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METHOD FOR CALCULATING THE RELAXATION ERRORS FOR MARKER NUCLEAR-MAGNETIC FLOWMETERS OF THE NUTATION-PHASE TYPE FOR LAMINAR FLOW

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A marker nuclear-magnetic flowmeter for proton-containing liquids is developed and a method for calculating its relaxation errors is proposed.

Methods and apparatus for measuring the flow rate of liquids are very important for modern production operations. Currently used flowmeters are becoming ineffective for low fluid flow rates owing to the significant effect of the contributed hydraulic resistance to the flow and the low accuracy, so that there is a general trend toward the use of no-contract methods, of which the most promising are methods based on nuclear magnetic resonance (NMR) [1, 2].

Amongst the well-known modifications of NMR flowmeters (amplitude, nutation, marker, etc.) the best parameters are obtained with marker flowmeters [1-3] which are the most accurate, informative, and easy to build.

In the design and construction of flowmeters it is necessary to evaluate the possible errors associated with the spread in the values of the relaxation times for different liquids. We shall examine a method for determining the relaxation errors for the example of a marker flowmeter of the nutation-phase type (Fig. 1).

This type of flowmeter operates on the principle of magnetic marking of the liquid and detection, with the help of the NMR effect, of the moment at which the marked liquid passes through the measuring section.

After flowing through the strong field of the polarizer B_p the liquid is polarized, i.e., the magnetic moments of the nuclei in it are oriented predominantly at an acute angle to the induction vector of the magnetic field B_p, as a result of which a nuclear magnetization vector M parallel to B_p is created. Then the liquid flows into the magnetic field B_n along the transport section of the tube L_T, where part of the liquid is marked by dynamic reorientation (nutation) of the nuclear magnetization vector [4, 5]. The marking is recorded in the analyzer, located at some distance $L_1 + L_a$ from the location of marking. At the same time the marked volumes of the liquid are demagnetized in the sections L_T and L_1 and completely magnetized in the field of the analyzer on the section L_a (to simplify the analysis we assume that there are no leakage fields from the magnet systems).

As the liquid flows along the measurement section $L_1 + L_a$ from the nutation section to the recording coil, owing to the distribution of velocities, each layer of liquid is demagnetized and magnetized to a different degree with a characteristic longitudinal relaxation time T_1. As a result, the contribution of the magnetization of each layer of liquid to the resulting magnetization in the volume of the recording coil depends on the relaxation time, while the recorded propagation velocity of the nuclear-magnetic marker differs from the average velocity of the liquid.

At the inlet into the marker coil the magnetization of the liquid can be written in the form

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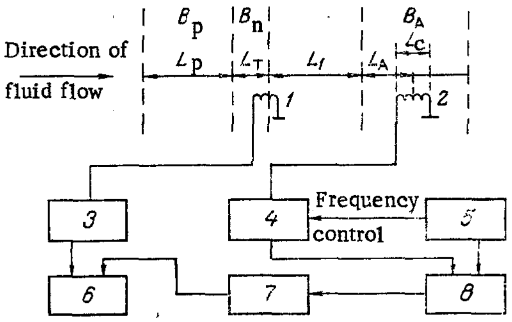

Fig. 1. Structural diagram of a marker NMR flowmeter of the nutation-phase type: 1) reference coil; 2) recording coil; 3) marker pulse generator; 4) spin detector; 5) modulator; 6) setup for analyzing and recording the flow rate; 7) filter; 8) synchronous detector.

$$M_1 = \chi_0 B_p \left[1 - \exp\left(\frac{-V_p}{QT_1}\right)\right] \exp\left(\frac{-V_T}{QT_1}\right).$$

When the liquid is marked periodically by pulses of the radiofrequency nutation field with a duty factor of 2, the magnetization of alternating equal sections of marked and unmarked liquid varies according to the law:

$$M_2 = \frac{4\chi_0 B_p}{\pi}\left[1 - \exp\left(\frac{-V_p}{QT_1}\right)\right] \exp\left(\frac{-V_T}{QT_1}\right) \sum_{n=1,3,5\ldots}^{\infty} \frac{\sin(n\omega t)}{n}.$$

Taking into account the velocity distribution in a laminar fluid flow, the time dependence of the avarage magnetization of the liquid in the volume of the recording coil can be expressed in the following form:

$$M_c(t) = 2\pi \int_0^R \chi_0 B_a \left(1 - \exp\left(\frac{-V_a}{2T_1 Q\left(1 - \frac{r^2}{R^2}\right)}\right)\right) r\,dr + \frac{16Q\chi_0 B_p}{\omega V_c} \sum_{n=1,3,5\ldots}^{\infty} \frac{1}{n^2} \int_0^R \left(1 - \exp\left(\frac{-V_p}{QT_1}\right)\right) \times \tag{1}$$

$$\times \exp\left(\frac{-V_T}{QT_1} - \frac{V_1 + V_a}{2QT_1\left(1 - \frac{r^2}{R^2}\right)}\right)\left(1 - \frac{r^2}{R^2}\right) \cdot \sin\left[n\omega t - \frac{n\omega(V_1 + V_a)}{2Q\left(1 - \frac{r^2}{R^2}\right)}\right] \sin\left[\frac{n\omega V_c}{2Q\left(1 - \frac{r^2}{R^2}\right)}\right] r\,dr.$$

The first term in the formula (1) is the constant component of the magnetization in the volume of the recording coil, arising owing to the additional magnetization of the liquid in the field of the analyzer, while the second term is the variable component of the magnetization, characterizing the motion of the marker.

The amplitude of the signal at the outlet from the spin detector is proportional to the magnetization in the volume of the recording coil. The voltage at the inlet into the setup for analyzing and recording the flow rate after passage through the filters is written in the form

$$U(t) = \frac{16Q\chi_0 B_p}{\omega V_c} \sum_{n=1,3,5\ldots}^{\infty} \int_0^R \frac{1}{n^2 \sqrt{(1 + n^2\omega^2\tau_l^2)}} \frac{1}{\sqrt{1 + \frac{1}{n^2\omega^2\tau_h^2}}} \left(1 - \exp\left(\frac{-V_p}{QT_1}\right)\right) \times$$

$$\times \exp\left(\frac{-V_T}{QT_1} - \frac{V_1 + V_a}{2QT_1\left(1 - \frac{r^2}{R^2}\right)}\right) r \sin\left[\frac{n\omega V_c}{2Q\left(1 - \frac{r^2}{R^2}\right)}\right]\left(1 - \frac{r^2}{R^2}\right) \times \tag{2}$$

$$\times \sin\left[n\omega t - \frac{n\omega(V_1 + V_a)}{2Q\left(1 - \frac{r^2}{R^2}\right)} - \operatorname{arctg}(n\omega\tau_l) + \operatorname{arctg}\left(\frac{1}{n\omega\tau_h}\right)\right] dr.$$

Therefore the analyzer field does not contribute errors to the measurement of the flow rate, since it does not affect the recorded variable part of the magnetization.

To evaluate the relaxation errors it is necessary to find from the formula (2) the dependence of the displacement times of the marker on the flow rates for different relaxation times. At the moment the marker arrives in the recording coil the variable part of the mag-

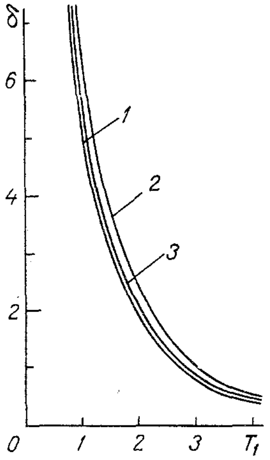

Fig. 2

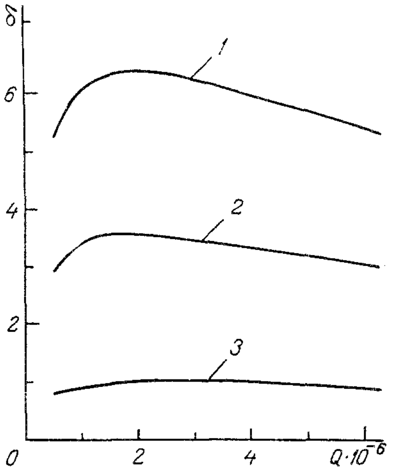

Fig. 3

Fig. 2. Relative error in the measurement of the flow rate per unit relaxation time versus the relaxation time: 1, 2, 3) flow rate of $0.5 \cdot 10^{-6}$, $2.5 \cdot 10^{-6}$ and $5 \cdot 10^{-6}$ m^3/sec, respectively; δ, %/sec; T_1, sec.

Fig. 3. Relative error in the measurement of the flow rate per unit relaxation time versus the flow rate: 1, 2, 3) relaxation time 1, 1.5, and 3 sec, respectively; Q, m^3/sec.

netization equals zero. Hence, the relaxation errors of the flowmeter can be calculated by equating the value of the magnetization from the formula (2) to zero and finding the displacement times of the marker for different flow rates and relaxation times.

The relaxation errors were calculated on a computer for the NMR flowmeter developed with the following parameters: $B_p = B_a = 0.3$ T (flowmeter with combined analyzer and polarizer), $\omega = 3.14$ rad/sec, $V_c = 1.7 \cdot 10^{-7}$ m^3; $\tau_\ell = 0.66$ sec; $\tau_h = 0.33$ sec; $V_p = 2.05 \cdot 10^{-5}$ m^3, $R = 3 \cdot 10^{-3}$ m, $V_T = 2.8 \cdot 10^{-7}$ m^3; $V_1 + V_a = 9 \cdot 10^{-7}$ m^3. The results of the calculation are presented in the form of graphs in Figs. 2 and 3.

The relaxation error for a flowmeter for liquids with known relaxation times can be determined from the graphs. For example, the relaxation time for water in the temperature range 20-40°C can vary from 3.6 to 2 sec depending on the concentration of dissolved gases [3]. The relaxation error in this case, as follows from the graph in Fig. 2, equals about 1.5%.

The method described above can be used to evaluate the relaxation errors for marker NMR flowmeters for laminar flow.

NOTATION

B_a, magnetic field induction of the analyzer; B_n, magnetic field induction at the location of the marker coil; B_p, magnetic field induction of the polarizer; V_a, volume of a segment of the measuring section of the pipe in the magnetic field of the analyzer; V_c, volume of the recording coil; V_p, polarizer volume; V_T, volume of the transport section; V_1, volume of the segment of the measuring section outside the field of the analyzer; L_a, length of the segment of the measuring section of the pipe in the magnetic field of the analyzer; L_c, length of the recording coil; L_p, length of the polarizer; L_T, length of the transport section; L_1, length of the segment of the measuring section outside the field of the analyzer; M, magnetization of the liquid at the outlet from the polarizer; M_c, average magnetization of the liquid in the volume of the recording coil; M_1, magnetization of the liquid at theinlet into the marker coil; M_2, magnetization of the liquid at the outlet from the marker coil; R, radius of the pipe; r, radial coordinate; T_1, longitudinal relaxation time of the nuclear magnetization of the liquid; t, time interval from the start of the marking of the liquid; τ_h, time constant of the high-frequency filter; τ_l, time constant of the low-frequency filter; U, voltage at the inlet into the setup for analyzing and recording the flow rate; ω, frequency of marking of the liquid by pulses of the radiofrequency nutation field; Q, flow rate of the measured liquid; χ_0, static nuclear magnetic susceptibility; and δ, relative error in the measurement of the flow rate per unit relaxation time.

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MODELING OF COOLDOWN OF THE SPIRAL ELEMENTS OF CIRCULATION SYSTEMS FOR CRYOSTATS WITH A GASEOUS COOLANT.

2. SYSTEM OF DISK COILS

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The effect of the thermophysical properties of the structural materials and thermohydraulic parameters of the coolant on cooldown of a superconducting magnet with nonuniform distribution of the collant flow rate in the cooling channels is studied.

In the first part of this work we studied the effect of the thermophysical properties of the structural materials as well as the properties and state parameters of the coolant on the nature of the temperature fields and the cooling time of a single spiral disk coil of a superconducting magnet. However, the windings of such magnets consist of a set of adjacent disk coils, whose cooling channels are connected hydraulically in parallel. Heat transfer through the electrical insulation occurs between neighboring disk coils. Insignificant technological deviations during the preparation of the disk coils could cause the hydraulic characteristics of the cooling channels to differ from one another. This could cause the disk coils in the winding of the magnet to cool down at a different rate. The latter is undesirable from the viewpoint of both minimizing the cooldown time of the winding and the appearance of additional mechanical stresses in the structure. As shown in [1], the cooldown time of two thermally insulated but hydraulically coupled "long" channels ($\text{St}^* = \alpha \Pi L/(Gc_p)_g \geq 100$) increases severalfold, if there initially exists a small (~5%) nonuniformity in the flow-rate distribution in the channels, but the total flow rate is constant. This is explained by the fact that the relative fraction of the coolant flow in the colder channel increases with time, as a result of which its rate of cooling continues to increase, while the rate of cooling of the other channel decreases.

Interchannel heat transfer causes a redistribution of the contribution of the channels to the cooling of the system, as a result of which the channel with the higher coolant flow rate participates in the cooldown of the channel with the lower coolant flow rate. In addition, the temperature gradient between the channels decreases. A relation which permits evaluating the cooldown time of two "long" parallel, straight channels as a function of the degree of nonuniformity of the distribution of the coolant flow rate and the magnitude of the thermal resistance of the interchannel insulation is recommended in [2]. This relation can be put into the following dimensionless form:

$$t(\Theta = 0{,}5) = 1 + \frac{\ln 0{,}5}{K_\perp}(2g - 1)(1 - g), \tag{1}$$

where

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