An electrical method for intelligent cooling liquid control systems

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ABSTRACT
The ability to determine and control normalized concentrations is established in this study using experimentally obtained dependencies of the active and reactive constituents of conductivity in the wide frequency range of the electromagnetic field on the composition of the multicomponent fluid and the impurity concentrations. A method for controlling the qualitative and quantitative composition is developed for highly aqueous substances dissolved in water (cooling liquids). It is based on a comparison of the measured and experimentally established active conductivity component and a comparison of the corresponding dependencies in the frequency field of the reactive component of conductivity. The developed electric method allows the quantitative and qualitative estimation of the composition of the coolant on the contents of controlled components in a short time (up to two seconds) in a non-laboratory environment and to ensure the uninterrupted operation of the equipment.

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1. INTRODUCTION

Water mixtures are the most commonly used objects for measurement and control in industry, medicine, agriculture, and environmental monitoring. The standard control characteristics in these industries are concentrations – the mass of substances, per unit volume of the object of control. To objectively determine the concentration of the dissolved substance, the object should be uniform throughout the volume. Therefore, analytical control methods are based on studies of homogeneous liquids. In cases where the object of research is in a solid or loose state, its composition is extracted in a liquid for further long-term analytical manipulations in a laboratory. Another important requirement for a liquid under standard controls is a two-component system – with the content of the control substance and the unchanged composition of the solvent.

The implementation of standard analytical definitions (electrical, optical, and chemical methods) for the rapid and automated control of the composition of multicomponent liquids, such as real objects, is complicated by lengthy analysis or inaudibility. The scientific research conducted to improve the rapid control methods of the composition of dissolved substances in liquids during the course of technological processes and environmental monitoring is outlined in this article.

The standard conductometric method is designed for expressive studies for binary solutions of concentrations of substances that affect the conductivity of a liquid. This method allows to determine the concentration of a single controlled substance in a multicomponent fluid, using a single measured value of the specific conductivity at a predetermined in the laboratory frequency of the electromagnetic field. Investigation of the electrical properties of aqueous solutions as liquid dielectrics and an analysis of the components of complex electrical parameters at different frequencies of the electromagnetic signal deepens the theory of the study of the dependencies of the electrical properties of liquids on their composition. Attention to such research has intensified due to the improvement of experimental technology and the need to improve the methods of control of technological processes [1]. Hence, there is a danger of overheating the engine, which leads to its failure. The antifreeze resource directly depends on its composition (the brand of the manufacturer) and the mileage of automotive equipment. When exhaust gases, air or water

evaporates into the cooling system, its "aging" is particularly intense.

Such a coolant should be replaced urgently. The technical certification of cooling liquids in our country is optional, so the validity of antifreeze (a cooling liquid) is not regulated by state standards. Standard techniques for controlling their composition require routine laboratory work.

2. REVIEW OF THE CONCEPT

Known non-destructive methods for the study of liquids are based on the use of conductometry and aquametry. These two methods are applied to non-electrolytes (some substances of inorganic composition and mainly all organic composition) for non-selective generalized analysis. Only the immittance method, which actually contains both conductometric and dielectric methods, is theoretically capable of studying liquids of different chemical natures.

The conductometric method is based on the measurement of the electrical conductivity of the entire measuring system, which depends on the concentration of only those substances that affect the electric current (electrolytes). This method is applicable for dual component liquids only.

In the dielectric method (aquametry), according to which the informative parameter is electrical permeability, the generalization of this indicator makes it difficult to control the composition of multicomponent fluids. The complex electrical parameters of the immittance method would give more information about the composition of such liquids. Immittance spectroscopy is used to analyse semiconductive, dielectric, and ion-electronic materials as well as electrochemical systems. The specific physical mechanisms of the response of systems to the applied sine wave signal in different external physical fields are studied. The mechanisms of electrical and kinetic phenomena occurring under the given conditions are investigated as a result of the analysis of the immittance data [4]–[7].

The authors, having completed the theoretical analysis, have proposed the study of the composition of objects of a non-electric nature (liquids) employing the method of immittance spectroscopy. In other words, for the experimental studies, a physical-chemical study with elements of conductometry has been employed. Aquametry and immittance spectroscopy have been carried out using a capacitive primary transducer.

The novelty of the research conditions is the use of a new approach of dielectric properties of objects of a non-electric nature.

The authors do not describe in this work all the scientific facts that were obtained during the research and used in practice. The purpose of this article is to describe only some of the scientific results that illustrate the possibility of developing a new approach to immittance studies of objects of a non-electric nature – multicomponent liquids containing non-electrolytes.

3. RESULTS

An investigation of the electrical parameters of liquids in a frequency-tuned electromagnetic field allowed us to obtain information about their composition in non-laboratory conditions for a short period of time. Therefore, the development of advanced methods for the operational control of cooling liquids, which can be carried out in field conditions is of great interest. The method involves measuring the value of the component of the electrical conductivity of the controlled fluid
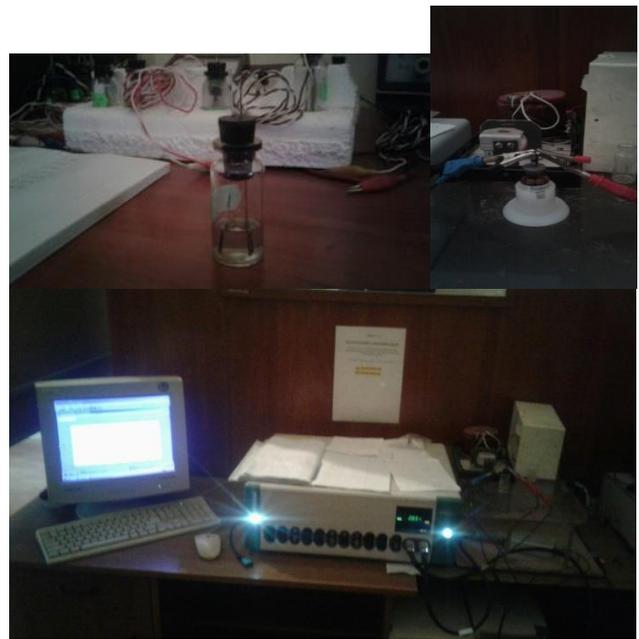
Figure 1. Primary transducer and experimental setup.

and comparing it with the corresponding values established in the laboratory by means of a simulation study.

The experimental measuring system consisted of a standard measuring device RLC-meter, a primary converter with capacity for the fluids studied, and a computer with software for processing the results of measurements (Figure 1).

The cell converter (sensor) consists of a specially graduated glass with a cover and permanently fixed immersed electrodes. The cell is placed on a grounded screen. For a sensor with carbon electrodes, the material obtained by high-temperature sintering of graphite powder designed for industrial galvanic baths is used. This technical solution provides the possibility of changing the volume of the test fluid (the amount of substance) located between the electrodes [2], [3].

As a result of the study of the immittance of model and real liquids with a composition of substances of different electrical natures (high and low), it is possible to identify the qualitative and quantitative composition by comparison with the experimentally determined normalized values of the active component with the established value of frequency. The methodology is based on the reaction of the features of the alcohol molecule of the homologous series, which is dissolved in water to the electrical properties of the mixture with its composition. As a result of the experiment, an algorithm for the method of operational control of the composition was established.

To determine the normalized parameters, a model sample study was performed. The - under laboratory conditions installed - value of the active component G_{norm} is determined at an arbitrarily selected frequency ν of the electromagnetic field, and the reactive component B_{norm} is measured at all possible frequencies. This value of the active component G_{norm} and the form of the plotted graphic dependence $B_{norm} = f(\nu)$ are the normalized control parameters. The algorithm for controlling the presence of dangerous high-resistance impurities in the liquid mixture contains measurements of the value of the active component G_m at the normalized signal frequency F_{norm}. The result of the comparison $G_m > G_{norm}$ and the absence of differences between the $B_{norm} = f(\nu)$ and $B_m = f(\nu)$ dependencies

indicate the presence of a toxic additive – methyl alcohol – in the solution. On the other hand, the result $G_m < G_{norm}$ and the absence of differences among the $B_{norm} = f(v)$ and $B_m = f(v)$ dependencies indicate the presence of butyl or propyl alcohol in the solution. The presence of differences in the comparison of $B_{norm} = f(v)$ and $B_m = f(v)$ imply the presence of inorganic impurities in the test mixture [8].

4. METHODS

The purpose of these studies is to develop an electrical method for the quantitative and qualitative analysis of the composition of cooling liquids. Dependencies of the reactive and active components of conductivity on the frequency of the electromagnetic field for the model liquids of a given composition have been studied. Using the experimentally obtained data, a method for the operational control of the composition and cooling liquids has been proposed.

The main results of the study are shown in Figure 1 and Figure 2.

Changes in the value of the reactive component are only due to the presence of the excessive water, causing higher values of the reactive conductivity than those established by industry standards (Figure 2). On the other hand, inhibitors lower the reactive component down to negative values.

The values of the active component of the object, as the function of the field frequency (Figure 3), indicate the presence of the poisonous ethylene glycol (if the value of the active component is in the range of min m.s. to max m.s.) or water (if the value of the active component is within the range of min m.s. to min e.s.).

The measured value of the reactive component indicates the presence of water (if the value of the reactive component is above row 1) or pollutants, for example, unauthorized inhibitors (if the value of the reactive component is in the range of row 1 to row 2).

The control methods vary depending on the chemical properties of the controlled substance (electrolytes or non-electrolytes) [9]–[15].

The developed methods for the operational control of the concentration of controlled substances in technical liquids and purified sewage water consist of two main stages: the study of control model – liquids with a boundary permissible concentration (BPC) of controlled substances carried out in
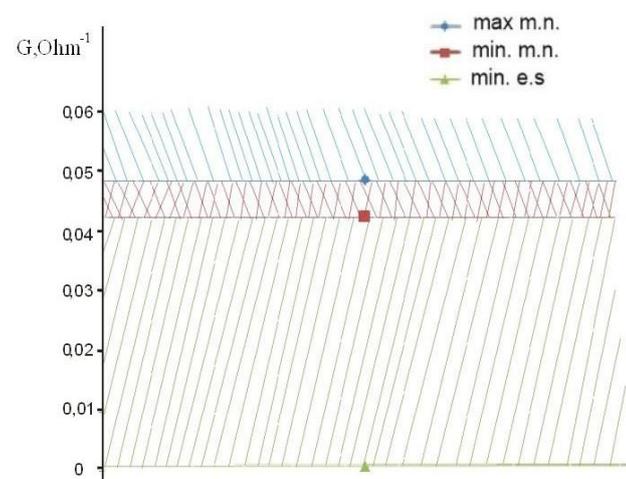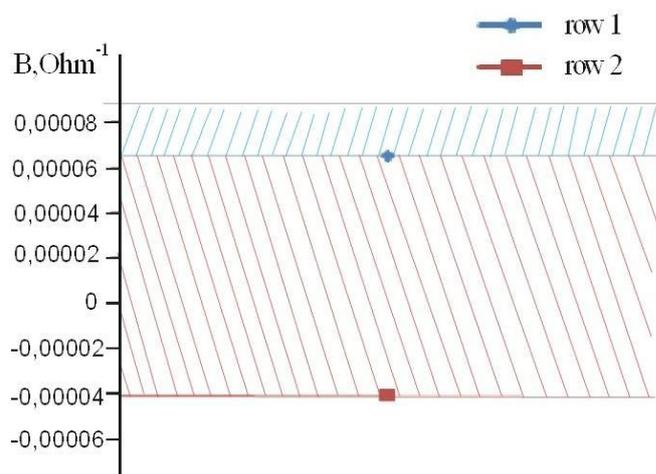
Figure 3. Dependence of the reactive conductivity components on the frequency of the electromagnetic field.

laboratory conditions – and the most operational control process for a real object (Figure 2).

In the first stage, a method for investigating liquids is used, where the dependencies of the active (reactive) conductivity component on the volume of the multicomponent fluid in the converter; the concentration of the controlled substance; the frequency of the electromagnetic field; and the concentrations of the matrix and temperature are applied. The second stage is the process of the operational control of normalized concentrations of controlled substances in a real object, determined in laboratory conditions (in stage 1) by the parameters, as described here:

Stage 1. Determination of control parameters: $G_{contr}(\Omega^{-1})$; $B_{contr}(\Omega^{-1})$; $F(Hz)$ by investigating $G = f(F)$; $B = f(F)$ ML (multicomponent liquids) with the control substance $C_{bpc}(g/l)$.

Stage 2. The process of the control of the BPC of non-electrolytes in a real object:

1. Measurement of $G_{contr}(\Omega^{-1})$; $B_{contr}(\Omega^{-1})$ by $F(Hz)$;

2. Conclusions drawn from the measurement data:

Comparison of $G \leq G_{contr}$, or $G \geq G_{contr}$, by B_{contr}:

$C \geq BPC$ or $C \leq BPC$ (depending on the chemical nature of the non-electrolyte).

Let us consider the method of calibration of the control channels of the electrical concentrators for the software and hardware monitoring of the equipment.

The method of determining the K (concentration) of a controlled substance in ML requires clarification of the value of the volume of the investigated ML. To estimate the uncertainty in determining the volume and the K of components, we constructed a mathematical model of the measuring cell. In the electrolytic cell, l is the distance between the electrodes; a and b are its height and width respectively and thus the geometrical dimensions of the electrodes; and a_1 is the height of the liquid part of the capacitor. These parameters form the volume of the investigated ML. The capacity of such an electrolytic cell, which consists of the air C_{x_1} and liquid C_{x_2} parts is defined as:

$$C_x = C_{x_1} + C_{x_2} = \varepsilon_n \varepsilon_0 \frac{(a - a_1)b}{l} + \varepsilon_p \varepsilon_0 \frac{a_1 b}{l}, \qquad (1)$$

where ε_n, ε_p is the dielectric constant of air and liquid solution and ε_0 is the dielectric constant of the vacuum.

In the mode of a given sinusoidal current for the converter, the expression for the output conductivity can be represented by the relation:

Figure 2. Dependence of the active conductivity components on the frequency of the electromagnetic field.

$$G_{\text{out}} = \frac{1}{Z_{\text{out}}} = j\omega\left(C_{x_1} + C_{x_2}\right) + \frac{1}{R_x} + \frac{1}{R_{\text{ic}}}, \qquad (2)$$

where R_x and R_{ic} are the active component of the resistance and the insulation resistance of the cell, respectively.

The mathematical dependence of the function of the transformation of the device (reactive and active constituents of conductivity) on the concentrations and parameters of the metering circuit is as follows:

$$N_G = k_A\, \omega\, \left(C_{x_1} + C_{x_2}\right)$$
$$= k_{Ab}\, \omega\, \varepsilon_0\, \frac{a\,b}{l}\left[\varepsilon_a\left(1 - \frac{a_1}{a}\right) + \varepsilon_l\frac{a_1}{a}\right], \qquad (3)$$
$$N_{Ga} = k_{Aa}\left(\frac{1}{R_x} + \frac{1}{R_{\text{ic}}}\right),$$

where c_{x_1} and c_{x_2} are the concentrations of the first and second substances of the liquid system, respectively; a, a_1, l, b are the known design parameters; k_A is the conversion factor of ADC; k_{Aa} and k_{Ab} are the conversion factors of the geometric parameters of the electrodes; ε_a and ε_l are the dielectric constants of the air and the liquid, respectively; R_x is the active component of the resistance; R_{ic} is the resistance of the cell's isolation; and ε_0 is the dielectric constant of the vacuum $\varepsilon_0 = 8,85 \cdot 10^{-12}$ *F/m*.

In general, the mathematical dependence of the transformation function of the reactive component of the digital immittance meter can be given in the form of

$$N_{G_b} = k_A\, \omega_i\, \varepsilon_0\, \frac{a_1 b}{l}\left[\varepsilon_a\left(\frac{a_1}{a} - 1\right) + (m_1 c_{x1} + m_2 c_{x2})\right] + \Delta_a, \qquad (4)$$

where N_{Gb} is the device display on the i-th frequency $\omega_i = 2\pi f_i$; m_1 and m_2 are the coefficients of transformation of the concentration of the test substance (hereinafter K) into the capacitive components for c_{x_1} and c_{x_2}, respectively; Δ_a is the additive component of the admittance meter, reduced to its output. In order to correct the additive component of the error of the measuring component of the reactive component, one measurement should be made in the absence of the electrodes of the test substance:

$$N_{G_0} = k_A\, \omega_i\, \varepsilon\, \frac{a_1\, b}{l}\, \varepsilon_a\left(\frac{a_1}{a} - 1\right) + \Delta_a, \qquad (5)$$

where ε is the dielectric constant of the investigated liquid.

From this point, the display of the device N_{G_i} should be adjusted by the value of the additive component N_{G_0}, and the value of N_G is thereby obtained:

$$N_G = N_{G_i} - N_{G_0} = k_A\, \omega_i\, \varepsilon\, \frac{a_1\, b}{l}\, (m_1 c_{x1} + m_2 c_{x2}). \qquad (6)$$

Taking into account the nonlinear relationship between the display of the device and the concentrations of the investigated substances, it is possible to calibrate any gauge of the admittance in the vicinity of the frequency of the polarity swap of the reactive component. For this purpose, in the vicinity of this frequency ω_0 of the polarity change of the reactive component, an admittance measurement is carried out for the case of n concentrations of control models of liquids, and the value of the frequency ω_{0n} is registered, according to which the value of the reactive component is measured:

$$N_{izn} = k_A\, \omega_{0n}\, \varepsilon_0\, \frac{a_1 b}{l}\, (m_{1zn} c_{1n} + m_{2zn} c_{2n}) = 0, \qquad (7)$$

where ω_{0n} is the value of the frequencies at which the meter of the reactive conductivity component has zero indications; c_{1n} and c_{2n} are the n-th concentration of the first and second controlled substances in the model sample, respectively; m_{1zn}, and m_{2zn} are the coefficients of the concentration of the test substance (hereinafter K) for the first and second substances into the reactive constituent of conductivity for K C_{1n} and C_{2n}, respectively.

From Equation (6), we calculate

$$\frac{m_{1zn}}{m_{2zn}} = -\frac{c_{2n}}{c_{1n}}. \qquad (8)$$

Then, in the vicinity of the values of frequencies ω_{0n}, the function of transforming the reactive component of the device can be written as follows:

$$N_{izn} = k_A\, \omega_i\, \varepsilon_0\, \frac{a_1\, b}{l}\, m_1\left(c_{x1} + \frac{m_2}{m_1}c_{x2}\right)$$
$$= k_A\, \omega_i\, \varepsilon_0\, \frac{a_1\, b}{l}\, m_1\left(c_{x1} - \frac{c_{1n}}{c_{2n}}c_{x2}\right). \qquad (9)$$

An analysis of Equation (9) enables a conclusion that the accuracy of the determination of K in the multicomponent substance (MS) is determined by the error of the preparation of the control models with the required K, the error in determining the geometric dimensions of the capacitive sensor, and the errors in the frequency measurement as well as the digital gauge of the reactive component of the impedance. For modern measuring instruments, the error may not exceed values from several tenths to 1 %, depending on the value of K and the frequency at which the research is carried out.

In order to improve the accuracy of the results of the analysis of the composition of liquids, both a method for planning a measuring experiment and an evaluation of the characteristics of the errors (uncertainty) of constructing linear grading characteristics are proposed. An electronic measuring unit can be made 'intelligent' by introducing a microprocessor into its structure. By the instrumentality of the corresponding microprogram support, the function of the electrochemical sensor can be expanded considerably in this case. This may enhance and enable the following features: the processing of data during the calibration (graduation) of ion-selective electrodes; the construction of calibration charts; and the memorization of the acquired calibration information. On the other hand, other features may also improve: automatic calculation according to the measurement of the difference in the potentials of ion concentrations taking into account both the actual temperature of the investigated solution as well as its dilution; the corrective supplements used and other side effects; fixing the date and time of measurement; the accumulation and formatting of data; the issuance of the acquired data in any of the user-specified units, not only on their digital display, but also to an external computer or to the communication network [16]–[18].

5. CONCLUSIONS

The results of studies using RLC-meters allow us to determine the dependence of electrical parameters of liquids in wide ranges of frequencies of the electromagnetic field on the chemical nature and concentrations of their components. The use of the established electrical parameters corresponding to the normalized concentrations of the components improves the informativity of conductometric studies of multicomponent liquids. This allows for the expansion of the list of controlled

substances of different electrical properties, increasing the selectivity, precision, and efficiency of analysis.

The introduction of an electrical method for the rapid determination of the characteristics of liquids will enhance the following issues: determining the required level of cleaning of technical liquids; predicting the quality of the return water of the enterprise in the future; and monitoring the normalized parameters of treated waste water for compliance with their normative documents related to production and specific categories of water use.

Descriptions of the experimental studies of the electrical acoustic properties of model liquids in an electromagnetic field of variable frequencies provide improvements such as:

1. Determining the concentration of a substance in a multicomponent fluid according to the measured values of admittance;
2. Controlling the maximum permissible concentration of the controlled substance in the multicomponent mixture according to the value determined by the measurement of the reactive component of the conductivity as well as to the value of the experimentally established frequency of the electromagnetic field.
3. Expanding the list of substances, the identification or concentration of which is controlled by the electric method.
4. Implementation of a new approach for the method of dielectric and conductometric measurement for the operational control of the composition of technical liquids, food products, medical products, and sewage characteristics.

On the basis of theoretical and practical research, the method of operational control of the composition of cooling liquids has been proposed based on the dependence of the value of the active and reactive components of the conductivity on the signal frequency. This method allows both the quantitative and qualitative evaluations of the composition of the liquid on the contents of the controlled components as well as the maintenance of the uninterrupted operation of the equipment in a small period of time (up to two seconds).

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