On possibility of controlling the flow rate and state of wastewater using nuclear magnetic flowmeter-relaxometer

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Abstract. Currently, one of the urgent tasks in environmental monitoring is monitoring the wastewater state. Wastewater is generated in any technological production, as well as in agriculture as a by-product of production. These wastewaters must be cleaned of hazardous elements before being discharged. Moreover, their condition control is necessary even if the water cycle is closed, i.e. there is reuse after treatment. It should be noted that such wastewater can contain pollution and other production waste which can cause damage to the measuring equipment. In this case, non-contact devices are preferable for wastewater control. The method of nuclear magnetic resonance is one of the promising solutions to this problem. The developed device allows measuring water flow at a flow rate in the range from 0.001 to 1.0 liters per second. In this range, relaxation constants are measured to determine the presence of both dissolved and undissolved impurities, as well as hazardous substances in water. Measurements can be made in the temperature range from 276 to 320 K. All measurements are carried out without contact with the investigated medium. Our work presents the results of such measurements.

1 Introduction

The development of industry, an increase in the demand and consumption of various goods and services, as well as the launch of new power plants have led to an increase in the load on treatment facilities [1-7]. At the same time, environmental degradation in the world has led to an ever-increasing demand for environmental control and monitoring systems [7-18]. Therefore, it is necessary to constantly develop new and improve existing methods for measuring environmental parameters [19-29].

Since various aggressive and toxic inclusions may exist in wastewater, non-contact devices are preferred when measuring their parameters [10, 18, 28, 30-32]. Moreover, in a number of cases, the purified medium is used again. Therefore, it is very important that measuring devices do not change its physical structure and/or chemical composition [30, 31, 32].

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It is also worth noting that when using automatic control systems, measurements must be carried out in real time [18, 19, 28, 37].

Many problems arise during the control of the flowing wastewater state. In addition, it is necessary to control the flow rate $q$ of the flowing medium to control the cleaning system [37]. Most of the devices produced are designed either for measuring the flow rate $q$ of liquid medium or for monitoring its condition [37-40]. In some cases, it causes a lot of problems. For example, there is not enough space for two devices or the medium has a high turbidity, which does not allow the use of flow optical spectrometers, or the pipeline is not completely filled (refractometer cannot be used) [18, 26].

The use of devices whose operating principle is based on the phenomenon of nuclear magnetic resonance (NMR) is one of the solutions to the problems considered. However, for the successful use of NMR devices for wastewater monitoring, it is necessary to make additional changes in their design.

2 Nuclear magnetic resonance method and experimental setup

Unlike in-service devices for measuring the parameters of the flowing liquid, such as various types of flow meters, flow refractometers or optical spectrometers, NMR devices allow you to monitor both the state of the medium and its flow $q$ with one device. In this case, the NMR method completely excludes the contact of the measuring systems of the device with the flowing medium.

The results of previous studies have shown that it is very difficult to implement classical methods based on registration of the NMR spectrum to control the flowing environment. Implementation difficulties arise since the liquid is located for a limited time in the NMR signal registration system [37, 38]. Therefore, the condition of the flowing liquid is monitored according to the measured time values of its longitudinal $T_1$ and transverse $T_2$ relaxation times.

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 the NMR spectrometer that allows to control both the state and the flow rate of a flowing fluid.

Fig. 1. The structural diagram of the nuclear magnetic spectrometer. 1 – polarizing magnet; 2 – polarizing vessel; 3 – nutation coil; 4 – modulation coil; 5 and 6 – generators of the nutation and modulation coils; 7 – analyzing vessel; 8 – modulation coils of the analyzing magnet; 9 – analyzing magnet; 10 – coil recording the NMR signal; 11 – signal registration scheme; 12 – processing and control scheme; 13 – electronic keys; 14 – RF generator; 15 – indication scheme; 19 – magnetic screens.
In the proposed method, the evolution of the magnetization vector along the liquid path from the polarizer magnet to the registration coil has been studied. The results of the studies showed the following. If the conditions of the adiabatic theorem are met on the whole path of the magnetized liquid flow from the polarizer to the registration coil, then the magnetization of the liquid changes only because of relaxation processes.

The magnetization $M_1$ depends on the volume of the pipeline section. Also, the amplitude of the recorded NMR signals is proportional to the value of $M_1$. Therefore, the ratio of amplitudes of the recorded signals is proportional to the ratio of magnetization change factors:

$$
\frac{U_1}{U_2} = \frac{e^{\frac{V_1}{T_1}}}{e^{\frac{V_2}{T_1}}}
$$

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

Which means that longitudinal relaxation time $T_1$ can be found as follows:

$$
T_1 = \frac{V_2 - V_1}{q \cdot \ln \frac{U_1}{U_2}}
$$

It should be noted that in this case, the error of $T_1$ determination is mainly determined by the error of measurement of $q$ value and the error of determination of volumes of connecting pipeline sections $V_1$ and $V_2$. 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.

The flow rate $q$ can be measured using techniques described in [39-40]. These techniques are based on the registering the instant when inversely magnetized liquid arrived from the nutation coil 5 into detection coil 10.

Since there is no technical restriction in measuring the longitudinal relaxation time using inversed magnetization instead of a regular one. Therefore, it is possible to simultaneously measure both $q$ and $T_1$.

3 Results and Discussion

Figure 2 shows the example of the recorded signals.

Fig. 2 (a, b). NMR signals from tap water for different volumes of pipeline connection section. Graph a) correspond to $V_1 = 146$ ml and graph b) correspond to $V_2 = 204$ 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 [37, 38,]. 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 \( V \).

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 Conclusions

The analysis of the obtained experimental results showed that the developed experimental setup allows to measure \( T_1 \) in real time simultaneously with the liquid flow rate \( q \). These measurements are possible even if the flow rate changes in the range of more than two orders of magnitude. This confirm the validity of the proposed method and the need to continue research in this area. Potential research areas are improvements in accuracy, sensitivity, and optimization of the experimental setup to reduce space and energy consumption. Also, this experimental setup can be used in agriculture [41-44], for example for monitoring the condition of liquid fertilizers.

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