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EFFECT OF A NONUNIFORM MAGNETIC FIELD ON THE TIME OF LONGITUDINAL RELAXATION T_1 OF A FLOWING LIQUID

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The behavior of the time of longitudinal relaxation T_1 for a flowing liquid in the strong nonuniform magnetic field of the magnet polarizer of a nuclear-magnetic-resonance (NMR) flow meter is studied theoretically and experimentally. An increase in the nonuniformity of this field reduces T_1. The magnitude and nonuniformity of the field have an optimum whose criterion is the signal/noise ratio in the recording scheme for the NMR signal and the weight and dimension characteristics of the instrument.

The observed trends for miniaturization of the structure of measuring devices has placed before the developers of measuring instruments whose principle of operation is based on the phenomenon of nuclear magnetic resonance (NMR) in a flowing liquid a number of serious problems that are related mainly to the preservation of the precision characteristics of these devices with a diminution of the structure of the magnetic systems of the polarizer and the analyzer.

The problems that arise with a diminution of the structure of the magnetic system of the analyzer are eliminated using new developed materials with a higher coefficient of magnetic energy. In the structure of the magnetic system of the polarizer, apart from the field H_p in the gap between the pole pieces, the time of residence of the flowing liquid τ in the field H_p is of significant importance. The time τ is defined as

$$\tau = V_p/q\,. \tag{1}$$

For complete magnetization of the liquid in the polarizer up to $M_p = X_0 H_p$, the relation $\tau >> 3T_1$ must hold [1]. Nonfulfillment of this relation impairs the signal/noise ratio in the recording scheme for the NMR signal and, as a consequence, lowers the measurement accuracy.

Miniaturization of the structure of the magnetic system of the polarizer in an NMR flow meter with a constant range of measured liquid flow rates q leads to a significant reduction in τ and hence a decrease in M_p that cannot be fully compensated for by increasing H_p. Therefore, the question as to ways of reducing the time of longitudinal relaxation of the liquid T_1 during its residence in the field of the magnet polarizer are.

The traditional method of controlling T_1 that involves variation of the temperature of the flowing liquid [2, 3] is inapplicable to NMR flow meters, since their structure is supplemented with a liquid heating and cooling system, which creates great technical difficulties and largely increases their weight and dimension characteristics. The proposed methods of decreasing T_1 by introducing paramagnetic ions into the polarizer vessel, which were confined in it by a special filter [1, 4], or by filling the polarizer vessel with sand [5] have some major drawbacks associated with additional drag in the measuring channel (especially in [3]), while any filter operates efficiently only for a certain time. Nuclear-magnetic-resonance flow meters are used mainly in systems with a continuous technological process or where conditions of sterility of the measuring process need to be observed, and therefore the proposed methods of decreasing T_1 could not find use in their structures.

The purpose of the paper was to study theoretically and experimentally the effect of a strong nonuniform magnetic field on the time T_1 of a flowing liquid in a magnetic polarizer to determine the expediency of applying the proposed method of decreasing T_1 to the structures of NMR flow meters.

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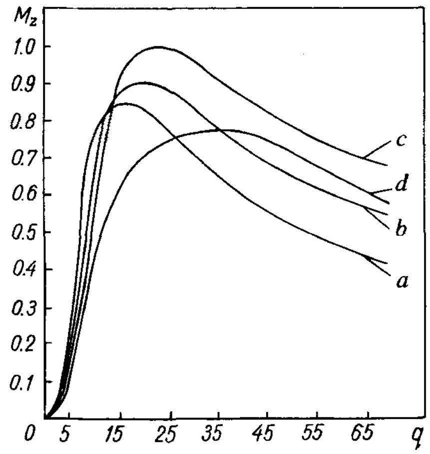

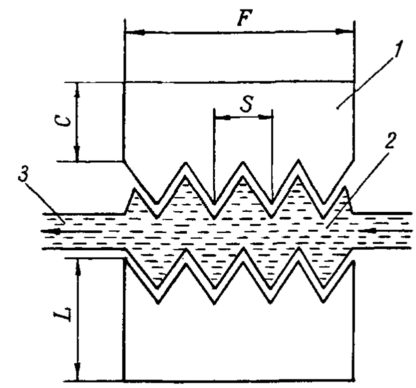

Fig. 1. Calculated dependence of the nuclear magnetization M_z on the liquid flow rate q for d = 16 mm, T_l = 3.7 sec, V_t = 17 ml, and V_p = 106 ml: a, b, c, and d) values of $\Delta H_{p.m}/H_p$ in cm^{-1}: 0, 0.081, 0.165, and 0.31. M_z, rel. units; q, ml/sec.

Fig. 2. Polarizer structure: 1) magnet-polarizer; 2) polarizer vessel, 3) section of the connecting tubing.

The relaxation processes in the flowing liquid must be described taking into account that rapid large-amplitude motion of the molecules in comparison with quiescence, in which it is has a random character, entails here inversion of individual molecules, their relative displacement in the flow, and migration of atoms or atomic groups from one molecule to another because of chemical exchange. If a molecule undergoes a rapid rotation or vibration about its center, a relaxation mechanism occurs (an effect of second order) that reduces the time T_l [4]. All molecules of the flowing liquid that are located in the polarizer can be subjected to the indicated effect by means of a strong nonuniform magnetic field.

The study is carried out using a classical scheme of an amplitude NMR flow meter that fully conforms to that described in [4]. Water is used as the working fluid. Since a water molecule contains two identical spins 1/2, the time of its longitudinal relaxation T_{lp} in the magnet polarizer can be evaluated using the equation [2, 3, 6]

$$T_{lp} = kT\,(3p^6/a^3 + 5/\pi N)\,(1 - d\Delta H_{p.m}/H_p)^2/(6\pi\gamma^4 h^2 \eta) + + 40/(6\gamma^2 H_p^2 \delta_z^2\,(1 + \eta^2/3)\,\tau_s)\,. \quad (2)$$

The first term in Eq. (2) is related to the rotational and translational motion of the molecules, and the second term is attributable to the combination of the anisotropic chemical shift and molecular reorientation. Since currently NMR flow meters mainly use polarizers with a magnetic field H_p higher than 10^6 A/m, the second term in Eq. (2) can be disregarded. Then, Eq. (2) assumes the form

$$T_{lp} = 4D\,(3\pi p^6 N + 5a^3)\,(1 - d\Delta H_{p.m}/H_p)^2/(3\gamma^4 h^2 \pi N a^2)\,. \quad (3)$$

The nuclear magnetization M_z that is recorded in the analyzer of the given NMR flow meter is calculated from the equation [1, 4]

$$M_z = M_p\,(1 - \exp\,(-\,V_p/(qT_{lp}))\,\exp\,(-\,V_t/(qT_l))\,. \quad (4)$$

As an example, Fig. 1 presents calculated dependences of M_z in the analyzer on the liquid flow rate q for different values of $\Delta H_{p.m}/H_p$. The calculations were carried out for known values of the parameters that

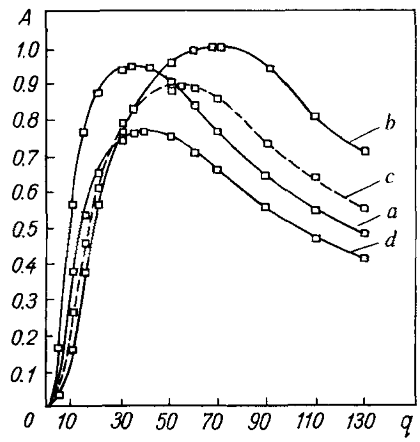

Fig. 3. Experimental dependence of the amplitude of the NMR signal A in the analyzer on the liquid flow rate q at F = 108 mm, V_p = 106 ml, and L = 44 mm for different structural parameters of the magnetic system of the polarizer (C and S in mm, $\Delta H_{p.m}/H_p$ in cm^{-1}): a) 44 and 0, 0.002; b) 26 and 6, 0.272; c) 26 and 12, 0.173; d) 26 and 24, 0.081. A, rel. units.

TABLE 1. Longitudinal Relaxation Time T_{1p} (sec) for Water in the Nonuniform Magnetic Field of the Polarizer at V_p = 106 ml and F = 108 mm

C, mm	L = 36 mm at S, mm			L = 44 mm at S, mm		
	6	12	24	6	12	24
20	1.782	2.684	3.195	1.803	2.741	3.262
26	1.793	2.752	3.247	1.136	2.382	3.104
32	2.573	3.072	3.384	2.112	2.956	3.318

enter into Eq. (3): $a = 1.74 \cdot 10^{-8}$ cm, $p = 1.58 \cdot 10^{-8}$ cm, $N = 6.75 \cdot 10^{22}$ cm^{-3}, and $D = 1.85 \cdot 10^{-5}$ sec/cm^2, and taking into account that, for pure water, T_1 = 3.7 sec.

For the experimental study, a structure of the magnetic system of the polarizer was developed (Fig. 2) that sets up a strong nonuniform magnetic field in the polarizer vessel.

Figure 3 presents some experimental dependences of the amplitude of the NMR signal A in the analyzer on the liquid flow rate q for different parameters of this structure.

Comparing the obtained experimental dependences at the points where A takes on a maximum value, with the aid of Eq. (4) we determine T_{1p} in the developed structure for various dimensions of it and nonuniformities of the magnetic field. Calculated results for T_{1p} are presented in Table 1. For the water used, T_1 = 3.42 sec was determined experimentally.

On the basis of the data of the table and figures, the following conclusions can be drawn:

1. The parameters of the magnetic field $\Delta H_{p.m}$ and H_p of the polarizer have an optimum whose criterion is the signal/noise ratio in the recording scheme for the NMR signal and the weight and dimension characteristics of the instrument.

2. A major contribution to T_1 of water in a strong nonuniform magnetic field is made by the rotational and translational motion of the molecules, and an increase in the field nonuniformity leads to a reduction in T_1.

3. The comparison of calculated results with experimental data shows their agreement, which validates the selected model of calculation [6] and the method of controlling T_1 in NMR flow meters.

The proposed method of decreasing T_1 is unsuitable for an NMR flow meter that is assembled according to a scheme with an integrated analyzer and polarizer [7] because, as measurements showed, the decrease in the signal/noise ratio due to the increase in the nonuniformity of the magnetic field (a misphasing of the spin moments and a broadening of the nuclear-absorption line) is much greater than its increase by the proposed method. However, since this structure of an NMR flow meter is applicable only to the measurement of low and slowly varying liquid flow rates, it is encountered very rarely, unlike the classical scheme of an NMR flow meter for which the above investigations were conducted.

The results are undoubtedly of interest to specialists concerned with the technique of NMR in a flowing liquid.

NOTATION

V_p, volume of the polarizer vessel located between the pole pieces of the magnet-polarizer; q, liquid flow rate; X_0, static nuclear magnetic susceptibility; k, Boltzmann constant; T, temperature of the flowing liquid; D, self-diffusion coefficient of the liquid; N, number of protons in 1 cm^3; a, radius of the solid sphere by which a molecule in rotation is approximated in the Stokes equation; p, proton spacing; $\Delta H_{p.m}$, mean nonuniformity of the magnet-polarizer field in the gap between the poles; d, gap size; V_t, volume of the connecting tubing between the polarizer and the analyzer; τ_s, stochastic time of correlation. Subscripts: p, polarizer; t, tubing; s, stochastic.

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