Nuclear magnetic spectrometer of differential type for
determining the longitudinal relaxation time in turbulent fluid
flows

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Abstract. The article substantiates the necessity of measuring the longitudinal relaxation time
$T_1$ of the flowing liquid to control its state. For such measurements, a new method for measuring
$T_1$ in a flowing fluid is proposed. This method allows to measure relaxation time in a wide range
of a flow rate (more than two orders of magnitude).

1. Introduction
Deteriorating global environmental conditions, as well as increased production and much more, required
the development of various methods for monitoring condensed media [1-9]. Various methods are
necessary, since their applicability depends on the measurement conditions, as well as on the tasks to be
solved [8-23]. In some cases, it is necessary to ensure the sterility of the measured process, therefore
non-contact instruments are used to control the media [6, 7, 11-14, 24-28]. In addition, additional
requirements have been imposed on the control devices. Namely, the measurements must be in real time
and the measuring process must not change the physical structure and chemical composition of the
medium [5-8, 11-15, 27-32].

When implementing these requirements, there are especially many difficulties with monitoring the
condition of the flowing liquid through the pipeline [12, 24, 33-37]. Such control is necessary to
determine the flowing liquid state both during experiments and during automation of industrial
production of various liquid media, biological solutions, etc. This is one of the tasks of the technical
physics [12, 24, 28, 29, 32, 37-40].

2. Nuclear magnetic spectrometer and method for control of flowing liquid state
One of the most promising methods to control the state of the flowing liquid is the use of the nuclear
magnetic resonance (NMR) phenomenon [34-42]. However, it is extremely difficult to register the NMR
spectrum since the liquid is located for a limited time in the NMR signal registration system [26-42].
Therefore, the condition of the current liquid is monitored according to the measured time values of its
longitudinal $T_1$ and transverse $T_2$ relaxation.

Since the monitoring devices of the flowing liquid must operate effectively when the value of liquid
flow rate $q$ changes in at least two orders of magnitude, a few problems arise. The main one is related
to the limitations of the previously developed methods for measuring $T_1$ relaxation time of a liquid. This
is because during the experiments or control of technological process it is difficult to perform
measurements of $T_1$ on optimum value of flow $q_{opt}$ when the flow rate $q$ changes within two orders or
more [12, 36, 37]. Therefore, it is almost impossible to use this method in industry.
Thus, the development of the method for determining the longitudinal relaxation time of the flowing liquid by the nuclear magnetic spectrometer is extremely relevant. Such measurement must be performed with an error of less than 1%, even in cases where the liquid flow rate varies by more than two orders of magnitude.

One of the possible solutions to this problem has been proposed in our work. Figure 1 shows the experimental setup of a differential type NMR spectrometer that implements a new method for measuring the longitudinal relaxation time $T_1$ of a flowing fluid.

**Figure 1.** The block diagram of the experimental setup: 1 is the pump; 2 is the magnet polarizer; 3 is the vessel polarizer; 4 is the connecting section of the pipeline; 5 is the content of the nutation coil; 6 is the flow switches; 7 is the a connecting section of the pipeline connected through flow switches; 8 is the flow switches; 9 is the magnet analyzer; 10 is the coil recording the NMR signal; 11 is the registration diagram; 12 is the oscilloscope; 13 is the modulation coils; 14 is the modulation generator; 15 is a processing and control diagram; 16 is the electronic keys; 17 is the nutation generator; 18 is the frequency counter; 19 is the magnetic screens.

To implement the new method, we have considered the evolution of the magnetization vector along all its paths from the polarizer magnet to the registration coil. As a result of the research it was found that under certain conditions the magnetization of the liquid changes only because of relaxation processes. These conditions are mean the fulfilling conditions of the of adiabatic theorem on the whole length of the magnetized liquid flow from the polarizer to the registration coil.

If two sections of the pipeline with different volumes are used, the magnetization $M_1$ of the liquid will change, and so does the amplitude of the recorded NMR signals. In this case, it was found that the ratio of amplitudes of the recorded signals was proportional to the ratio of magnetization change factors:

$$\frac{U_1}{U_2} = \frac{e^{-\frac{V_{c_1}}{qT_1}}}{e^{-\frac{V_{c_2}}{qT_1}}}$$

(1)

where $T_1$ is the time of longitudinal relaxation of the liquid.

After some mathematical conversions, this ratio takes the following form:
\[ T_1 = \frac{V_{c2} - V_{c1}}{q \cdot \ln \frac{U_1}{U_2}} \]  

(2)

It should be noted that in the developed method, the error of \( T_1 \) determination with the use of the formula (2) is mainly determined by the error of measurement of \( q \) value and the error of determination of volumes of connecting pipeline sections \( V_{c1} \) and \( V_{c2} \). The error of measuring amplitudes of NMR signals has no significant impact on the error of measuring \( T_1 \) since the formula (1) uses their ratio [24, 38, 42].

The liquid flow rate \( q \) is measured by the method developed by the authors [39–42], based on the registration of the time of arrival of the NMR signal with the inversion of the magnetization in the detection coil 10 from the nutation coil 5.

It should be noted that in the developed method in the ratio for measuring \( T_1 \) it is possible to use measured values of amplitudes \( U_1 \) and \( U_2 \) from NMR signals with magnetization inversion. This allows simultaneous measurements of \( q \) and \( T_1 \).

3. Results of experimental research and discussion

Figure 2 shows the example of the recorded signals.

**Figure 2 (a, b).** NMR signals from tap water for different volumes of pipeline connection section. Graph a) correspond to \( V_{c1} = 146 \) ml and graph b) correspond to \( V_{c2} = 204 \) ml.

An analysis of the obtained NMR signals shows that in the case of an increase in \( V_c \), the amplitude of the recorded NMR signal decreases, which corresponds to [39–42]. To confirm the obtained data, NMR signals with inversion, which is created in the nutation coil 6, were studied.

Figure 3 presents, as an example, the recorded NMR signals from tap water with magnetization inversion at two volume values \( V_c \).
For tap water at $T = 276.3$ K, using the new method, the value of the longitudinal relaxation time was measured. The measured value is $T_1 = 1.436 \pm 0.014$ s. The relaxation time measurement cycle was repeated 10 times to average the data and estimate the measurement error in accordance with standard methods. A sample of the same water at $T = 276.3$ K was studied on a Minispec mq20M stationary NMR relaxometer (made by BRUKER). The measured value is $T_1 = 1.4338 \pm 0.0028$ s. The obtained values of $T_1$ coincided within the measurement error.

4. Conclusion
The analysis of the obtained experimental results showed that the experimental setup we have developed using a new method allows to measure $T_1$ with an error of less than 1% in real time simultaneously with the measurements of $T_2$ and liquid flow rate $q$ when it changes in the range of more than two orders of magnitude. This allows us to offer the developers of NMR measuring devices, on the basis of the developed design of the experimental setup and our proposed new method for measuring $T_1$, to develop a new NMR design of a flowmeter-relaxometer, both for conducting scientific research and for solving various problems in the energy and industry.

Acknowledgments
This research work was supported by the Academic Excellence Project 5-100 proposed by Peter the Great St. Petersburg Polytechnic University.

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