An adaptive magnetization structure and method for low field NMR two-phase flow measurement

LI Li-pin¹,a, HAN Rui-qiang²,b, HUANG Yan-qun³,c, CHEN Huan⁴,d

¹Shanxi Key Laboratory of Measurement and Control Technology for Oil and Gas Wells Xi’an Shiyou University Xi’an, China
²Shanxi Key Laboratory of Measurement and Control Technology for Oil and Gas Wells Xi’an Shiyou University Xi’an, China
³Xi’an Modern Control Technology Research Institute, Xi’an, China
⁴Shanxi Key Laboratory of Measurement and Control Technology for Oil and Gas Wells Xi’an Shiyou University Xi’an, China

¹lilipin@xsyu.edu.cn, ²Hruiqiang1@163.com, ³huangyanqun203@163.com, ⁴chen1104huan@163.com

Abstract. In low field NMR multiphase flow measurement, the magnetization time and magnetization length are affected by the two-phase flow velocity and water fraction, so it is difficult to realize the complete magnetization of multiphase flow with fixed length magnet. In this paper, an adaptive magnetization structure for two-phase flow is proposed. The pre-magnetization model of the adaptive structure is established based on the magnetization theory of nuclear magnetic resonance. And parameters of the adaptive magnetization structure are determined by analyzing the influence of two-phase flow parameters such as velocity and water fraction on magnetic susceptibility. Finally, the simulation analysis shows that the adaptive magnetization structure can achieve complete magnetization effect for two-phase flow in the range of water fraction 0-36% and flow rate 0-4.66m/s, which provides the necessary conditions for the accurate measurement of NMR two-phase flow and provides a new idea for the design of NMR two-phase flow measurement sensor.

1. Introduction

The commonly used two-phase flow measurement methods include Venturi tube and orifice plate methods[1], mass flow method[2-3], ray method[4-5], optical probe method[6], electrical method[8], tomography method[7-8]. There are limitations in measurement volume and structure for Venturi tube and orifice plate methods which are difficult to be applied to downhole two-phase flow measurement. The application and development of ray method are limited by the problems of environmental safety and statistical error. Optical probe method is a contact measurement method. In the process of measurement, the medium is easy to adhere to the surface of optical fiber, which results in the decrease of sensor sensitivity. Electrical method can measure the water-liquid ratio in a small range which is greatly affected by flow pattern. Tomography method has some problems of slow speed image reconstruction and low image resolution. Nuclear magnetic resonance (NMR) has overcome the technical limitations of traditional measurement methods and become a new research direction in the field of two-phase flow measurement, which has the advantages of wide measurable velocity range,
large dynamic range of water-liquid ratio, and is not affected by macroscopic physical characteristics such as two-phase flow pattern, velocity and viscosity.

In recent years, low-field NMR has become a research hotspot in multi-phase flow measurement of nuclear magnetic resonance with the advantage of fast measuring speed[9-16]. Most of the existing literature focus on the relationship between NMR FID signal and water content and flow rate, the corresponding measurement model is established, the important factor affecting the measurement of low field NMR two-phase flow is whether the measured fluid reaches the fully magnetized state. In NMR two-phase flow measurement, the magnetization time and magnetization length are affected by the two-phase flow velocity and water fraction, so it is difficult to realize the complete magnetization of two-phase flow with fixed length magnet. Therefore, in this work, we construct an adaptive magnetization structure for low field NMR two-phase flow measurement, with the ability to adjust automatically magnetization length and time according to the parameters of two-phase flow. Thus, the influence of non-uniform magnetization on the measurement results can be reduced.

In this paper, an adaptive magnetization structure for two-phase flow is proposed. The pre-magnetization model of the adaptive structure is established based on the magnetization theory of nuclear magnetic resonance. And parameters of the adaptive magnetization structure are determined by analyzing the influence of two-phase flow parameters such as velocity and water fraction on magnetic susceptibility. It provides the necessary conditions for the accurate measurement of NMR two-phase flow and provides a new idea for the design of NMR two-phase flow measurement sensor.

2. Structure and Methodology

2.1. Adaptive magnetization Structure

An adaptive magnetization structure for low field NMR two-phase flow measurement is constructed, which is shown as Fig. 1. The adaptive magnetization structure consists of section 1 and section 2, which of section 1 includes four electromagnets of same length and the length of section 1 can be adjusted according to the measured fluid parameters by controlling the circuit. The section 2 is a permanent magnet of fixed length and the latter part inside of which is detector coil.

Figure.1 An adaptive magnetization Structure for low field NMR two-phase flow measurement

2.2. Methodology

Macroscopic magnetization vector

$$M_0 = \frac{\rho \gamma h^2}{4kT} B_0$$  \hspace{1cm} (1)

Where $\rho$ is Proton density, $\gamma$ is spin-to-magnetic ratio, $h$ is Planck constant, $T$ is absolute temperature, $k$ is Boltzmann constant, $B_0$ is external magnetic induction intensity.

It is assumed that the polarization field intensity of section 1 is $B_{01}$, when the fluid enters the static polarization field section 1, the hydrogen nucleus is partially polarized after a period of time $t_1$. According to Bloch equation, the magnetization vector after static magnetic field is as follows:

$$M_1 = M_0 [1 - \exp(-t_1 / T_1)]$$  \hspace{1cm} (2)

The polarizability after section 1:

$$\frac{M_1}{M_0} = 1 - \exp(-t_1 / T_1)$$  \hspace{1cm} (3)
When the multiphase fluid enters the static magnetic field \( B_{02} \) formed by permanent magnet at time \( t_1 \), the magnetization vector after time \( t_2 \) is as follows:

\[
M_2 = M_{02}[1 - \exp(-t_2 / T_1)] + M_1 \exp[-(t_2 + t_{pd}) / T_1]
\]

(4)

Where \( t_{pd} \) is the time of the fluid flows through the non-magnetized zone. \((t_{pd} = L_{sl} / \nu, 2L_{sl} / \nu, \ldots)\)

The polarizability after section 1 and section 2:

\[
M_2 / M_{02} = M_{02} / M_{01}[1 - \exp(-t_2 / T_1)] + [1 - \exp(-t_1 / T_1)]
\]

\[
\exp[-(t_2 + t_{pd}) / T_1]
\]

(5)

Assuming \( k = M_{02} / M_{01} \), the susceptibility can be expressed as the following function:

\[
f(k, t_1, t_2, t_{pd}, T_1) = k[1 - \exp(-t_2 / T_1)] + [1 - \exp(-t_1 / T_1)]
\]

\[
\exp[-(t_2 + t_{pd}) / T_1]
\]

(6)

Assuming \( g_2 = t_2 / T_1, g_1 = t_1 / T_1, g_3 = t_{pd} / T_1 \), it can be expressed as

\[
f(k, g_1, g_2, g_3) = k[1 - \exp(-g_2)] + [1 - \exp(-g_1)]
\]

\[
\exp[-(g_2 + g_3)]
\]

(7)

3. Simulation and Experimental Results and Discussions

3.1. The parameters optimization of NMR system

The materials containing hydrogen atoms are magnetized in a stable and strong magnetic field to make their hydrogen atoms move in the same direction. For a single-phase fluid, the magnetization builds-up exponentially and can be characterized by the spin-lattice relaxation time \( T_1 \) (in Eq.(2)). Time-dependent magnetization for water is build-up as shown in Fig. 2a. The relationship between the magnetization vector and the magnetization length is established when the materials moving through the stable magnetic field at a certain velocity (in Eq.(3)). Build-up of magnetization and magnetization length for oil and water with the mean velocity of 0.12 m/s is shown as Fig. 2b. There is longer magnetization length for water than oil at the same velocity because the spin-lattice relaxation time \( T_1 \) of water is longer than oil. Therefore, it is necessary to optimize the magnetization length under different parameters for achieving good magnetization effect for oil-water mixture.

![Figure 2](image)

Figure 2 (a) The relationship between magnetization time and magnetization vector. (b) The relationship between the magnetization length and the magnetization vector.

3.2. Analysis of the Effect of Two-stage Magnetization

By setting parameters of \( k=2, g_1=0,0.3,0.6,0.9, g_3=0 \), the variation rule of susceptibility with \( g_1 \) is calculated through simulation, as shown in Fig. 3a, if the static magnetic field \( B_{02} \) which is higher than the original static magnetic field \( B_{01} \) is used to magnetize in a short time, the time when the magnetic susceptibility reaches 100% can be greatly shortened. As shown in Fig. 3b, the effect of magnetic field intensity in accelerating magnetization section on shortening magnetization time. It can be seen from Fig. 3b when \( k \) is fixed, \( f \) increases with the increase of \( g_2 \). The total magnetization time is \( t_1 + t_2 = (g_1 + g_2)T_1 = 0.285s \) (Assuming \( T_1 =0.15s \)). If there is no accelerated magnetization section, \( g_1 = 5 \).
the time to complete magnetization is 0.75s, obviously the magnetization time is greatly reduced after accelerating the magnetization section. Please see Fig. 3c, the electromagnet A, B, C and D are all turned on, and the magnetic field intensity of section E is greater than that of ABCD section.

As shown in Fig. 4a, \( g_1 = 1.2, \ g_2 = 0, 0.3, \ldots\), the curve of magnetic susceptibility changing with \( g_2 \). As can be seen from Fig. 4a, after the first stage reaches 70% polarizability, with the increase of \( g_3 \), the time \( t_1 \) needed for the second stage magnetization increases correspondingly. This is because the magnetization vector of the fluid in the closing section of the electromagnet will be weakened, so the magnetization time in the permanent magnet part will increase correspondingly. Fig. 4b and c show that the magnetization time of multiphase fluid with different flow velocity and water content can be adjusted reasonably by using adaptive mode in the electromagnet part to make the multiphase fluid achieve better magnetization state and improve the magnetization efficiency.
susceptibility of 70%. Therefore, under different flow velocity and water content, the adaptive magnetization of fluid is realized by adjusting the on-off of electromagnet.

\[ \frac{M}{M_{01}} = 1 - \exp(-t/T_i) = 1 - \exp(-L_{M1}/\nu T_i) \]  \hspace{1cm} (8)

![Figure 5](image)

(a) WH=10%  
(b) WH=30%

![Figure 6](image)

(c) v=0.1  
(d) v=0.3

Fig. 5 (a) The moisture content is 10%. (b) The moisture content is 30%. (c) The rate of 0.1m/s. (d) The rate of 0.3m/s.

Fig. 6a shows the flow rate of 1.66m/s, the variation law of magnetization length required to achieve 70% susceptibility with different water content. When the water content is 0% (pure oil), 12%, 24%, 36%, the magnetization lengths needed to reach 70% susceptibility are 0.3m, 0.6m, 0.9m and 1.2m respectively. The above simulation results show that the magnetization requirements of different water content can be achieved by adaptive selection of magnetization length.

Fig. 6b shows that the rate of water content is fixed at 5%, the change of magnetization length required to achieve 70% susceptibility at different flow rates. When the velocity is 2.33m/s, 3.50m/s, 4.6m/s, the magnetization length for 70% magnetic susceptibility is 0.6m, 0.9m, 0.9m. The magnetization requirements at different flow rates are achieved by controlling the on-off of the electromagnet ABCD.

![Figure 6](image)

(a) v=1.66m/s  
(b) WH=5%

Figure 6 (a) The flow rate is 1.66m/s (b) Water content is 5%

The above simulation shows that the magnetization effect of two-phase flow with different flow rates and phase holdup is effective. According to Fig. 7a the simulation results are shown in v=1.66m/s, WH=36%, 24%, 12%, 0% (The corresponding \(LM_{pd}=0m, 0.3m, 0.6m, 0.9m\)), when the second strong magnetic field magnetization section \(LM_2 = 0.4 \text{ m}\), the effect of complete magnetization can be achieved. The simulation results of Fig. (a) and Fig. (b) are the same, so it is determined that the magnetic susceptibility of \(LM_2\) basically reaches 100% when the length of \(LM_2\) is 0.4m.
4. Conclusion

In low field NMR two-phase flow measurement, whether the fluid is completely magnetized will directly affect the accuracy of the measurement results. In this work, we construct an adaptive magnetization structure for low field NMR two-phase flow measurement, with the ability to adjust automatically magnetization length and time according to the parameters of two-phase flow. Thus, the influence of non-uniform magnetization on the measurement results can be reduced.

The simulation results show that the length of adaptive magnetization section A, B, C and D is 0.3m, and that of accelerating magnetization section is 0.4m. The adaptive magnetization structure can achieve complete magnetization effect for two-phase flow in the range of water fraction 0-36% and flow rate 0-4.66m/s. It provides a new idea for the design of NMR two-phase flow measurement sensor.

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