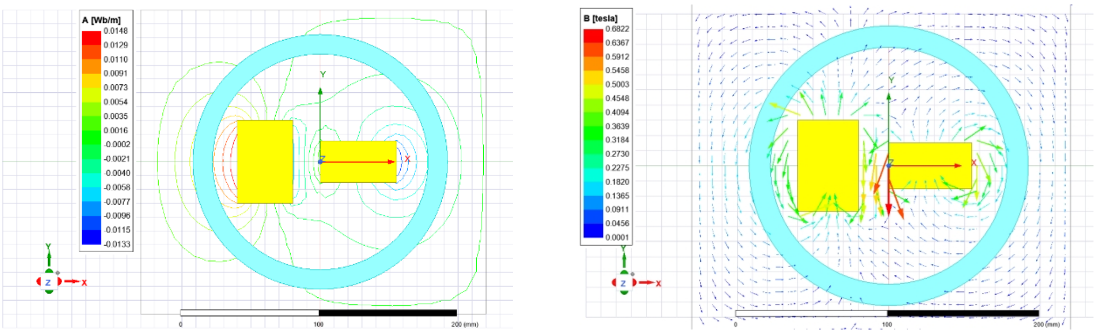
2.2.3 Simulation Analysis of MREx Probe

The material used in this MREx magnet is samarium cobalt material, with a relative permeability of 1.03 and a coercivity of-732100 A/m. The relative permeability of the formation medium is 1. Since the cross-sectional structure of the probe structure at each point on the Z axis is consistent, a two-dimensional plane simulation model is established. The magnetic induction line distribution and magnetic induction intensity vector distribution of the MREx magnet are obtained by finite element calculation, as shown in Fig. 6.



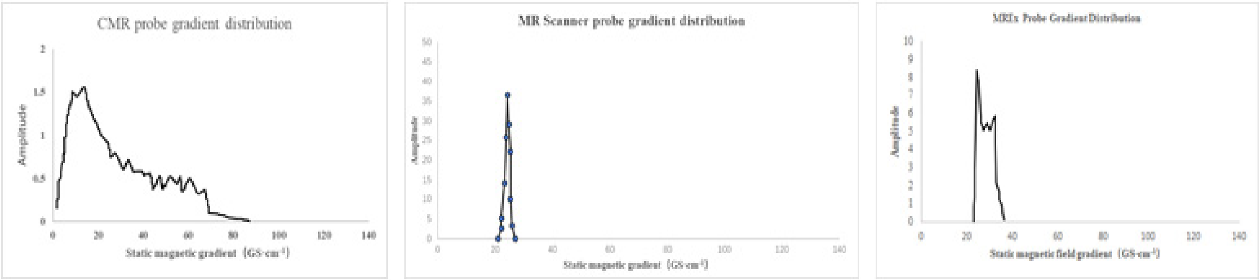
(a) The distribution of magnetic induction line of MREx magnet (b) magnetic induction intensity vector of MREx magnet

Fig 6. Magnetic field of MREx magnet

2.3 Detection Performance Analysis of Nuclear Magnetic Resonance Logging Probe.

Through the static magnetic field distribution of the probe of the nuclear magnetic resonance logging instrument, the gradient field analysis of the probe can be calculated, and the results are displayed by means of contour lines. The calculation method of the gradient field is to calculate the modulus of the static magnetic field first, and then calculate the gradient modulus distribution of the modulus $\|\nabla B\|$.

$$\|\nabla B\| = \left(\left[B_x(n_x,n_y) - B_x(n_x-1,n_y)\right]^2 + \left[B_y(n_x,n_y) - B_y(n_x-1,n_y)\right]^2\right)^{1/2} \tag{1}$$



(a) Gradient distribution in resonance region of CMR probe (b) Gradient distribution in resonance region of MR Scanner probe (c) Gradient distribution in resonance region of MREx probe

Fig 7. Gradient distribution in resonance region of different NMR logging tools

The gradient statistics of each probe in the resonance region at the characteristic operating frequency are shown in table 2. The gradient distribution in the resonance region of different NMR logging tools is shown in Fig. 7. By comparing Fig. 7 and Table 2, the regular magnet magnetic field equipotential lines and gradient equipotential lines are easier to coincide. For example, for the MR Scanner probe, the magnetic field strength equipotential line and gradient equipotential line are close to the concentric circle of the magnet, and the resonance region must be on the magnetic field strength equipotential line, so the gradient variation range in the resonance region is very small.

Table 2. Gradient statistical table of each probe resonance region

Type of probe	Gradient mean (GS cm^{-1})	Minimum gradient (GS cm^{-1})	Maximum gradient (GS cm^{-1})	Gradientrelative standard deviation%
CMR	28.1	1.4	150.1	73.2
MREx	27.8	23.4	34.2	9.2
MR scanner	23.6	22.3	26.4	2.7

3. Design and Optimization of New Nuclear Magnetic Resonance Logging Probe

3.1 New NMR Logging Probe Magnet Design

The magnet structure of the new eccentric NMR logging tool is divided into main permanent magnet and vice permanent magnet. The main permanent magnet adopts ferrite material, and a sub-permanent magnet is set on both sides of the main permanent magnet. The three-dimensional model is shown in Fig. 8.

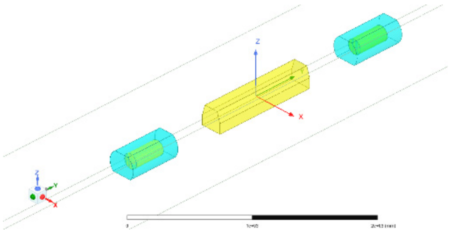


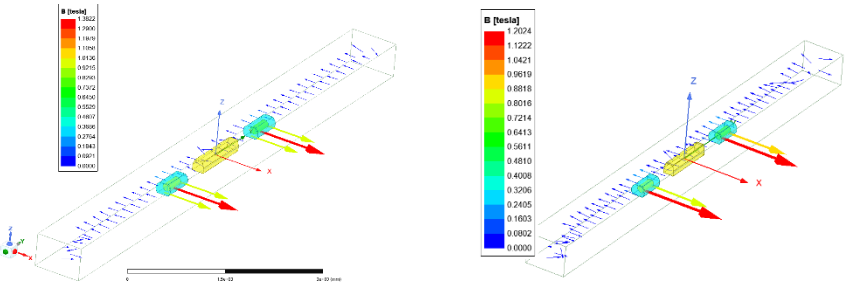
Fig 8. Three-dimensional model of permanent magnet

3.2 New NMR Logging Probe Magnet Optimization

3.2.1 Optimization Design of Magnet Materials

In the case of the remaining conditions unchanged, the cylindrical magnet structural materials were selected NdFeB material and samarium cobalt material for simulation analysis. The coercivity of samarium cobalt material is 820 KA/m. The magnetic field direction of the main permanent magnet is consistent with that of the secondary permanent magnet, and the magnetization direction is set to X axis to establish a three-dimensional model.

After the finite element calculation, in order to make the results more reasonable and accurate, the YZ surface is used as the analysis surface of the simulation results. The magnetic induction intensity vector distribution of the two materials is shown in Fig. 9.



(a)Magnetic induction intensity vector distribution of permanent magnet of NdFeB material

(b)Magnetic induction intensity vector distribution of permanent magnet of Samarium cobalt material

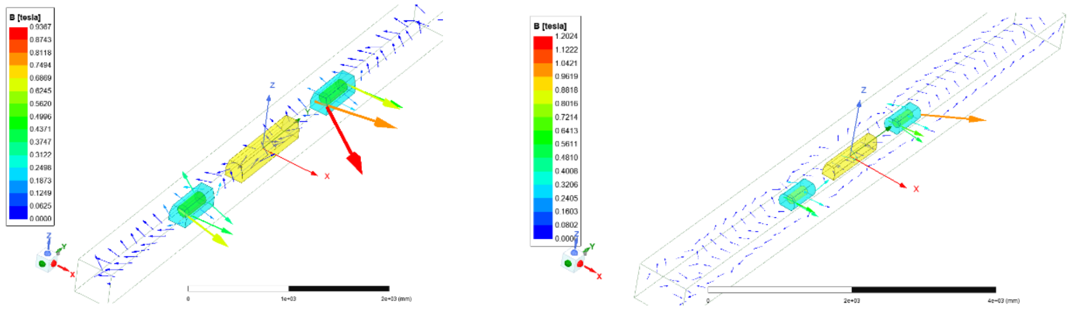
Fig 9. Magnetic induction intensity vector distribution of different magnet materials

From the simulation results of Fig. 9, it can be seen that the magnetic properties of NdFeB materials are better than those of samarium cobalt materials. However, the Curie temperature of NdFeB materials (380°C) is much lower than that of samarium cobalt materials (850°C), and the magnetic properties of NdFeB materials will be attenuated in high temperature environment. Because the temperature coefficient of NdFeB materials is-0.4 %/K, and the temperature coefficient of samarium cobalt materials is-0.2 %/K, under the same conditions, the influence of temperature on samarium cobalt materials is much smaller than that of NdFeB materials. Therefore, samarium cobalt will be selected as the structural material of the sub-permanent magnet cylindrical magnet.

3.2.2 Optimization Design of Magnet Shape

The shape of the magnet has a great influence on the magnetic field gradient distribution. The more regular the shape of the magnet, the more uniform the gradient distribution in the resonance region. According to the above, the structure of eccentric NMR permanent magnet is determined as follows : the top surface of the main permanent magnet and the vice permanent magnet is N pole, and the bottom surface is S pole ; the secondary permanent magnet adopts samarium cobalt material. The magnetic field direction of the main permanent magnet is consistent with that of the secondary permanent magnet, and the magnetization direction is set to X axis.

Samarium cobalt is a brittle magnetic material, which will break and break when subjected to strong mechanical stress or impact. Therefore, when designing the vice permanent magnet structure, the cylindrical magnet structure is designed to avoid sharp structure. The finite element calculation of the cylindrical magnet structure and the prismatic magnet structure is carried out respectively. The XY surface is used as the analysis surface of the simulation results. The distribution of the magnetic induction intensity vector is shown in Fig. 10.



(a) Magnetic induction intensity vector distribution of permanent magnet of straight hexagonal prism structure

(b)Magnetic induction intensity vector distribution of permanent magnet of cylindrical structure

Fig 10. Magnetic induction intensity vector distribution of different magnet shapes

From the simulation results of Fig. 10, it can be seen that when the deputy permanent magnet has relatively more sharp structures, its magnetic induction intensity vector distribution is relatively cluttered, and its magnetic induction intensity is relatively weak, so the cylindrical structure is more suitable for eccentric NMR logging permanent magnets.

4. Conclusion

Based on the simulation of the typical NMR logging tool probes and the analysis of the magnetic field gradient distribution generated by the probes of the major logging tools, the possible development direction of the NMR probe to the combined magnet is considered. Based on this development trend, a new permanent magnet structure of NMR logging tool is designed. The experimental results show that:

(1) From the choice of magnet materials. Under the same conditions, the influence of temperature on samarium cobalt material is much smaller than that of neodymium iron boron material. Therefore, in the face of the logging tool in the downhole high temperature and high pressure environment, samarium cobalt is selected as the magnet structure material.

(2) By comparing the shape of the magnet, it is found that the magnetic induction intensity vector distribution of the magnet with a straight prism shape is relatively disordered, and its magnetic induction intensity is also relatively weak. In addition, samarium cobalt is selected as a brittle magnetic material, which will break and disconnect when subjected to strong mechanical stress or striking. Therefore, the design of a tubular magnet structure can also avoid sharp structure as much as possible.

The main permanent magnet of the improved NMR logging tool probe is made of ferrite material. The upper section is a straight quadrangular prism composed of isosceles right-angle trapezoids, and the lower section is a straight quadrangular prism composed of rectangles. The secondary permanent magnet adopts a cylindrical structure of samarium cobalt material; the magnetic field intensity is the largest.

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