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Original contribution

New magnet array design for downhole NMR azimuthal measurement

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ABSTRACT

In low-field NMR, depth information and radial profile information of downhole formation can be easily acquired with the help of static gradient magnetic field produced by permanent magnets, called downhole NMR imaging. Based on the hypothesis that the formation is homogeneous, average signals detected by centralized or decentralized sensors can provide enough information for petrophysical parameters. In fact, the inhomogeneity of formation may have serious impact on description of the characteristics of formation and oil/gas location which is rarely studied in NMR well-logging. To improve this, we design and implement a new quadrupolar magnet array aimed at achieving azimuthal measurement in this paper. A new quadrupolar magnet array is consisted of four bread-shaped magnets combined with additional small hexangular magnets to produce enough strength and high homogeneity of static field along with circumferential direction at deeper DOI (depth of investigation). Azimuthal measurements are achieved by using coil array combined with quadrupolar magnet array.

1. Introduction

Oil/gas is one of the most significant energy on earth which is mainly rich in pores of underground rocks with depth of thousands of meters. Low-field NMR is a non-invasive technique for oil/gas investigation and the acquired petrophysical properties are interpreted from signal inherently from fluid saturated in rock matrix. Therefore, NMR well-logging is a unique approach to characterize fluid presence and transportation in formation as compared to other conventional well logging techniques [1,2].

In 1960s, Brown and Gamson [3] proposed a NMR well-logging tool based on earth field. This tool has no ability of radial profile and azimuthal resolution and the dead time of its probe is too long to capture the microstructure information. Nevertheless, "inside-out" permanent magnets geometry designed by Jackson [4–6] leaded to a period of rapid development of NMR well-logging tools [7–16]. Multi-frequency switching technique brought the ability of imaging to these tools with radial profile selection. Based on the hypothesis that the formation is homogeneous, average signals detected by centralized or decentralized sensors can provide enough information for geophysical characterization. In fact, the inhomogeneity of formation may have serious impact on description of the characteristics of formation, such as improper porosity evaluation and oil/gas location. In order to better understand formation, azimuthal measurement provides more comprehensive data and is widely applied in acoustic, density and electrical logging tools.

Early research work about NMR azimuthal measurement is published by Prammer [17]. The layout of magnet array used in this design is based on Jackson geometry. Because of the specialized antenna design and advanced algorithm in signal processing, this system is able to differentiate the data from azimuthal regions. However, the decomposed information would be strongly affected by the signal contributed from neighboring azimuthal area, leading to poor azimuthal resolution.

In conventional NMR measurement, the samples are preferred to be loaded inside the chamber of magnet array. Dipolar Halbach magnet array [18,19] has unique advantage to perform relaxometry and MRI measurements because of its high magnetic strength and homogeneity inside the magnet bore. Moreover, by adjusting the relationship between azimuthal positions and magnetization directions of magnet blocks in Halbach array, multipolar field can be generated at internal or outer area of the magnet system [20]. This magnet shape has many applications in magnetic bearings, motors and free electron lasers and so on [21–23].

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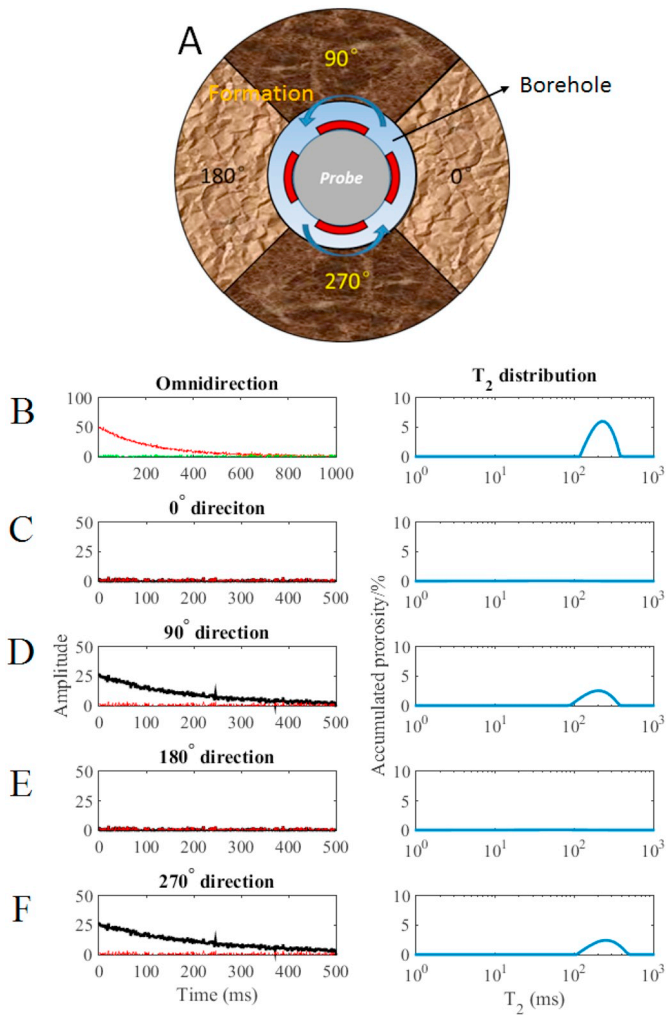

Fig. 1. The azimuthal measurement of inhomogeneous formation. A illustrates the inhomogeneous formation model; B describes the omnidirectional measurement of A; C–F represent azimuthal measurement respectively.

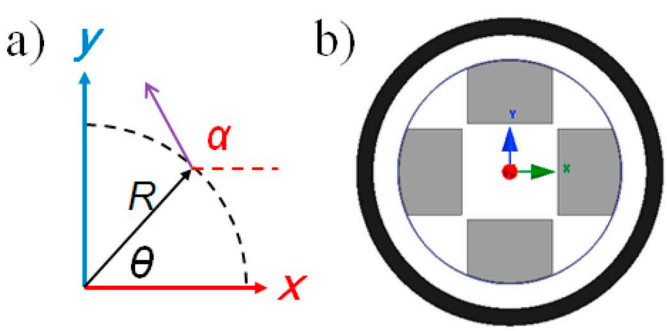

Fig. 2. Illustration of magnet array model.

In this paper, we design and implement a new quadrupolar magnet array aimed at achieving downhole azimuthal measurement. A new quadrupolar magnet array is consisted of four bread-shaped magnets combined with additional small hexangular magnets. This magnet array is capable to produce higher field strength and higher homogeneity of static field along with circumferential direction at deeper DOI (depth of investigation). Azimuthal measurements are achieved by using coil array combined with quadrupolar magnet array.

2. Azimuthal measurement of downhole NMR imaging

The azimuthal measurement can be described as shown in Fig. 1. By scanning the formation surrounding the sensor, different azimuthal information can be acquired. Fig. 1A illustrates an inhomogeneity formation model, and the properties of this formation are azimuthally different (represented by two different colors). The sensor is operated at centralized state to scan the formation. As shown in Fig. 1B, if an omnidirectional measurement mode is implemented by a sensor, the detected average signals cannot reflect the property of the inhomogeneous formation, which leads to improper formation evaluation. In order to improve this, the azimuthal measurements can be carried out and are shown from Fig. 1C to F. From these plots it can be readily found that, each azimuthally directional information, such as fluid volume and pore structure can be obtained from the regional T_2 distribution. Here, assuming that, the porosity of 0°, 90°, 180° and 270° directions is 0, 0.5, 0, 0.5 respectively.

3. Magnet array design

Halbach magnet array can be linear, circular, cylindrical and spherical geometry. These magnet arrays can produce dipolar or multipolar field inside or outside the magnet bore. In 2D polar coordinate system, the relationship between azimuthal position and magnetization direction of a magnet piece in circular or cylindrical Halbach array can be expressed as followed:

$$M(R,\theta) = M_0 \begin{Bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{Bmatrix} \tag{1}$$

here, $\alpha = (m + 1)$ and $m \in Z$. R represents the radius of Halbach array; α is the magnetization direction of magnet block; θ is the located azimuthal angel; m is integer, represents the number of pole-pairs, *e.g.* $m = 1$ for dipolar, $m = 2$ for quadrupolar and so forth [20]. The advantage of Halbach magnet array is that it can be constructed by using magnets with simple geometry. Therefore, the manufacture is easy to achieve. The feature of Halbach magnet array is that it can offer strong magnetic field strength and relative homogeneous field in the magnet chamber. However, it is not suitable to apply this magnet system in the well-logging since the stray field is very weak, *e.g.* the operating frequency in NMR well logging is within a range of 250 kHz to 1.1 MHz. The stray field strength outside the Halbach magnet chamber is mainly decided by the number and geometry of used magnet blocks. Less number of the magnet block will lead to magnetic flux lines cannot be totally enclosed in the internal of Halbach magnet chamber. In order to utilize Halbach array in this situation, we choose to use four bread-shaped magnet blocks by optimizing its geometry parameters to enhance the stray field outside the magnet array which can satisfy the aforementioned operating frequency range in deeper depth of investigation.

3.1. Magnet array modeling

The magnet arrays for downhole NMR tools are mostly dipolar structure, *e.g.* cylindrical or rectangle magnets [24–29], which can produce magnetic field decayed along with distance r as a ratio $1/r$ or $1/r^2$. However, these magnet structures can not be suitable for azimuthal measurement. In order to solve this, we propose first prototype magnet model by using two opposite positioned magnets combined with circular focusing magnet array and high permeability materials.

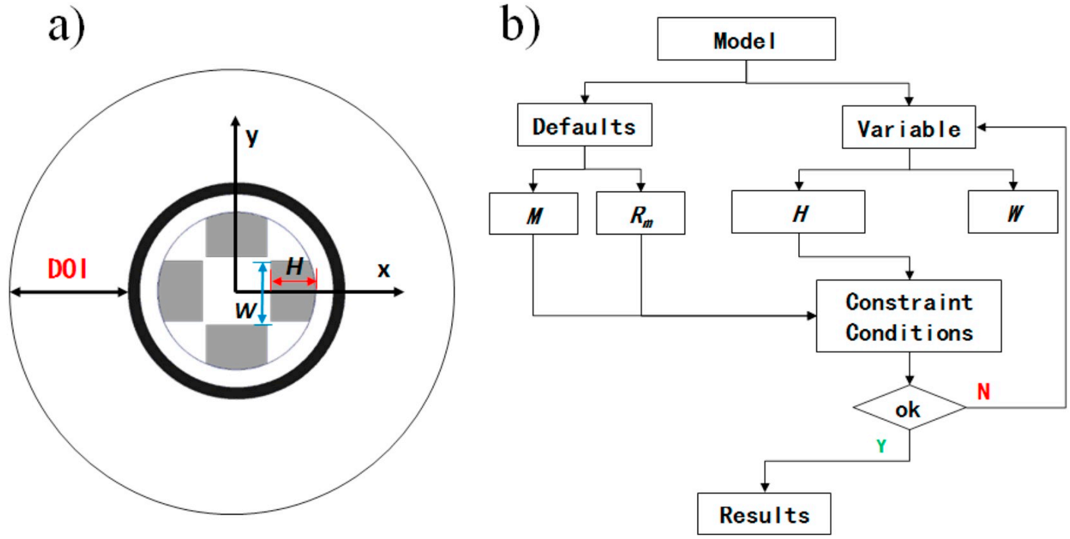

Fig. 3. The workflow of optimization.

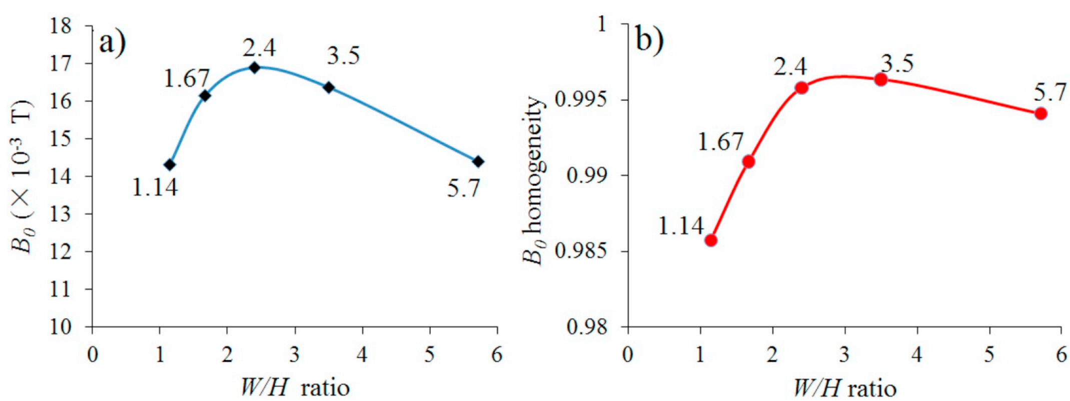

Fig. 4. Optimization results. a) is the field strength variation related to *H* and *W*; b) is the homogeneity variation related to *H* and *W*.

More details are included in another literature [30]. In this paper, a further new quadrupolar magnet array is proposed as shown in Fig. 2. Fig. 2a is a sketch of the coordinate system and the angles used for the designed magnet array corresponding to Eq. (1). Fig. 2b illustrates the quadrupolar magnet array model. Solid black ring is fiberglass. The sensor is of diameter 171.5 mm. Considering the eddy current effect on surface coil and field strength, the diameter and length of magnet array is set to be 120 mm and 1200 mm respectively. For a quadrupolar magnet array, we choose $m = 2$ as aforementioned.

3.2. Optimization of magnet array

The sensor is operated at centralized way. In order to achieve magnet optimization for downhole azimuthal measurement, some restricted conditions should be considered: First, regarding the size of borehole and possibly existed drilling mud invasion, the DOI (depth of investigation) need to be equal and larger than 10 cm (from the surface of sensor to target formation); Second, homogeneity of magnetic field along with circumferential direction at DOI = 10 cm should be larger than 99%, where homogeneity of magnetic field is defined as followed expression: homogeneity = 1 − (max($B_{0circle}$) − min($B_{0circle}$)) / average ($B_{0circle}$), and $B_{0circle}$ means the field strength distribution at a circle of radius 10 cm concentric with sensor.

In 2D model, the length of magnet array can be considered as infinity. In this work, Ansys Maxwell was adopted as our numerical simulation tool to provide modeling and parameter optimization by using FEM method. As shown in Fig. 3a, the optimized variables are the width and height of these magnet blocks and each magnet block has the same size. Fig. 3b illustrates the work flow of this optimization procedure, where *M* is the magnetization and R_m is the outer radius of the magnet piece.

Fig. 4 shows the optimization results about variables *H* and *W*, where *H* and *W* is the height and width of bread-shaped magnet block respectively. When the ratio of $H/W = 2.4$, the field strength and field homogeneity reach to maximum value. However, considering some mechanical conditions, the ratio of H/W will be changed a little to satisfy the mechanical structures. Eventually, we choose ratio of $H/W = 1.67$ as the suitable size parameter. The changed size of magnet block will decrease field strength and homogeneity so that four additional small hexangular magnet blocks are used to compensate magnetic energy loss. Fig. 5b and d shows it is helpful to utilize hexangular magnet blocks to improve the field distribution in horizontal plane or *x*-*y* plane.

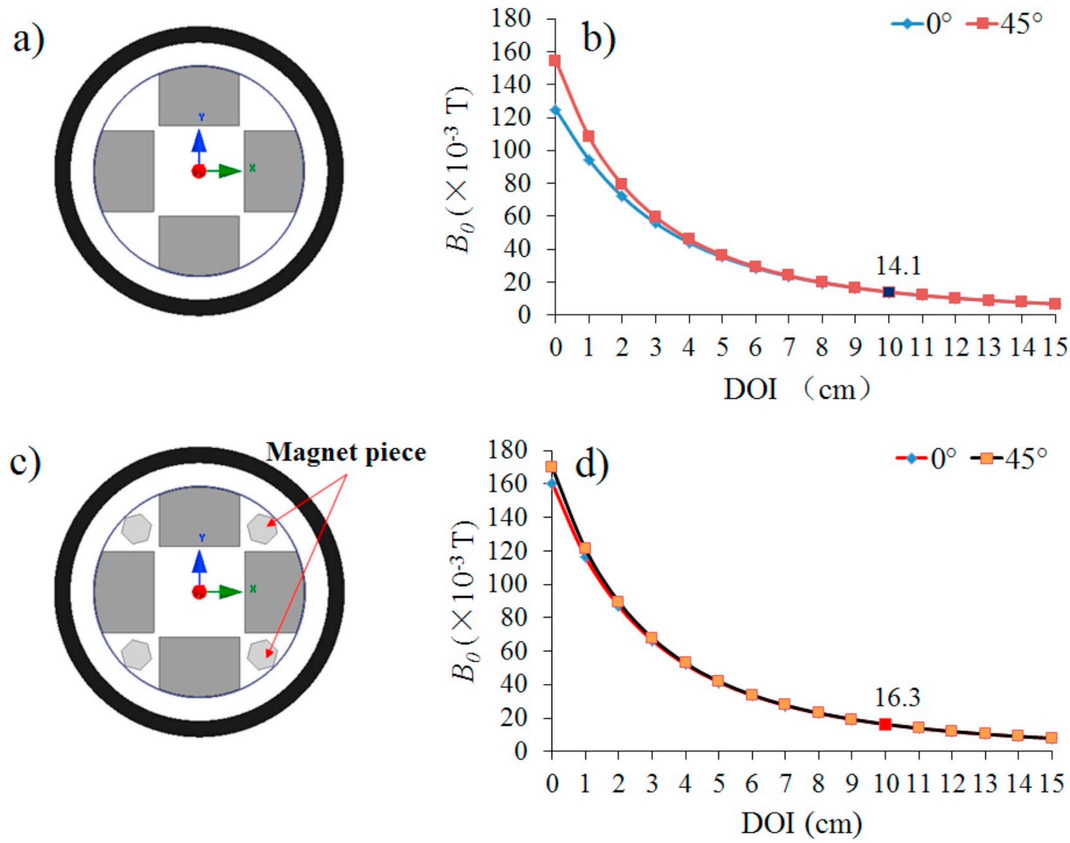

Fig. 5. Hexangular magnet blocks used to compensate magnetic energy loss. a) is the original model; b) is the field distribution of original model; c) is the model with hexangular magnet blocks; d) is the field distribution of changed model.

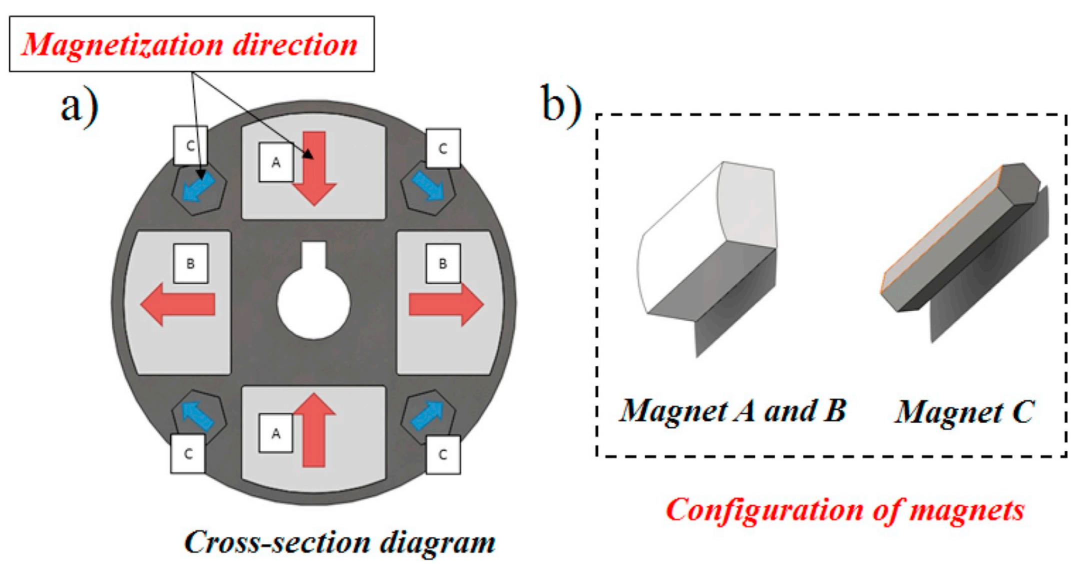

Fig. 6. Schematic illustration of magnet array.

3.3. Field map of magnet array

The finally decided magnet array is shown as Fig. 6. The array is consisted of types three magnet blocks. Magnet A and B have the same geometry but with different magnetization direction obeyed as Eq. (1); magnet C is small hexangular magnet adding at the corner between magnet A and B array. Fig. 7 describes the field map of this new magnet array. As shown in Fig. 7a, the arrangement and magnetization of the magnet array can produce quadrupolar field inside and outside the magnet bore, the magnetic flux is starting from magnet B and ending at magnet A. Interestingly, the flux produced by magnet C would not influence the shape of flux lines but enhance the field strength and

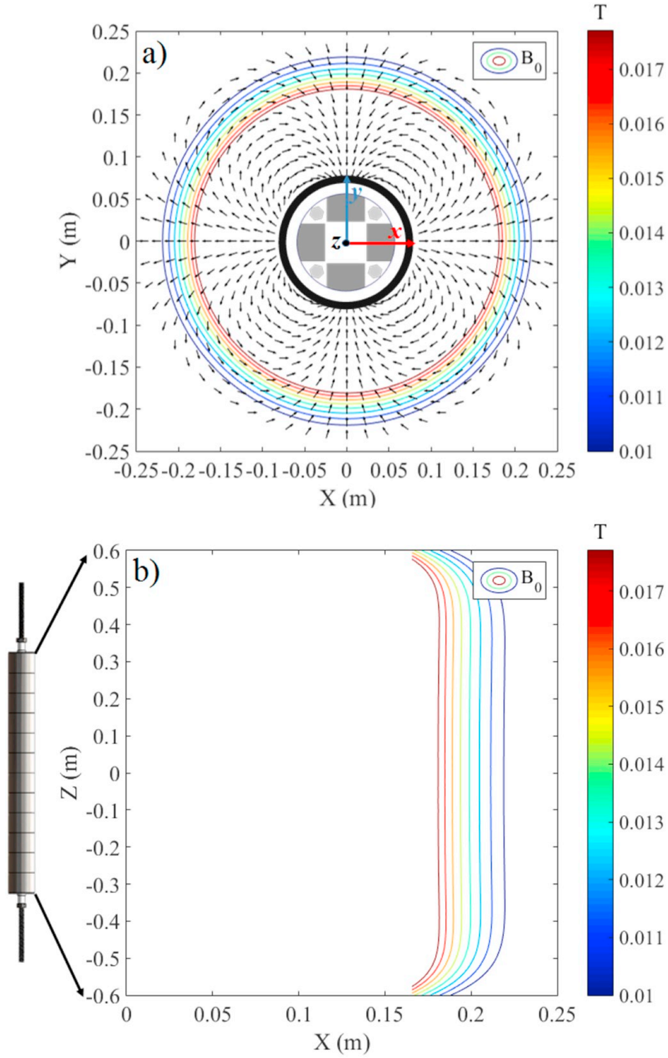

Fig. 7. Field map of magnet array. a) is illustration of magnetic flux and B_0 vector distribution in *x-y* plane; b) is the isolines of magnetic strength in *x-z* plane.

homogeneity. The field direction at 0°, 90°, 180° and 270° direction is different which lead to the azimuthal selection of field. The isolines of field strength in Fig. 7b illustrate that, for a certain operating frequency, each azimuthal measurement has the same DOI (depth of investigation) in the formation. Isolines of field strength for one azimuthal direction in *x-z* plane and within the range from −40 cm to 40 cm (related to point z = 0 cm), the homogeneity along with *z*-axis is satisfactory. Due to the edges effect caused by finite length of magnet array, the field strength will rapidly decrease at the edges. The suitable length of magnet array need to decided referring to practical operation requirement and pre-polarized magnets can be added at the edges of aforementioned magnet system to provide higher pre-polarization ratio.

4. Experimental results

In order to achieve a reasonably matching degree between B_0 and B_1 field, the coil array, rather than a sole RF coil, is used in the senor. The coil array is consisted of four surface coil units with the same configuration and performance. As shown in Fig. 8a, the coil units are located at four azimuthal directions. Although this arrangement results in weak coupling coefficient between these coil units, it still produce split peaks when these coils are tuned at the same frequency, *e.g.* operation frequency is 675 kHz. This issue can be solved by introducing capacitor decoupling network [31,32].

The azimuthal measurement is tested by inserting the quadrupolar magnet array sensor into a water tank which has sectional space to simulate inhomogeneous formation. As shown in Fig. 8b, the volume of the cylindrical water tank is equally divided into eight sectors. Sector 1, 3, 5, 7 are full of copper sulfate solution with different T_2 values while other sectors are empty. The sensor is centered at the hole of water tank, each coil unit is directed at sector 1, sector 3, sector 5 and sector 7 respectively. Coil switching circuit [33] is implemented to switch on/off the corresponding coil. The operating frequency is 675 kHz for this experiment and 55 groups of raw echo trains are acquired to testify the operating stability of this sensor. T_2 distribution results are illustrated in Fig. 9 and the information of fluids in sector 1, 3, 5, 7 can be distinguished.

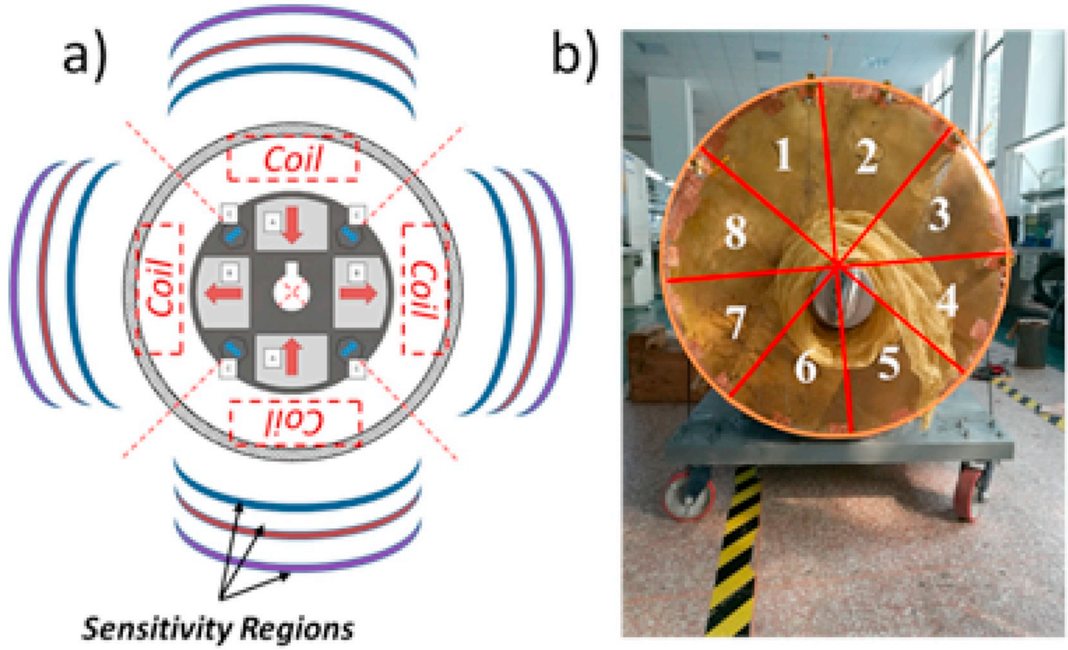

Fig. 8. Experimental test for quadrupolar magnet array sensor. a) schematic illustration of sensor in cross-section; b) water tank for inhomogeneous formation model.

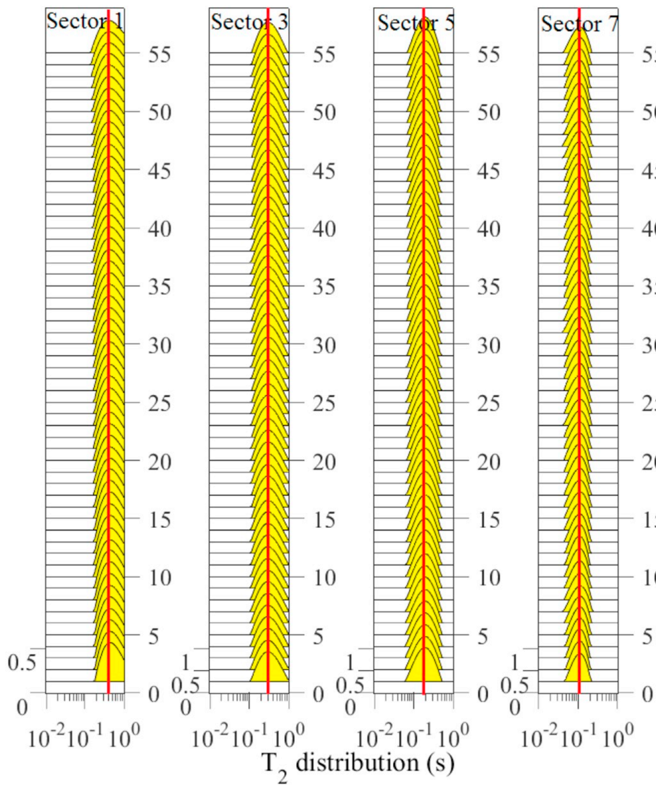

Fig. 9. Experimental results for quadrupolar magnet array sensor. Different sectors are corresponding to different T_2 value.

5. Conclusion

A new quadrupolar magnet array design is proposed to aim at achieving azimuthal measurement to make NMR logging tools have the ability of downhole three-dimensional investigation. Combined with coil array, the azimuthal measurement can be achieved. In comparison with Jackson geometry, this magnet design will produce higher field strength while possess azimuthal selection. In the future, azimuthal measurement will help downhole NMR technique to resolve the inhomogeneity message of targeting formation, and to acquire high resolution data to evaluate the reservoir resources.

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