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The Multifunctional Nuclear Magnetic Flowmeter for Control to the Consumption and Condition of Coolant in Nuclear Reactors

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Abstract: The necessity of coolant flow consumption measurement accuracy increase in the nuclear reactor primary circuit has been substantiated. Additionally, the need to control the coolant condition in the current flow inside the pipeline is shown. Nowadays, the real-time coolant's condition control function is not implemented at stationary nuclear power plants or mobile nuclear power plants used in moving objects. It is shown that a coolant consumption measurement error decreases and its condition data availability increases the heat transfer efficiency and the electrical energy generation (without the nuclear reactor and steam generator design change). Problems arising during coolant consumption control using various flowmeters models in the nuclear reactor primary circuit are considered. It has been found that nuclear magnetic flowmeters can solve these problems. New difficulties are noted as emerging when using pulsed nuclear magnetic flowmeters designs developed for measuring hydrocarbons, water, biological compounds consumption, and condition control. A new nuclear magnetic flowmeter design has been developed using a modulation technique for nuclear magnetic resonance signal recording. Methods for measuring the coolant flow's longitudinal T_1 and transverse T_2 relaxation times are presented. Investigations of coolant flow parameters (consumption and relaxation times) inside the pipeline have been carried out. It is found that the measurement error for these parameters does not exceed 1%. The prospects of using the developed nuclear magnetic flowmeter-relaxometer design in the nuclear reactor first circuit are shown.

Keywords: nuclear power plant; coolant; control; consumption; nuclear magnetic resonance; magnetization; longitudinal T_1 and transverse T_2 relaxation times; measurement error

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1. Introduction

Nuclear energy is one of the most promising fields for producing electrical energy globally [1–5]. The use of nuclear power plants (NPP) will make it possible to meet the ever-growing needs of humankind regarding the necessary capacities of electrical energy at any time of the day [3–7]. It should be noted that the production of electricity at nuclear power plants, unlike other types of power plants, does not depend on many external factors. These factors are connected with changes in climatic conditions for hydroelectric power plants, solar installations or wind turbines, or fuel reserves for thermal power plants [8–11]. The production of the required electrical power at a nuclear power plant is determined by the plant system's operational reliability and the provision of optimal operating modes for various nuclear steam generator (NSG) units [6,7,11–14]. It also applies to NPPs used on mobile offshore objects.

One of the parameters ensuring the NSGs' optimal operation is the coolant consumption q_c in the primary circuit of a nuclear reactor [4–7,12–20]. Some difficulties arise during measuring instruments' operation while controlling the value of q_c in all models of NSGs. Over time, this increases the q_c measurement error up to 5% or more. Due to coolant q_c measurement-dependence on its composition, these difficulties are due to various factors. Melts of lead (Pb) or lead with bismuth (Pb-Bi), sodium melt (Na^{23}), lithium melt (Li^7) with various additives, or an aqueous solution ($H_2O + H_3BO_3$) with plutonium nitride filling are used as coolants. Additionally, various types of flowmeters (electromagnetic, Coriolis force, and magnetic) and measuring devices (flow washers and Venturi nozzles) are used [20–26]. The main problem is caused by device measuring elements in contact with a fast coolant flow at a high temperature [7,14–17,20–29]. For example, for the Brest-300 reactor, the maximum coolant temperature $T_c \approx 923$ K, the consumption reaches $q_c \approx 0.08$ m^3/s [30–33], and for the SVBR-100 reactor, the maximum value of $T_c \approx 973$ K at $q_c \approx 0.1$ m^3/s [30,34]. In some cases, the coolant has high chemical activity in addition to a high flow rate and temperature. For example, it happens in the BN-600 reactor with uranium-plutonium nitride fuel (liquid sodium melt is used as the coolant) [4,14]. Long-term interaction of flowmeter mechanical elements or measuring contacts with such a medium leads to their destruction or structural erosion. The measurement error of q_c drastically increases. It is impossible to replace these devices during the operation of a nuclear reactor.

Problems also arise in the operation of electromagnetic flowmeters. In these devices, a calibration dependence is used to determine the volumetric consumption q, which was obtained at the enterprise manufactured device [35–37]:

$$q = \frac{\pi \times D \times E}{4 \times B \times k}, \quad (1)$$

where E is the potential difference arising from the interaction of moving electrically conductive liquid with a magnetic field and B is the magnetic induction. D is the distance between the ends of the electrodes (coincides with the inner diameter of the flowmeter pipeline made of a non-magnetic material), and k is a correction factor that depends on temperature T and the composition of the liquid medium (set by the enterprise when calibrating the device).

In the region of high temperatures T (more than 800 K), the coefficient k has a nonlinear dependence on T. This dependence must be corrected during the operation of the device, primarily if the device is used to measure liquid media with large temperature and flow-rate differences. At the initial stage of the flowmeter operation, relation (1) makes it possible to determine q_c with no more than 2% relative error. However, during the long-term electromagnetic flowmeter operation for measuring the consumption q_c of the coolant, several peculiarities arise that are somewhat difficult to consider in the subsequent coefficient k value determination. This leads to the q_c measurement error increase.

The main issues are associated with the fact that potential difference E in the electromagnetic flowmeter is recorded by electrodes placed perpendicular to the liquid stream in the pipeline. During their operation, various deposits accumulated in the area of electrode location (on the pipeline walls). This led to a change in the nature of the dependence of k on T. It is impossible to correct the values of k under the device's operating conditions as part of the NSG. Under such circumstances, the consumption measurement error can increase up to five percent or even more. One of the solutions to this problem would be the placement of electrodes in the non-magnetic layer of the pipeline wall. Contact of the electrodes with the flowing stream, in this case, would be excluded, leading inevitably to a decrease in the device's sensitivity to coolant consumption values changes and, consequently, to an increase in the q_c measurement error.

Another reason for the q_c measurement error increase is associated with the fact that a strong magnetic field (induction $B > 0.4$ T) must be used to measure q_c values at high flow rates in electromagnetic flowmeters. A strong magnetic field in an electromagnetic flowmeter creates electrodes polarization, leading to significant errors in consumption measuring for any media [37,38]. Therefore, in these cases, the electrodes are made of special materials (carbon) or protected with special coatings (platinum or tantalum). Carbon electrodes are susceptible to temperature changes even when placed inside the pipe wall. In addition, deposits from the coolant accumulate at the joints of the electrode and the pipeline. This significantly increases the q_c measurement error up to 5% and more. The use of electrodes coating prevents electromagnetic flowmeters from measuring the liquid consumption with ionic conductivity (Li, K, and Na). Then, they can only be used to measure the liquid consumption with electronic conductivity, e.g., water or hydrocarbons [39,40]. For a coolant, these are media containing, for example, Pb and Bi, limiting the functionality of electromagnetic flowmeters in the NPP usage.

There is also another factor limiting electromagnetic flowmeters in the nuclear power plant. The q_c coolant consumption must be measured inside the primary reactor circuit sealed system. Only devices resistant to high temperatures and γ-radiation can be placed in this zone (the radiation exposure dose is ca. 530 mSv/h). The use of instrumentation impulse lines (with a control and measuring device) for retrieving q_c value from electromagnetic flowmeters is not very effective as it leads to huge errors (more than 10%). These lines are used to control pressure and coolant levels in the pipeline. Scientists are currently trying to solve the considered problems since they significantly limit the functional possibilities of using electromagnetic flowmeters in nuclear power.

In addition, during the operation of the NSGs, various oxides can enter the coolant (e.g., due to the pump or pipeline wear). In this case, the measurement error q_c will increase several times, and the presence of these oxides in the coolant cannot be determined using an electromagnetic flowmeter. The efficiency of electricity generation is decreasing. Ultrasonic flowmeters [41] for measuring the coolant consumption at Russian NPPs are currently not used. This is due to some technical limitations and the inability to carry out a full-fledged primary calibration of instruments after their installation on the actual parameters of the coolant in the pipeline system.

On the other hand, to ensure the efficient operation of the steam generator, it is necessary to ensure the optimal heat transfer coefficient k_n (Nusselt criterion) between the first and second circuits depending on the coolant and feed water consumptions as well as their conditions. These parameters must be controlled with an error of less than 1.5%.

Many scientific studies and technical developments are now aimed at solving this problem during the operation of the NSGs. In addition, when the reactor operates at high power levels, it is necessary to ensure efficient heat removal from the reactor rods [1,4,7,12,16] using the coolant stream. It is especially critical for nuclear reactors on offshore mobile objects. The q_c value, in this case, is one of the most critical parameters.

Therefore, the development and implementation of new models of devices operating on other physical principles for measuring the consumption and the coolant condition control are extremely important, especially for newly developed models of NSGs. One of the possible solutions to this problem can be the use of devices operating based on the phenomenon of nuclear magnetic resonance (NMR) [42–47].

2. Nuclear Magnetic Resonance Method

The problem of measuring the flowing medium consumption or rate in a pipeline using the phenomenon of NMR has been considered in various works for over 60 years [41–53]. The experiments using NMR to research the flow effects were first reported by Suryan [50], who found that the nuclear absorption signal changed in proportion to liquid velocity. Early developments of NMR flowmeters to study blood flow began in 1956 at the National Heart, Lung, and Blood Institute [51], with the first in vivo experiments demonstrated by Singer [52]. Vander et al. [53] introduced the first industrially orientated NMR flowmeter in late 1968.

Further, this direction of NMR began to develop rapidly. This happens because pulsed methods for recording the NMR signal from various nuclei with a magnetic moment have been developed [42–44,48,49,54,55]. The primary nuclei used in research are presented in Table 1.

Table 1. Characteristics of nuclei used in nuclear magnetic spectroscopy.

Nuclear Isotope	Magnetic Moment μ	Spin Nucleus I	Gyromagnetic Ratio γ MHz/T	Sensitivity (Relative Intensity of the NMR Signal to the Isotope of the ^{13}C Nucleus)	Natural Content %
^{1}H	2.7928	1/2	42.57637513	5.87×10^{3}	99.989
^{2}H	0.8574	1	6.560085	5.52×10^{-3}	0.0155
^{7}Li	3.2564	3/2	16.561322	1.59×10^{3}	92.41
^{11}B	2.6886	3/2	13.675834	7.77×10^{2}	80.11
^{13}C	0.7024	1/2	10.707945	1.0	1.07
^{15}N	−0.2851	1	4.333247	2.25×10^{-3}	0.368
^{19}F	2.6266	1/2	40.106214	4.89×10^{3}	100.0
^{23}Na	2.2176	3/2	11.277214	5.45×10^{2}	100.0
^{29}Si	−0.5552	1/2	8.496837	2.16	4.68
^{31}P	1.1316	1/2	17.253987	3.91×10^{3}	100.0
^{33}S	0.6438	3/2	3.283846	1.01×10^{-1}	0.76
^{35}Cl	0.8218	3/2	4.192008	7.69	75.78
^{37}Cl	0.6841	3/2	3.489402	8.87	24.22
^{55}Mn	3.4677	5/2	10.567234	1.05×10^{1}	100
^{65}Cu	2.3845	3/2	12.134765	8.76	31.1
^{75}As	1.4394	3/2	7.342051	1.49×10^{2}	100.0
^{77}Se	0.5350	1/2	8.187478	3.15	7.61
^{81}Br	2.2696	3/2	11.532617	6.27	49.4
^{115}In	5.5006	9/2	9.331453	2.18×10^{3}	4.5
^{119}Sn	−1.0473	1/2	16.025042	2.66	8.59
^{195}Pt	0.6095	1/2	9.326623	2.07×10^{1}	33.83
^{199}Hg	0.5058	1/2	7.740854	9.89	13.18
^{210}Pb	0.5822	1/2	8.908461	1.18×10^{1}	22.11
^{209}Bi	4.0796	9/2	6.657445	1.07×10^{1}	100

Analysis of the data presented in Table 1 shows that for all types of coolant [1,4–7,12–20] used now in nuclear reactors, it is possible to use devices based on the NMR phenomenon to measure the consumption and its condition control. To date, many different models of NMR flowmeters have been developed for measuring the aqueous media, oil, biological solutions consumption, and condition control [55–68]. Analysis of these NMR models' characteristics and other earlier developments [42–49,69,70] showed that it is very difficult to use these NMR flowmeters designs to measure the flowing coolant consumption and condition control in nuclear reactors, due to several problems that cannot be solved simultaneously. Let us consider them in detail.

Most of the developed NMR flowmeters are intended for measuring low flow rates of liquid media (not exceeding 10 mL/s using pipelines of small diameter (several mm)), especially those that use a single magnet (magnetic assembly of the Halbach-Array type) [44–48,54]. In nuclear reactors, pipelines from 300 to 700 mm are used in the primary circuit. The coolant consumption varies from 0.01 to 0.9 m^3/s. This comparison is sufficient to understand that a different design is required in NMR meters. It is necessary to use a special polarizer magnet with induction B_p to create the magnetization of the flowing liquid and a system located at some distance from this magnet in a different magnetic field to record the NMR signal. Such designs of various NMR flowmeters have also been developed [57–70]. These instruments use pulsed methods to record the NMR signal and are now successfully used in various NMR spectrometers to study condensed matter in a stationary state [71–75]. Using pulse methods to measure the coolant consumption and its condition control leads to the following problems. All models of flowmeters must measure the change in flow by at least one order of magnitude with a specified error (not exceeding 1.5%). The consumption measurement error Δq depends on the signal-to-noise ratio of the recorded NMR signal [57–70,76–79]. The amplitude of the recorded NMR signal A_{NMR} depends on the value of magnetization M_p at the exit from the magnet-polarizer; on the value of magnetic field induction B_a, in which the NMR signal is recorded; and on its inhomogeneity, ΔB_a [57–70,76–79]. For this, the range of the measured value q must ensure the fulfillment of the condition of complete magnetization of the liquid in the field of the magnet of the polarizer B_p to the value $M_p = \chi_0 B_p$ (χ_0 is the static nuclear magnetic susceptibility) at one of the consumptions [76–79]. This condition is determined by the time t_p of the flowing liquid in the field of magnet-polarizer B_p [45,47–49,53,54,76–79]:

$$t_p \geq 3T_1, \tag{2}$$

where T_1 is the flowing medium longitudinal relaxation time.

Suppose the liquid medium is in the polarizer for a short time (less than $t_p = V_p/q$, V_p is the volume of the vessel-polarizer). In that case, this leads to its incomplete magnetization (M_p will be less than $\chi_0 B_p$) and consequently to a recorded NMR signal amplitude decrease and signal-to-noise ratio decrease. If the signal-to-noise ratio becomes less than 3.0, it is impossible to measure q values with a measurement error of no more than 1.5% [46,47,54,57,59,62,65,67,69,70,76–79]. The q measurement error will increase to 2% or more. It should be noted that the time T_1 varies with the temperature T [79–82]. The transverse relaxation time T_2 value also changes with temperature [79–82]. The measured values of T_1 and T_2 in some instrument designs are used to determine the consumption q [45,48,49,54,61,68], and in other models of pulse NMR flowmeters they are used for monitoring the state of the flowing medium [57,69,76–79]. Figure 1 shows the measured values of the relaxation times T_1 and T_2 of distilled water and an aqueous solution ($H_2O + H_3BO_3$) with plutonium nitride (PuN) filling for various temperatures T. At Russian NPPs, this aqueous solution is used as a coolant in VVER-1200 nuclear reactors [1,15–17] and in the last two VVER-1000 reactors put into operation at NPPs. Previously, in VVER-1000 in an aqueous solution ($H_2O + H_3BO_3$), KOH hydroxide was used as an inhibitor. The measurements were carried out on a stationary NMR relaxometer Minispec mq 20 M (BRUKER, Germany) with a thermo-block.

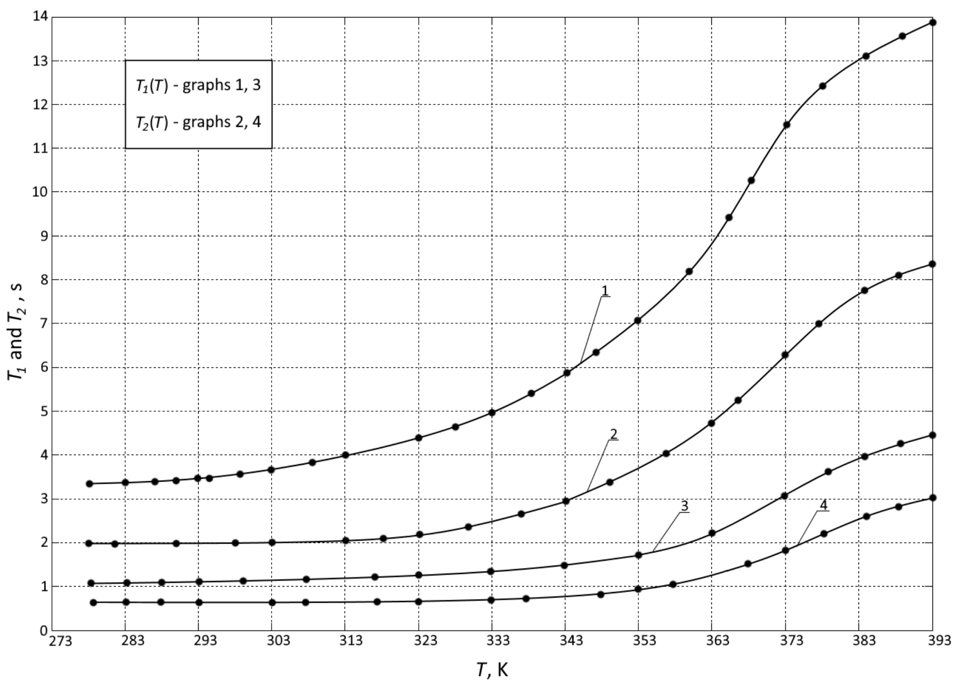

Figure 1. Changes in the longitudinal T_1 and transverse T_2 relaxation times versus temperature T. Graphs 1 and 2 correspond to the values of T_1 and T_2 for distilled water, and graphs 3 and 4 correspond to the values of T_1 and T_2 of an aqueous solution ($H_2O + H_3BO_3$) with plutonium nitride filling.

The analysis of the dependencies shown in Figure 1 shows an increase in the values of T_1 and T_2 with increasing T. The technical capabilities of the NMR relaxometer Minispec mq 20 M made it possible to measure T_1 and T_2 only up to T = 393 K. There are no other industrial instruments for measuring T_1 and T_2 of liquid media at higher temperatures in the world. Therefore, we extrapolated the obtained dependences to the region of higher temperatures. Previously, we used such methods to estimate the heat capacity C of the nuclear reactor secondary circuit feed water for various temperatures and pressures. Comparison of the results with the data obtained on the experimental stand (the value of the heat capacity C was measured along the absorption line) showed that the error in determining the value of C, in this case, did not exceed 5%. Figure 2 shows the results of extrapolation of the values of T_1 and T_2 to the high-temperature region. The average temperature of the coolant considered in the article in the reactor's primary circuit is about 960 K.

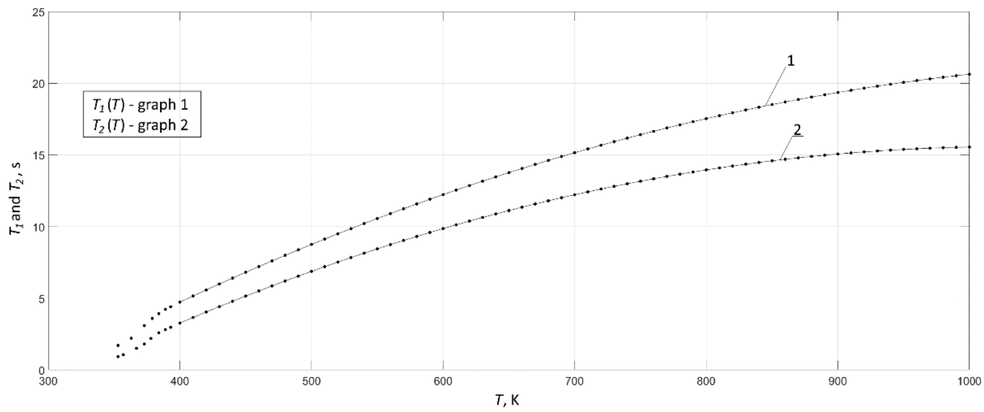

Figure 2. Extrapolation of the change in the values of the longitudinal T_1 and transverse T_2 relaxation times from the temperature T of an aqueous solution (H_2O + H_3CO_3) with plutonium nitride filling. Graph 1 corresponds to the change in the value of T_1, graph 2—T_2.

As a result, we determined the values of T_1 = 20.23 ± 1.02 s and T_2 = 15.54 ± 0.76 s for T = 960 K. Such data on the relaxation times of an aqueous solution (H_2O + H_3BO_3) with plutonium nitride filling were obtained for the first time in the world. To satisfy the condition listed in Equation (2), the time t_p must be at least 61 s. The obtained results show that the previously developed designs of pulse NMR flowmeters [60–69,78] for small pipe diameters (no more than 40 mm) and low flow rates of liquids at temperatures below 320 K are challenging to apply. The use of small-size magnetic assemblies of the Halbach-Array type for magnetizing the flowing liquid [57,58,60,61,68] is excluded. It will be extremely difficult to fulfill condition (2) with their use.

Another problem associated with the residence time of a liquid segment in the recording coils of a pulsed NMR flowmeter for measuring the consumption q and relaxation times T_1 and T_2 cannot be solved under current operating conditions in nuclear reactors. This is because particular sequences of pulses and time intervals for the repetitions are used for measurements [80,81]. There are no problems in the study using the pulsed method of stationary media. In flowing media for measurements, it is necessary to provide a straight section of the pipeline on which the NMR signal registration coil will be located (it is also used to influence pulses on a magnetized flowing liquid). In the case of pipeline turns in a magnetic field, the fulfillment of the conditions of the adiabatic theorem [80,81] is violated, and the pulse technique cannot be used to register the NMR signal. In addition, at bends with a fast fluid flow, turbulent flows arise, which destroy the magnetization marks made by the pulses [54]. The measurements become unreliable. In [62], the most optimal measurement of the consumption q and relaxation times T_1 and T_2 using the pulse technique shows that the total time t_s of the liquid segment in the recording coils should be more than $4T_2 + 6T_1$. Only in this work [62], small diameters of the pipeline and low flow rates are used. For an aqueous solution (H_2O + H_3BO_3) with plutonium nitride filling at T = 960 K, the value is t_s > 184 s. With an average flow rate of the coolant through the pipeline of the order of 25–30 cm/s, the coil distance will be more than 64.5 m. It is also necessary to add at least 20% to this distance, and this will be the length of the straight section of the pipeline for placing the coil for recording the NMR signal (almost 80 m). It is complicated to provide such a section of the pipeline at a nuclear power plant in the protective zone of a nuclear reactor. On a moving object, this task becomes even more problematic. It is an extremely difficult task to provide the necessary magnetic field uniformity for recording an NMR signal with such a recording coil length in the immediate vicinity of a nuclear reactor operating at maximum power.

Therefore, to ensure the measurement error of consumption q of the current coolant and the relaxation times T_1 and T_2 less than 1.5% in the primary circuit of a nuclear reactor, it is necessary to develop other technical solutions and methods for measuring these parameters. These developments must consider the research results obtained in the works [46,47,57–71,79–82].

3. The Design of a Nuclear Magnetic Flowmeter-Relaxometer and Measuring Method

Based on the analysis of various data on the designs of NMR flowmeters [46,47,57–71,79–82] and the results of our research [76,77,83], the design of a laboratory nuclear magnetic flowmeter-relaxometer was developed. The block diagram of the device we have developed is shown in Figure 3.

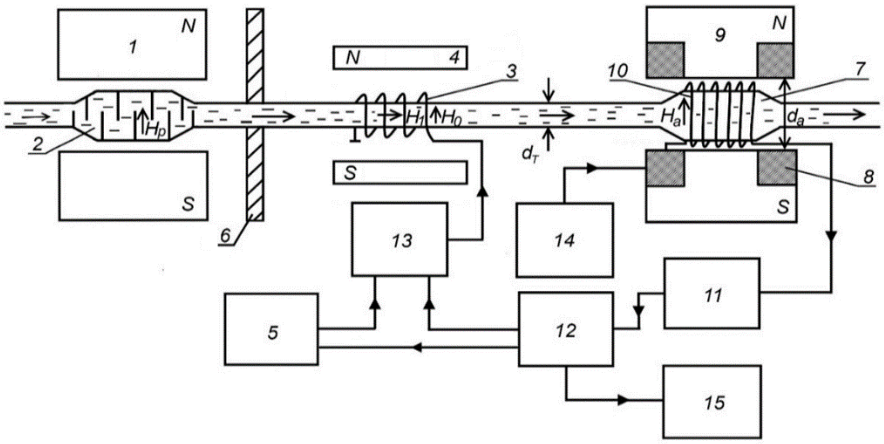

Figure 3. Structural diagram of the laboratory model of NMR label flowmeter and relaxometer: *1*—polarizer magnet; *2*—polarizer vessel; *3*—nutation coil; *4*—magnet of the constant field; *5*—generators of nutation and modulation coils; *6*—magnetic shield; *7*—analyzer vessel; *8*—coils for modulating the field of the analyzer magnet; *9*—analyzer magnet; *10*—coil for recording NMR signal; *11*—circuit for recording an NMR signal; *12*—processing and control diagram; *13*—electronic keys; *14*—radio frequency generator; and *15*—indication circuit.

The flowing medium enters the polarizer vessel *2* through the pipeline. The polarizer vessel is in the magnetic system *1*, which creates a strong magnetic field of 1.532 T with inhomogeneity of 0.02 cm^{-1} in the gap between the pole pieces. In this vessel, the medium acquires the nuclear magnetization vector M_p. Further, from the polarizer vessel, the liquid enters the nutation coil *3* through the connecting section of the pipeline 350 mm in diameter. In the coil, under the action of the resonant variable radio field $H_{1,}$ the magnetization vector orientation of nuclear moments M_p changes. This change after the liquid passes the measuring section of the pipeline is processed by coil *5*, which is in the field B_a of the analyzer magnet *6* (B_a = 0.353 T, the inhomogeneity of 0.002 cm^{-1}, d_a = 398 mm), connected to a high-frequency generator of weak vibrations (autodyne), which is a part of the registration circuit *9*. Modulation coils *8* are placed on the analyzer magnet, and a radio frequency generator *12* is connected to them. To improve the *S/N* ratio and measurement accuracy, analyzer vessel *7* is made in the form of a cylinder with a 384 mm diameter in the area where the registration coil *5* is located. A complete inversion of magnetization

M_p—rotation of the vector by the angle φ_n = 180°—occurs at the resonant frequency f_n of the radio field H_1. The frequency f_n is related to the magnetic field H_0, in which the nutation coil is located, as follows:

$$f_n = \gamma H_0, \tag{3}$$

where γ is the gyromagnetic ratio of nuclei.

It should be noted that the maximum signal-to-noise ratio in the registration circuit *9* corresponds to a certain amplitude of the radio field H_1 in the nutation coil with a frequency f_n. An automatic frequency control circuit located in the processing and control device *12* adjusts the frequency f_n of the nutation generator *5* to the *S/N* ratio maximum.

In the developed design of the NMR flowmeter-relaxometer to register the NMR signal, a modulation technique is used (the field of the analyzer magnet *9* is modulated by an alternating magnetic field with induction B_m and frequency f_m). For this, modulation coils *8* are used. A radio-frequency signal is received from generator *14* (the value of the modulation frequency f_m in our device design varies from 0.01 to 100 Hz). In this case, when the magnetic field B_a passes through the resonance, an NMR signal is recorded. Figure 4 shows the recorded NMR signal from an aqueous solution (H_2O + H_3BO_3) with plutonium nitride filling at T = 333 K.

Figure 4. Time dependence of the change in the amplitude of the recorded NMR signal. The modulation frequency of the magnetic field is f_m = 0.1 Hz.

Analysis of the data presented in Figure 4 shows that NMR signals from an aqueous solution are recorded at the same time intervals $\Delta T_m = T_m/2 = 1/f_m$ = 2.5 s. Figure 5 shows the line shape of the recorded NMR signal with a single passage through the resonance.

The dependence of the change in the maxima at the peaks of the recorded NMR signal (Figure 5—graph 1) is approximated by the following function for the decay of free induction [80,81]:

$$U(t) = U_0 \times \exp\left(-\frac{t}{T_2^*}\right) \times \cos\frac{at^2}{2}, \tag{4}$$

$$a = \gamma\frac{dH_z}{dt} = d\left(\frac{\Delta\omega}{dt}\right), \tag{5}$$

where a is the rate of change in the magnetic field detuning, $T_2{}^*$ is the transverse relaxation effective time, and U_0 is the maximum value of the amplitude of the recorded NMR signal.

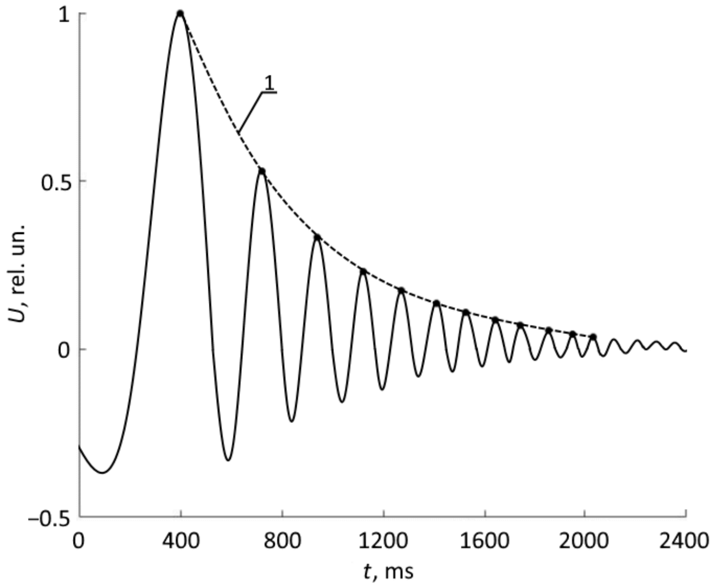

Figure 5. Dependence of the change in the amplitude *U* of the recorded NMR signal on time *t*. Graph 1—curve characterizing the process of attenuation of the peaks after passing through the resonance.

The transverse relaxation time T_2 of the flowing medium, in this case, is determined using the following formula [80,81]:

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{\gamma \Delta B_a}{\pi}, \quad (6)$$

where ΔB_a is the inhomogeneity of the magnetic field in the location of the coil for recording the NMR signal.

In the case of small values of ΔB_a, its contribution to Formula (6) while determining the T_2 value is negligible and $T_2 \approx {T_2}^*$. The transverse relaxation time can be immediately determined using the recorded NMR signal. With an increase in the inhomogeneity of the magnetic field ΔB_a, the number of peaks in the recorded NMR signal (Figure 5) decreases. The error in determining ${T_2}^*$ increases. Our earlier studies of various liquid media in small-sized NMR spectrometers and relaxometers using a modulation technique for recording the NMR signal [70,76,77,80,83–85] made it possible to establish the following. The recorded NMR signal must contain five or more peaks (excluding the main one-maximum amplitude of the NMR signal) to determine T_2 with 1% or less error. In the received NMR signal (Figure 5), the number of peaks significantly exceeds 5.

A different number of impurities can enter the coolant during its operation at a nuclear power plant (for example, scale or oil due to wear of the main central pump or various pipeline pieces due to degradation of a pipe or a welded joint). So, it is necessary to measure the values to control its two relaxation times T_1 and T_2, as in NMR flowmeters when monitoring the parameters of various hydrocarbons [46,47,55,57,58,62,64]. To measure the value of the longitudinal relaxation time T_1 in the design of an NMR flowmeter-relaxometer, we use a method developed by us using two modes of modulation of the *Ba* field [84,85]. This method is successfully applied in NMR devices developed by the authors for condensed media condition express control. In this case, to implement measurements of two values of the relaxation times T_1 and T_2, the investigated segment of the coolant must be in the registration coil for more than 1 s. At a coolant flow rate of 25–30 cm/s, there will be no problems with the placement of an NMR signal registration system with a coil less than 40 cm long on a straight section of the pipeline in the zone of a nuclear reactor, in contrast to the cases of the possible use of impulse NMR flowmeters to control the consumption and condition of the coolant.

To measure the consumption q_c of the coolant in the developed design of the NMR flowmeter-relaxometer, we used two NMR signals with inversion (Figure 6) and without magnetization inversion (Figure 5).

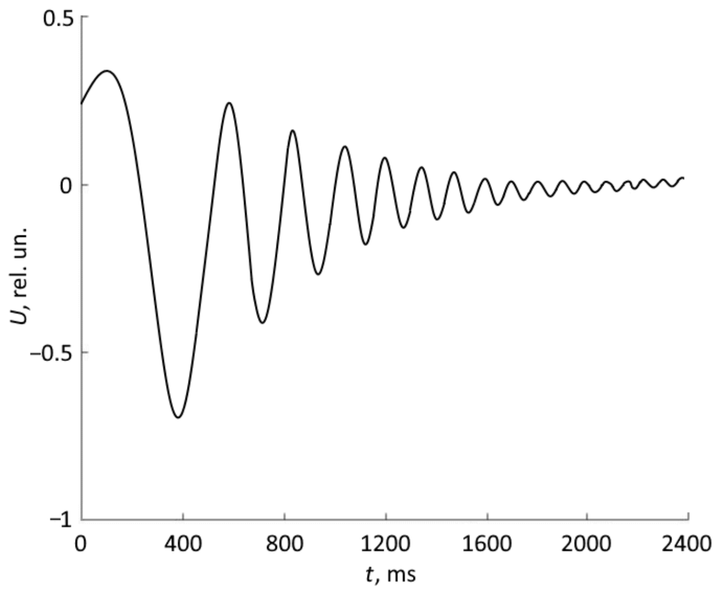

Figure 6. Dependence of the change in the amplitude U of the recorded NMR signal on time t with magnetization inversion at f_n = 246103 Hz and H_1 = 18.4 A/m.

Let us consider the principle of measuring the consumption q_c. The magnetization inversion in the coolant is formed in coil *3*. After a certain interval of time t_n, the magnetization inversion enters the registration coil *10*. The NMR signal with the magnetization inversion is recorded (Figure 6). After its registration, an impulse is generated in the control unit *12*. This pulse opens one of the keys of the system *13*. The sinusoidal voltage supply from generator *5* to the nutation coil *3* stops. The magnetization inversion in the coolants from this moment in coil *3* does not occur.

Further, this coolant without magnetization inversion enters the registration coil *10* after a while. After recording the NMR signal without magnetization inversion (Figure 5), a rectangular pulse is generated in block *12*, which closes one of the switches *13*. A sinusoidal voltage is supplied to the nutation coil *3* from generator *5*. In nutation coil *3*, an inversion of magnetization is formed in the current flow of the coolant.

In this case, information on the consumption q_c of the coolant is presented in the form of a rectangular pulse (meander), the period of which T_n is equal to twice the time t_n of the stream of the liquid medium from the nutation coil *3* to the registration coil *10* (Figure 3). In this case, the liquid consumption determines the next equation:

$$q_c = \frac{V_c}{t_n} = \frac{2V_c}{T_n}, \tag{7}$$

where V_c is the pipeline volume connecting section between nutation coil *3* and registration coil *10*.

In this case, the error in determining the coolant consumption Δq_c is determined by the stability of the operation levels of the comparators in the control circuit (this error is less than 0.3%). Moreover, on value Δq_c affects the error in determining the volume V_c (with all permissible errors in measuring the inner diameter of the pipeline and the distance between coils *3* and *10*, this error will be less than 0.5%). The pipeline degrades during the nuclear reactor operation (its internal diameter changes). It leads to changing the value of V_c and an increase in error Δq_c up to 1% or maybe slightly higher. We do not consider a more significant degradation of the pipeline since this will lead to a disruption of the technological cycle in the operation of a nuclear reactor and a sharp decrease in the power of the generated electrical energy.

4. Results

Figure 7 shows, as an example, the research results of an operating works of an NMR flowmeter-relaxometer design. We researched the change in the signal-to-noise ratio A_r of the recorded NMR signal as a function of the change in the coolant consumption q_c for different temperatures T.

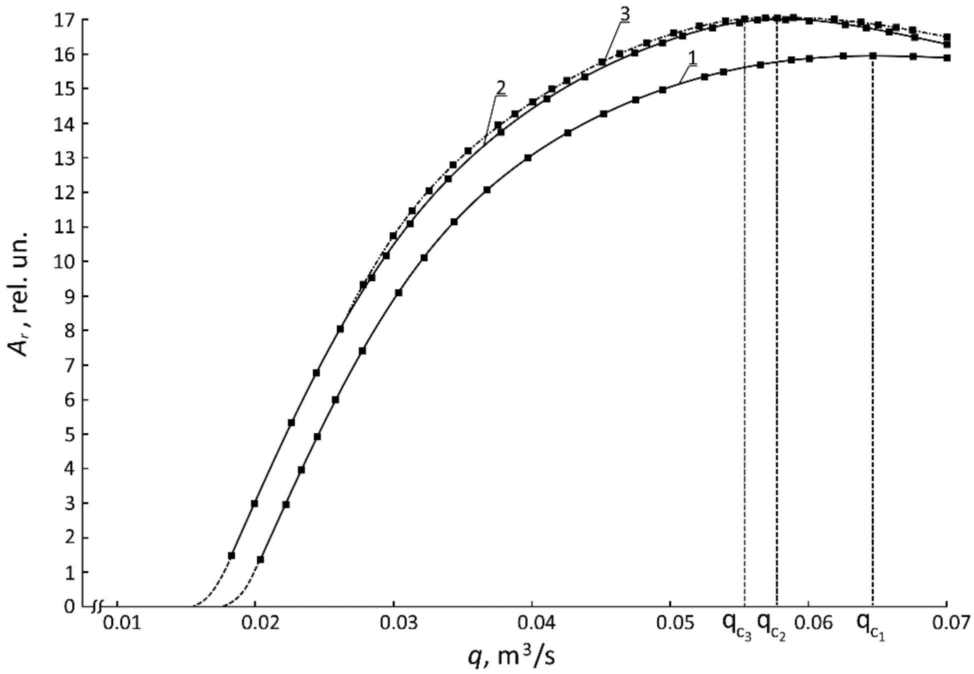

Figure 7. Dependence of the change of A_r on coolant consumption q_c. The graphs 1, 2, and 3 corresponds to the value of T in K: 303.2, 333.5, and 344.6.

It should be noted that as a research result, the values of the optimal coolant expenditures q_c (q_{c1} = 0.0648 $\pm$ 0.0006 m^3/s, q_{c2} = 0.0577 $\pm$ 0.0005 m^3/s, and q_{c3} = 0.0553 $\pm$ 0.0005 m^3/s) were obtained for various temperatures T. These values correspond to the maximum value of A_r of the registered NMR signal. The research at a coolant consumption of more than 0.07 m^3/s is not carried out due to the circular pump's attainment of the maximum power at the experimental stand. The results of q_c are compared with measuring the consumption performed using an electromagnetic flowmeter WATERFLUX 3050 (company KROHNE, Germany) to check the reliability of measuring the consumption with the device developed by us. The measurement error of the WATERFLUX 3050 at the initial stage of its operation is less than 1.0%. The results of comparing the measured consumptions with the two devices are presented in Table 2.

The relaxation times T_1 and T_2 of an aqueous solution (H_2O + H_3BO_3) with plutonium nitride filling for various temperatures T were measured using the design of the developed NMR flowmeter-relaxometer and compared with the results of measurements on an industrial NMR relaxometer Minispec mq 20 M (BRUKER, Germany). A comparison of the results obtained is presented in Table 3.

Table 2. Results of measuring the consumption q_c of an aqueous solution (H_2O + H_3BO_3) with plutonium nitride filling at a temperature of T = 333.5 K in the pipeline of the experimental stand by various devices.

Measurement Number	The Developed Device	Electromagnetic Flowmeter WATERFLUX 3050
1	0.0212 ± 0.0002 m^3/s	0.0211 ± 0.0002 m^3/s
2	0.0244 ± 0.0002 m^3/s	0.0243 ± 0.0002 m^3/s
3	0.0285 ± 0.0002 m^3/s	0.0286 ± 0.0002 m^3/s
4	0.0326 ± 0.0003 m^3/s	0.0327 ± 0.0003 m^3/s
5	0.0402 ± 0.0004 m^3/s	0.0401 ± 0.0004 m^3/s
6	0.0476 ± 0.0005 m^3/s	0.0477 ± 0.0005 m^3/s
7	0.0508 ± 0.0005 m^3/s	0.0510 ± 0.0005 m^3/s
8	0.0563 ± 0.0005 m^3/s	0.0565 ± 0.0005 m^3/s
9	0.0577 ± 0.0006 m^3/s	0.0579 ± 0.0006 m^3/s
10	0.0601 ± 0.0006 m^3/s	0.0603 ± 0.0006 m^3/s
11	0.0626 ± 0.0006 m^3/s	0.0629 ± 0.0006 m^3/s

Table 3. Results of measuring the relaxation times T_1 and T_2 of an aqueous solution (H_2O + H_3BO_3) with plutonium nitride filling at different temperatures T with two devices.

T, K	The Developed Device		Industrial NMR Relaxometer Minispec mq 20 M	
	T_1, s	T_2, s	T_1, s	T_2, s
288.1	1.0291 ± 0.0091	0.6551 ± 0.0062	1.0284 ± 0.0031	0.6536 ± 0.0018
293.2	1.0643 ± 0.0092	0.6614 ± 0.0063	1.0627 ± 0.0032	0.6585 ± 0.0018
303.2	1.1396 ± 0.0105	0.6755 ± 0.0064	1.1402 ± 0.0034	0.6731 ± 0.0019
317.6	1.2135 ± 0.0115	0.6846 ± 0.0066	1.2118 ± 0.0036	0.6824 ± 0.0020
323.2	1.2527 ± 0.0117	0.6946 ± 0.0067	1.2514 ± 0.0037	0.6951 ± 0.0021
333.5	1.3438 ± 0.0122	0.7164 ± 0.0069	1.3443 ± 0.0040	0.7143 ± 0.0021
338.6	1.3873 ± 0.0125	0.7308 ± 0.0071	1.3869 ± 0.0041	0.7284 ± 0.0022
343.4	1.4451 ± 0.0134	0.7465 ± 0.0073	1.4443 ± 0.0043	0.7474 ± 0.0022
348.2	1.6218 ± 0.0147	0.7669 ± 0.0075	1.6225 ± 0.0048	0.7646 ± 0.0023

Since our system's capabilities on an experimental stand with a circular pump and heating a liquid medium were limited to a temperature of 351.6 K, Table 3 presents data on the values of T_1 and T_2 measured at temperatures up to 348.2 K.

5. Discussion

The analysis of the results obtained in Figure 7 shows that with an increase in the coolant temperature T, the value of the optimal consumption q_c at which A_r is maximum decreases. This allows for an industrial device for nuclear power plants to obtain the maximum value of A_r at the optimal consumption q_c by changing the values of polarizer volumes V_p and connecting section of pipeline V_c, which corresponds to the stream rate of the coolant in the pipeline in the range from 25 to 30 cm/s. In this rate range lies the most efficient heat removal from the reactor rods and heat transfer between the primary and secondary circuits for various models of nuclear reactors. In all these cases, the consumption of q_c was measured with less than 1% error.

It should also be noted that the dependencies obtained in Figure 7 makes it possible to establish the following. In the design of the developed NMR flowmeter-relaxometer, in the case of a change in the consumption of q_c for various reasons (for example, a decrease in technological power), even by 40% of the optimal value, the signal-to-noise ratio A_r is 2–3 times higher than 3. This will make it possible to measure q_c with less than 1% measurement error. If the value of q_c is increased by more than 40%, the developed NMR flowmeter-relaxometer will also provide q_c measurements with an error of less than 1%. During the operation of nuclear power plants in the Russian Federation, this situation has arisen only once. It led to the decommissioning of the nuclear reactor for some time.

The declared error in measuring the coolant consumption of q_c is confirmed by the data presented in Table 2 (an industrial flowmeter with a measurement error not higher than that of the device we developed is used to compare the results). Measuring the consumption q_c by the two devices coincided with the measurement error.

Analysis of the obtained results of measurements of relaxation times T_1 and T_2, presented in Table 3, shows that they coincide within the measurement error. It should be noted that the error in measuring the relaxation times T_1 and T_2 in the industrial NMR relaxometer Minispec mq 20 M is 0.03%. This error is less than in the NMR flowmeter-relaxometer developed by us (the error in measuring relaxation times is 1% over the entire range of measured flow rates q). good agreement exists between the results because the registered NMR signal provides a resolution of more than five peaks, with a signal-to-noise ratio greater than 3.0. In pulse industrial NMR flowmeters-relaxometers, the measurement error of relaxation times is less than 1.5%. This fact once again confirms the validity of using our proposed methods for values measuring T_1 and T_2 in the developed design of an NMR flowmeter-relaxometer.

6. Conclusions

The data obtained as a result of the research show the high reliability of the proposed design of the NMR flowmeter-relaxometer for controlling the consumption and condition of the stream coolant. The presented research results and their detailed analysis with comparisons with other types of flowmeters (including pulsed NMR flowmeters) confirm the promising nature of the developed device design for solving problems of coolant parameters control in nuclear power plants.

In addition, the device developed by us, in which the pulsed technique is used to record the NMR signal, has several advantages over pulsed NMR flowmeters-relaxometers. Using the modulation technique in the device for measuring q, T_1, and T_2 (compared to the pulse technique) makes it possible to reduce the required length of the straight section of the pipeline in the NMR flowmeter-relaxometer from 80 m to 1.5 m. The linear dimensions of the developed device can be reduced at least 16 times, and its weight at least 12 times (compared to the NMR flowmeter-relaxometer, which uses a pulse technique for measuring q, T_1, and T_2). It should be noted that the nuclear-magnetic flowmeter-relaxometer developed by us is easier to maintain than the pulsed nuclear-magnetic flowmeter-relaxometer. The flow measurement range q with an error of about 1% in the device developed by us is at least three times greater than in a pulsed nuclear magnetic flowmeter-relaxometer.

The modulation technique for measuring q, T_1, and T_2 in a flowing liquid has a fundamental limitation. It is associated with the need to provide a magnetic field with an induction of at least 0.3 T in the zone of registration of the NMR signal with uniformity (no worse than 0.0025 cm^{-1}) with a diameter of the poles of the magnetic system of at least 0.5 m (this is necessary for measuring the coolant parameters). With the large diameters of the pipeline, it is extremely difficult to provide such parameters of the magnetic field and the magnetic system. In addition, in the case of a very high flow rate in the pipeline, the method proposed by us will also have limitations. The dimensions of the magnetic system for recording the NMR signal cannot be infinitely increased (pipeline expansion in the NMR signal recording zone is limited). This disadvantage can be eliminated if there are no strict restrictions on the size and weight of the measuring device (such situations are extremely rare).

It should be noted that, according to various estimates of scientists and specialists in NPP operation [4–6,14], constant monitoring of the coolant parameters (q_c, T_1 and T_2) with an error of less than 1.5% will increase the efficiency of electric power generation at the NPPs in operation by up to 1.5%, depending on the model. For example, the electric power of each power unit with a VVER-1200 type reactor at the Leningrad NPP (Russia) is 1198.8 MW (there are four such power units at the station). If we take 1%, then the electric capacity of the Leningrad NPP will increase by 47.95 MW. It is about 10% of the electric power generated at a modern thermal power plant, which emits too many harmful substances into the atmosphere. In addition to preserving fuel reserves on Earth for future generations, the ecological situation can be improved. The number of harmful emissions at NPPs will not increase with the commissioning of the developed NMR flowmeter-relaxometer.

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