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Increasing the accuracy of measuring the physicochemical parameters of wastewater samples when implementing a new informative method

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ABSTRACT

Purpose: The necessity of developing new multi-parameter electromagnetic methods to obtain the information on controlled wastewater samples from fruit juice production has been proved. Based on the universal transformation functions $G = f(x)$ and $\varphi = f(x)$ obtained in the work, which relates the amplitude and phase components of the multi-parameter MFP signal with the parameters of wastewater samples, a three-parameter method for joint measurement control of the electrical conductivity χ, relative dielectric constant ε_r and temperature t of wastewater samples from the production of apple juice. An algorithm for joint multi-parameter measurements of the parameters χ, ε_r and t based on a transformer electromagnetic transducer (MFP) has been developed, the switching scheme provides for heating a wastewater sample during measurement control to simulate production conditions. Since the amplitude and phase components of the MFP multi-parameter signal depend on the temperature t, sample heating also makes it possible to create information redundancy and improve the accuracy of wastewater sample identification. The implementation of the proposed method makes it possible to indirectly determine the composition of wastewater samples, using only one transducer with known physical properties, all this leads to an increase in the accuracy of measuring the parameters of wastewater samples in comparison with reference methods and measuring instruments and ultimately allows choosing a promising method of wastewater treatment in accordance with the analysis of experimental data. The data obtained indicate the acidic composition of wastewater; therefore, it is proposed to neutralise industrial waste at the outlet of the finished product. The methodology of the above studies lies in the fact that, within the framework of a specific scientific approach, it is necessary to expand the functional and technical capabilities of the electromagnetic device by implementing a new multi-parameter electromagnetic method for joint measurements of the physicochemical parameters of wastewater samples.

Design/methodology/approach: The essence of the proposed three-parameter method of joint measurement control of parameters χ_t, ε_r and t is based on the analysis of the interaction of an external homogeneous magnetic field with the magnetic field of eddy currents induced in a conductive electrolytic liquid (in a wastewater sample). Based on the input of special normalised parameters, as well as the obtained universal transformation functions $G = f(x)$ and $\varphi = f(x)$, which relate the physicochemical parameters χ, ε_r and t of the electrolytic liquid medium (wastewater samples from apple juice production) with the amplitude and phase components of the multi-parameter signal MFP, at a constant frequency of the magnetic field f, the implementation of a three-parameter electromagnetic method of joint measurement control of the electrical conductivity χ, relative permittivity ε_r and temperature t have been proposed. At the same time, using the thermal MFP switching circuit, it is necessary to measure two magnetic fluxes: the reference magnetic flux F_0 in the absence of a glass tube with liquid in the converter and the magnetic flux F_2 (if there is a wastewater sample in the converter) and the phase angle φ between the flows F_0 and F_2. To this end, three wastewater parameters, χ_t, ε_r and t, are determined jointly by the same MFP in the same control zone. Implementing the proposed method makes it possible to indirectly assess the composition of wastewater, select a promising treatment method, and then take preventive measures related to environmental protection.

Findings: The possibility of applying the MFP operating theory to the realisation of an informative three-parameter electromagnetic method of joint measurements of specific conductivity χ, relative permittivity ε_r and temperature t parameters of wastewater has been studied. An algorithm for modelling the process of joint multi-parameter measurements of specific conductivity χ, relative permittivity ε_r and temperature t based on MFP has been developed. The basic relations describing a three-parameter method of joint measurements of specific conductivity χ, relative permittivity ε_r and temperature t of controlled wastewater samples are presented. The obtained numerical values of the physicochemical parameters of the wastewater sample are in good agreement with the data obtained using the controlling methods. Implementation of the proposed three-parameter method allows to increase in the accuracy of identification of wastewater samples due to the obtained multi-parameter information, as well as to determine indirectly the composition of wastewater samples, using a single transducer with certain physical properties; all this leads to increased accuracy of wastewater sample parameters in comparison with the reference methods and measuring tools, and allows to choose a rational and inexpensive treatment method.

Research limitations/implications: The method studied has the following limitations: the range of variation of the diameters is 20 mm to 55 mm. The lower limit is set by the frequency of the electromagnetic field, and the upper limit by the diameter of the transducer frame, 57 mm. Measurements are made in homogeneous longitudinal magnetic fields, and the length of the MFP winding must be ten times the diameter to achieve such field homogeneity. The sample length must be greater than or equal to the winding length of the transducer, i.e., $lo \geqslant ln$. The radial misalignment of the product does not affect the measurement results, as the magnetic field of the transducer is homogeneous. The MFP frame limits product misalignment. It is found that sample misalignment in the range of ±4% to 6% has no practical effect on the measurement results of physicochemical parameters of wastewater samples. The change in temperature causes a change in the resistance r of the magnetising winding, so the windings of the converter must be thermally insulated from the environment (wrapped with mitre tape, coated with BF-19 adhesive and then this structure is baked at the temperature t = 300°C in the EKPS-500 muffle furnace).

Practical implications: The practical significance of the work lies in the fact that as a result of the analysis of the obtained values of the physicochemical parameters of wastewater samples, it is possible to timely prevent the reasons for the deviation of wastewater from the specified indicators of international standards governing the discharge of wastewater into the city sewerage and to take measures to prevent pollution of artificial and natural reservoirs located in the residential areas, as well as to develop effective methods of wastewater treatment of food and processing industries. The obtained relations, which describe the universal transformation functions $G = f(x)$ and $\varphi = f(x)$, algorithms for measuring and calculating operations for determining the specific electrical conductivity χ, relative permittivity ε_r and temperature t of wastewater samples based on MFP, make it possible to design, construct and create automated measuring installations based on intelligent devices that have a phenomenological approach to the measuring control of physical and chemical parameters of electrolytic liquid media as the basis of their operating theory.

Originality/value: The electromagnetic transducer (EMT) theory has been further developed with a sample of a weak electrolytic liquid with an acidic composition (a sample of wastewater from apple juice production).

Keywords: Non-contact eddy current method, Three-parameter informative method, Physicochemical parameters of wastewater, Wastewater sample, Eddy current transducer

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CLEANER PRODUCTION AND BIOTECHNOLOGY

1. Introduction

Currently, the wide range of clarified juices, juices with pulp and nectars, is due to the needs of the modern market and significant consumer demand [1]. Due to the popularity of fruit juices, mini plants (as well as lines) for producing fruit juices are becoming increasingly widespread. Wastewater generated during the fruit juice production of depends on manufacturing technologies (related to raw material preparation: cleaning, washing, primary heat treatment of vegetable raw materials), and also on the composition of raw material washing water, and washing water of equipment (pasteurisers and centrifuges) [2-6]. Wastewater from juice and nectar production processes is usually acidic and less often alkaline (due to rinsing water from detergents, disinfectants, etc.) [6-9]. Wastewater also contains organic contaminants and dilute solutions containing carbohydrates and proteins of plant origin. As a result of the decomposition process of carbohydrates and proteins, some of the pollutants decompose into weak carboxylic acids (oily, lactic, oleic, acetic, benzoic, etc.); in turn, the discharge of residual raw materials also causes decomposition and reduces the pH of natural and artificial ponds when entering untreated or improperly treated wastewater from sewers, resulting in the output of the technological process, wastewater, which has an acidic composition [8,9].

It should be noted that polluted wastewater from the production of juices and nectars, when it enters water bodies, causes a reduction in the amount of dissolved oxygen due to its consumption for the oxidation of organic acids that enter the water body. At the same time, the pollutants contained in wastewater, which contribute to the creation of an acidic environment, enter artificial and natural water bodies and, as a result of their accumulation in the soil, can quickly decompose and worsen the sanitary condition of the environment. In turn, wastewater containing detergents and disinfectants creates alkaline pollution, which also affects fish, birds and other flora and fauna, sometimes leading to the death of the entire ecosystem. In addition, the deterioration of water quality caused by the discharge of heated sewage water leads to a sharp decrease in oxygen solubility in both artificial and natural waters, i.e., eutrophication occurs as a result of such anthropogenic impacts [10].

At present, the problems of climate variability and the disruption of the sustainability of ecosystems bring to the fore the challenges of sustainable development of food production enterprises and mini factories located in urban areas and large megacities so that the tasks of sustainable development of production must include a series of measures against pollution by specific enterprises of entire residential areas. All this implies the efficient use of energy and water resources and, within the framework of the prevention of negative consequences, the development and improvement of measurement methods and equipment for their implementation to increase the accuracy of measurements of wastewater samples, allowing to determine the composition of wastewater from food and processing industries and to choose a rational treatment method [9,10].

Thus, when choosing the methods of treatment at the enterprises of the processing industry, it is necessary to take into account peculiarities of wastewater, which are caused by: production technologies, methods of wastewater treatment, as well as technical capabilities of informative methods for monitoring the standard characteristics of wastewater: specific electrical conductivity χ, relative permittivity ε_r, density ρ, temperature t, pH value, hardness dGH, salt content TDS values (total mineralisation). Since the acidic composition of wastewater from fruit juice mini-factories hurts the environment and also leads to the failure of the corresponding treatment devices, in order to choose treatment methods in further prospective studies, it is necessary to implement new informative methods for joint measurements of electrical conductivity χ, relative permittivity εr, temperature t and other characteristics of controlled electrolytic liquid media correlating with these physicochemical parameters: RTD, dGH and pH.

Modern methods of determining wastewater parameters do not provide the necessary accuracy and require several measuring devices to determine the state of wastewater [11-18]: conductometers, AC bridges, pH meters, RTD meters, t and hermometers), with the need for only one primary transducer – electromagnetic transducer, through which information redundancy is created. And then, based on the theory of indirect and aggregate measurements, can determine several characteristics of samples. The main advantages of these methods are contactless, simplicity of universal conversion functions and schematic implementations, high reliability and sensitivity, and the possibility of automation of the measurement process – all this contributes to the further development of electromagnetic methods and devices in the direction of measurement of many physical and chemical parameters of wastewater of food and processing industries.

As a result, the range of the set tasks is considerably extended. It becomes more complicated, forming an important scientific and practical problem connected with the creation of new informative methods of joint multiparameter measurements of normative parameters of electrolytic liquid samples (wastewater of food and processing production) with the purpose of further choice of cheap rational methods of wastewater treatment of mini-factories and juice production lines located in residential areas. The topicality of the subject and the research problem consists in increasing the accuracy of measurements of parameters of wastewater samples of mini-factories and fruit juice production lines by creating new multi-parameter informative methods of joint measurements of normative indices mentioned in international standards. Within the framework of solving this problem, the new multiparameter electromagnetic method of joint measurements of specific conductivity χ, relative permittivity ε_r and temperature t of apple juice production wastewater is proposed. As a result of the implementation of the three-parameter electro-magnetic method, it is possible to increase the accuracy of measurements of parameters of wastewater samples with acidic composition and to choose a rational and inexpensive method of wastewater treatment from apple juice production. The originality of the investigated informative method consists in the fact that the theory of the operation of the thermal transformer electromagnetic converter (MFP) with the sampling of a weak electrolytic liquid, which has an acidic composition (a sample of wastewater from apple juice production), has been further developed.

2. Literature review

At present, conductometric methods [11,12], potentiometric methods [12,13], coulometric methods [14,15], photoelectric methods [16,17] and methods based on electrical impedance [18-20] are widely used in modern technical literature. It should be noted that in the development of conductivity meters [11,12], a number of factors influencing the measurement error of conductivity χ have to be considered: the temperature dependence of specific electrical conductivity χ, the cell capacitance of the connecting wires C_0 as well as polarisation phenomena at the electrode-solution interface. At the same time, the approximate range of variation of the specific conductivity χ of wastewater from the food industry [$7 \cdot 10^{-8}$ - 80 cm/m] leads either to the need for several measuring devices or to a significant complication of the entire measuring setup [12,13]. Other disadvantages include a lengthy process of preparing liquid samples, the need for standard samples, standard solutions and passport calibration dependencies, and the lack of theoretical and experimental methods for their realisation, which result in obtaining absolute values of the electrode potential [14].

Potentiometric methods are also used to control the regulatory parameters of wastewater from processing and food industries: direct potentiometry and potentiometric titration [12,13]. The implementation of direct potentiometric methods consists in determining the concentration of ions in wastewater solutions by means of the electrode potential. In the implementation of potentiometric titration methods with a known amount of titrant, the concentration C and electrical conductivity χ of the wastewater sample are determined by applying the second derivative of the potential by the amount of titrant, which is a conversion function in modern automated measuring systems [12,13]. The work [12] is devoted to the development of a potentiometric method with a concentration cell equipped with applications that allow simplifying and accelerating measurements of physical and chemical parameters of the liquid medium under investigation. It should be noted that the implementation of potentiometric titration methods does not change the composition of the test sample, so that the solution can still be used for its intended purpose. In [13], the application of active potentiometry in a salt solution with phosphate buffer at different pH values is described. A common disadvantage of potentiometric titration methods, from the point of view of measuring control of parameters of wastewater from food production, is the impossibility of using this method for continuous control of electrolytic liquids and the difficulty of determining too low concentrations in research solutions, for example, wastewater from apple juice production. The implementation of coulometric methods for the determination of normative parameters of wastewater from the processing and food industries is based on the laws of electrolysis [14,15]. In addition to direct coulometric methods, coulometric titration is the most commonly used method [14,15]. The presence of the analyte is determined by the amount of electricity used to generate the amount of titrant υ required to react with the analyte [14,15]. In [15] the method of determining the parameters of carbonic acid H_2CO_3 and phthalic acid $C_8H_6O_4$ was studied on the basis of the proposed theoretical curve of coulometric titration. The influence of CO_2 in the system was studied, and acid dissociation constants were obtained. The general disadvantages of coulometric methods include the difficulty of finding the equivalence point and the endpoint of the titration, all of which explain the need to use additional potentiometric and optical methods [16].

The work [16] is devoted to the investigation of the photovoltaic model in the context of the optimisation of the turbulent flow of water. The results show the closeness of the calculated power-voltage and volt-ampere response curves when compared with experimental data as well as with competing optimisation algorithms. In [17], a photoelectric multi-parameter transducer is provided for measuring milk flow parameters based on the measurement of milk flow intensity F, electrical resistivity λ and temperature t. A common disadvantage of the works [16,17] is the instability of the technical characteristics of photoelectric transducers and the influence of interfering factors on the measurement results, for the compensation of which additional measuring devices are required.

There are also known works [19,20] devoted to research and development of methods for the determination of electrical conductivity χ and relative permittivity ε_r of aqueous electrolyte solutions on the basis of electrical impedance. In the paper [19], the change of the test signal frequency *Δf* at reaching the extremum of the reactive component of the voltage *E* of the sample is used as an informative parameter of the aqueous solution sample, controlled by a measuring device. Limitations of the methods studied in the works [19,20] should be referred to difficulties arising in the control of parameters of electrolytic liquids of different chemical compositions.

Electromagnetic methods and transducers are now widely used in many areas of science and industry. In particular, they are used for the detection of surface and deep defects in metal products and structures, for the control of the thickness of coatings (metallic and dielectric), for the non-contact determination of magnetic, electrical and geometrical parameters of parts, as well as strength, hardness, presence of dominant impurities in materials, distortion of the product structure due to the effects of various types of treatment (mechanical, thermal and chemical) on the structure [21-23]. At the same time, electromagnetic methods and devices were practically not used to determine the informative parameters of electrolytic liquids due to the complex nature of the dependence of electromagnetic transducer signals on the electrical and temperature parameters of electrolytic liquid samples [24-27].

In [24-27], modern multi-parameter electromagnetic methods of measuring specific conductivity χ and temperature parameters *t* of electrolytic liquid media based on inductive parametric electromagnetic transducers are considered. In this case, the simplest parametric transducer is an inductance coil [24-27]. The sensing of the controlled object by the magnetic field ultimately leads to a change in the electrical parameters of the coil (resistance r and winding inductance *L*) and, as a result, to a change in the current *I*, which is registered by measuring circuits [24-27]. The common disadvantage of electromagnetic methods of measurement control of parameters of liquid media, the implementation of which is based on parametric transducers, is that the operation of such a transducer has a significant influence on external factors, such as temperature *t*. Variation of temperature essentially affects the active resistance of coil *r*, which leads to a variation of current *I* and magnetic flux *F* and, consequently, to the significant errors of measurement of normative parameters of liquid media.

In [18], the electrical conductivity of dimethyl sulfoxide (DMSO) + KI solutions were determined based on the implementation of the impedance spectroscopy method. The method is very complicated, and the value of the specific electrical conductivity χ of the solutions has to be recalculated, knowing the limiting χ_0 and equivalent values of the electrical conductivity χ_g. In addition, for multi-parameter methods to determine the electrical conductivity χ, temperature *t* and concentration *C* when estimating the errors of the measurement result in [18], it would be advisable to investigate the systematic errors of indirect measurements of the function of many variables that relates the signal components of the primary transducer with the characteristics of samples of controlled liquid media.

Electromagnetic measurement methods based on a transformer eddy current transducer (TECT), compared with conductometric and impedance methods, have a number of advantages; first of all, the possibility of joint measurements of a number of parameters to identify the test object, the simplicity of conversion functions and circuit implementations, high reliability and sensitivity, fast data processing when connected to information processing facilities, relatively small values of measurement errors [15,16]. When measuring various characteristics of samples of weak electrolytic liquids, several measuring devices are used (conductivity meters, AC bridges, pH meters, TDS meters, thermometers). At the same time, it becomes necessary to use only one primary transducer – an electromagnetic (eddy current) transducer, with the help of which information redundancy is created. Then, based on the theory of indirect and cumulative measurements, it is possible to determine several characteristics of samples of liquid media simultaneously. As a rule, the information signal of an electromagnetic transducer is an alternating current signal, the components of which include the magnetic flux amplitude, ϕ the phase angle of the shift between the (reference) magnetic flux and the normalised informative one, as well as the frequency of the magnetic field f, which probes the sample of the controlled liquid medium under study, while the metrological characteristics of the primary eddy current transducer determine the metrological characteristics of the entire automated system for measuring the physicochemical parameters of liquid media [17-20].

Electromagnetic measurement methods based on electromagnetic transformers (MFP) have a number of advantages in comparison with the methods considered above; first of all, it is the possibility of joint measurements of a number of parameters for identification of the control object, simplicity of conversion functions and schematic implementations, high reliability and sensitivity, fast data processing when connected to information processing tools, relatively small values of measurement errors.

It should be noted that in practice, the main task of the study of theoretical bases of new informative methods of measurement of parameters of wastewater samples is the choice of universal and economically feasible methods and technological schemes of treatment. The following types of wastewater treatment are used in food and processing industries [28-32]: 1) Preliminary mechanical treatment, during which contaminants are retained on screens and filters and primary sedimentation takes place [28]; 2) Biological treatment [29,30], particularly on modern biological treatment processes. In [29], a wastewater treatment scenario for a field hospital is considered. Compared to domestic wastewater, hospital wastewater is much more dangerous as it contains a wide range of toxic substances (antibiotics, radionuclides, spent analysis, pharmaceutical dyes, etc.). The wastewater pathways into the environment (soil and open water) are considered. A review of wastewater treatment methods has been carried out. Based on the analysis of existing treatment methods, a combined treatment method involving a combination of microbiological reactor technology and the Fenton process is recommended. This reduces the cost, reactor size and number of reagents required for treatment. However, this article does not deal with methods for determining the normative parameters of hospital wastewater, and the authors of the paper use experimental and computational data obtained in other articles.

In [30], an improved device for removing organic matter from wastewater and recovering bioelectricity based on a microbial fuel cell (MFC) was developed. It is shown that the power generation of the MFC can be improved by using a cathodic catalyst to overcome the sluggish oxygen reduction reaction (ARR) at the carbon electrodes. A limitation of this method is that bioremediation systems require sophisticated electronics to function properly. All this makes it difficult to use biochemical wastewater treatment methods for mini-mills and juice production lines installed in supermarkets and cafes. A common disadvantage of biological treatment methods is the increased technogenic load on the environment due to the large volumes of sludge produced. 3) Physicochemical treatment, including neutralisation of the wastewater and dosing of reagents. Currently, a promising direction and alternative to biological wastewater treatment is aqueous phase reforming, which consists of the catalytic conversion of aqueous solutions of carbohydrates and alcohols – the main products of animal, plant and domestic biomass processing – into hydrogen and elementary alkanes. The paper [31] analyses the application of aqueous phase reforming as a method for the purification, utilisation and valorisation of fruit juice wastewater, allowing the production of H_2 and alkanes from renewable sources. Limitations of the method are the use of special process equipment and an expensive catalyst (3% Pt/C). In [32], a method for treating fruit juice concentrate wastewater based on coagulation was investigated. As a result of studying the COD range, optimum conditions for purification and decolourisation were obtained using an Al(+)/Fe(-) electrode pair, cell current I = 0.8 A and pH = 5.5 for a time period T = 10 min. Limitations of the method are that its implementation does not consider the consequences of contamination of the interelectrode space by flake sediments, which leads to a reduction in the performance and durability of the device, as well as the generation of non-recyclable waste.

In order to choose a promising method of wastewater treatment for apple juice production, the application of the theory of operation of a transformer-type electromagnetic converter (MFP) to the measurement control of the specific electrical conductivity χ, relative permittivity ε_r and temperature t of wastewater samples are studied in this paper.

3. Aim and objectives of the research

The work aims to study a multi-parameter eddy current method for joint measurements of specific electrical conductivity χ, relative permittivity ε_r and temperature t of wastewater parameters of apple juice production.

To achieve the goal, it is necessary to solve the following tasks:

- to explore the possibility of applying the theory of TECT operation about implementing an informative three-parameter eddy current method of joint measurements of electrical conductivity χ, relative permittivity ε_r and temperature t of wastewater for apple juice production.
- to develop an algorithm for modelling the process of joint multi-parameter measurements of electrical conductivity χ, relative permittivity ε_r and temperature t based on TECT.
- to give the main ratios describing the three-parameter method of joint measurements of electrical conductivity χ, relative permittivity ε_r and temperature t of controlled wastewater samples.

3.1. Approach

The essence of the proposed three-parameter method of joint measurement control of the parameters χ_t, ε_r, t is based on the analysis of the interaction of the external homogeneous magnetic field with the magnetic field of eddy currents induced in the conducting electrolytic liquid (in the wastewater sample). On the basis of input of special normalised parameters as well as received universal conversion functions $G = f(x)$ and $\varphi = f(x)$, which relate physicochemical parameters χ, ε_r and t of the electrolytic liquid medium (the wastewater sample of apple juice production) to amplitude and phase components of the multi-parameter MFP signal at a constant frequency of the magnetic field f. Implementing a three-parameter electromagnetic method for joint measurement control of specific conductivity χ, relative permittivity ε_r and temperature t has been proposed. In this case, using the thermal MFP inclusion circuit, it is necessary to measure two magnetic fluxes: the reference magnetic flux F_0 in the absence of a glass tube with liquid in the converter and the magnetic flux F_2 (in the presence of a wastewater sample in the converter) and the phase angle φ between the fluxes F_0 and F_2, after which three parameters of the wastewater χ_t, ε_r and t are determined together by the same MFP and in the same control zone. The implementation of the proposed method makes it possible to evaluate indirectly the composition of the wastewater, choose a promising treatment method and then carry out preventive measures related to the protection of the environment.

3.2. Limits of analysis

The test method has the following limits: the range of variation of the diameters is 20 mm to 55 mm. The frequency of the electromagnetic field sets the lower limit, and the upper limit is set by the diameter of the transducer cage, 57 mm. Measurements are made in homogeneous longitudinal magnetic fields, and to achieve such a homogeneous field, the length of the transducer winding must be 10 times the diameter. The sample length must be greater than or equal to the winding length of the transducer, i.e. $lo \geqslant ln$. The radial misalignment of the product does not affect the measurement results, as the magnetic field of the transducer is homogeneous. The MFP frame limits product misalignment. It is found that sample misalignment in the range of ±4% to 6% has no practical effect on the measurement results of physicochemical parameters of wastewater samples. The change in temperature causes a change in the resistance r of the magnetising winding, so the windings of the converter must be thermally insulated from the environment (wrapped with mitre tape, coated with BF-19 adhesive and then this structure is baked at the temperature t = 300°C in the EKPS-500 muffle furnace).

3.3. Practical implications

The practical significance of the work lies in the fact that, as a result of the analysis of the obtained values of the physicochemical parameters of the wastewater samples, it is possible to prevent the causes of the wastewater deviation from the specified indicators of the international standards governing the discharge of wastewater into the municipal sewerage system, to take measures to prevent the pollution of the artificial and natural waters located in the areas of settlements, as well as to develop effective methods of treating the wastewater of the food and processing industries. The obtained relations describing universal functions of transformation $G = f(x)$ and $\varphi = f(x)$, algorithms of measurement and calculation operations for the determination of specific conductivity χ, relative permittivity ε_r and temperature t of wastewater samples based on MFP allow to design, construct and create automated measuring installations based on intelligent devices having a phenomenological approach to measurement control of physical and chemical parameters in their operation theory.

3.4. The prospects for further research

The prospects for further research are related to the increase of the accuracy of joint measurements of normative parameters of wastewater samples based on the statistical robustness of the measured characteristics of wastewater samples from food and processing industries. The development of measurement methodology and the improvement of mathematical data representation methods, as well as the development of promising measurement algorithms and computational procedures in implementing multi-parameter electromagnetic methods, are connected with the need to expand research into methods of processing measurement results. The determination of errors of multi-parameter measurements of wastewater parameters allows to establish rational modes of operation of measuring equipment, to increase the accuracy of measurements of physical and chemical parameters of electrolytic liquids and then, based on the obtained experimental data, significantly increase the efficiency of the treatment process, to choose a rational method of wastewater sample treatment.

3.5. Materials and equipment under study used in the experiment

A wastewater sample from apple juice production was studied using a thermal transformer electromagnetic transducer (MFP). Geometric parameters of the wastewater sample: glass tube radius a=55·10^{-3}m, sample tube length l=0.45m, magnetic constant $\mu_0 = 4\pi \cdot 10^{-7}$ Gn/m; temperature coefficient of resistance (TCR) for α =1,89·10^{-2} 1/°C; temperature measurement range of the wastewater sample t = [12....33°C]. MFP parameters: number of turns of measuring and magnetising windings W_1 = 600 and W_2 =1200; value of magnetising current I = 37.11 mA; frequency of electromagnetic field f = 18 MHz; MFP EMF without the sample E_0 = 305.20мV.

4. Implementation of an informative three-parameter electromagnetic method of joint measurements of physicochemical parameters of wastewater samples

As noted above, in this case, it is proposed to use TECT using a longitudinal magnetic field, on the basis of which a non-contact three-parameter eddy current method is implemented for joint measurements of electrical conductivity χ, relative permittivity ε_r, and temperature t of wastewater from apple juice production. It should be noted that with the help of TECT, we simulate the heating of wastewater samples in the juice production process, due to a specially provided heating device - HD in a thermal TECT, which in turn allows us to control the parameters of semi-finished fruit juices in the production process and heated wastewater, which are mostly acidic.

Figure 1, considering the results of works [15-18], shows the switching scheme on the TECT for measuring the physicochemical parameters of wastewater samples. The circuit contains a recorder with a stroboscopic device *C*, a generator *G* of sinusoidal signals, a frequency counter *Fc*, voltmeters V_1, V_2, V_3, a phase meter *F*, a working converter WC and a reference converter RC, an oscilloscope *Os*, a sample *S*. The primary windings of WC and RC are connected in series-accordingly, and secondary windings of WC and RC are connected to voltmeters V_2, V_3 and phase meter *F*. Voltmeter V_2 measures the total EMF of the measuring winding of TECT. The V_3 voltmeter registers EMF MFP without the sample in RC (in this case the RP and RP are two identical converters).

The phase meter F measures the angle ϕ_0 between E_0 and E_Σ. EMF E_Σ is the vector sum of EMF $\dot{E}_2$ and $\dot{E}_1$, i.e.:

$$\dot{E}_\Sigma = \dot{E}_2 + \dot{E}_1, \qquad (1)$$

where $\dot{E}_2$ is the EMF due to the passage of the probing sample, the magnetic flux F_2, EMF $\dot{E}_1$ is the part of the total EMF due to the passage of the magnetic flux F_1 in the air gap between the sample and the measuring winding of the TECT. The diagram includes a heater- H to change the temperature of the wastewater sample to be monitored. During the operation of the MFP circuit in Figure 1, a self-recording unit *C* with a stroboscopic device is used to monitor the shape of the magnetising current and the AC source voltage *D*. The frequency of this current change is recorded by a frequency meter *C*, and the current value is determined by an ammeter *A*. The thermal MFP combines three functions: creating a magnetic flux in the sample to be heated, measuring the EMF and its phase at the ends of the secondary winding and heating the sample with the heater – *H*. The voltage meter B_1 determines the total EMF of the thermal MFP E_Σ, which also depends on the temperature. In contrast, the shape of this EMF is determined simultaneously with the oscilloscope *Os*. The RP has the same number of turns, length, *l* and radius a_n. The output signal of the voltmeter B_2 is connected to an input of the phase meter *F*. The input of the MFP is connected to another input of the phase-shift meter, and the measured signals of the MFP also depend on the temperature.

The phase meter *F* determines the temperature-dependent phase shift angle φ between the total EMF of the thermal MFP $E_{\Sigma t}$ and the EMF E_0 of the MFP without sample. The circuit also uses a heater – *H*, with the wastewater sample monitored inside *H*.

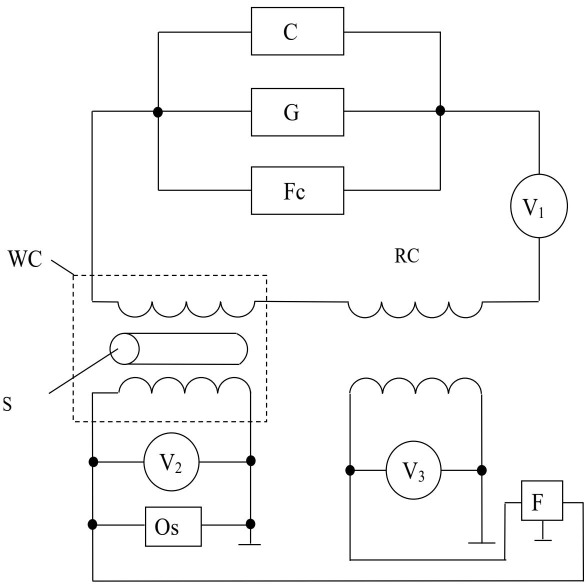

Fig. 1. Scheme of TECT for the implementation of an informative three-parameter electromagnetic method of joint measurements of electrical conductivity χ, relative permittivity ε_r and temperature *t* of a wastewater sample

The operation of a three-parameter TECT with controlled wastewater samples is based on a system of equations:

$$\begin{cases} G = F_1(\text{d,x}) \\ x = F_2(\text{d},\chi) \\ \lambda = F_3(\text{d},\varepsilon_r,\text{t}) \end{cases}, \qquad (2)$$

where *G* is the normalised amplitude component of the TECT signal; F_1, F_2 and F_3 are the designations of the functional dependencies of the universal conversion functions that connect the TECT signals with the parameters of the controlled liquid medium, *d* is the diameter of the glass tube with the wastewater sample; x_t is the generalised magnetic parameter at specific temperatures from the range under study *t* = [12….33°C]; χ is the specific electrical conductivity of wastewater samples; ε_r is the relative permittivity of the sample; *t* is the sample temperature.

The generalised magnetic parameter x_t at different temperatures *t* of the investigated sample of the liquid medium is determined by the formula:

$$x_t = d\sqrt{\mu_0 \cdot \chi_t \cdot \omega}\,, \qquad (3)$$

where μ_0 is vacuum magnetic permeability, μ_0 = 4π·10^{-7} H/m; ω is the cyclic frequency; index *t* indicates that the value under study is temperature dependent.

Thus, with the known values of the electrical and magnetic constants, as well as the geometrical parameters of the TECT and the wastewater sample, the expressions connecting the signal components of the three-parameter TECT and the physicochemical characteristics of the wastewater samples have the following form:

$$G_t = \frac{\Phi_{2t} \cdot a_n^2}{\Phi_0 \cdot a^2} = \frac{2 \cdot a_n^2}{x_t \cdot a^2} \sqrt{\frac{ber_1^2 x + bei_1^2 x}{ber_0^2 x + bei_0^2 x}}, \quad (4)$$

$$tg\phi_t = \frac{2}{x_t} \cdot \frac{bei_1 x(ber_0 x + bei_0 x) + ber_1 x(ber_0 x - bei_0 x)}{bei_1 x(ber_0 x - bei_0 x) - ber_1 x(ber_0 x + bei_0 x)}, \quad (5)$$

where Φ_0 is the reference magnetic flux; $tg\phi$ is the tangent of the phase angle between the reference magnetic flux Φ_0 and the magnetic flux in the sample probing liquid Φ_{2t}; a_n is the radius of the glass tube with the liquid sample, a is the radius of the liquid sample ($a_n = a$); $ber_n-, bei_n-, ber_0-, bei_0-, ber_1 -$ and bei_1 - Kelvin functions of the nth, zero and first order [15]; f is the frequency of the TECT magnetic field probing the wastewater sample. At the same time, using the representations of the Kelvin functions in the form of power series [15-18], the universal transformation functions $G = f(x)$ and $\phi = f(x)$ were obtained, the tabular values of which for the wastewater sample are given in Table 1.

Table 1.
Dependences of the normalised parameters G_t and φ_{2t} on the generalised magnetic parameter x_t

φ_{2t}, degrees	G_t	x_t
-6.51	0.9889	0.9601
-6.69	0.9883	0.9724
-6.80	0.9869	0.9915
-6.88	0.9861	1.0137
-7.33	0.9850	1.0209
-7.47	0.9841	1.0319
-7.70	0.9828	1.0544
-8.07	0.9817	1.0725
-8.26	0.9808	1.0830
-8.48	0.9800	1.0927
-8.71	0.9783	1.1104

Table 1 shows the calculated values of the universal transfer functions. In order to establish the universal conversion functions, which relate the parameters of the electrolytic fluid medium sample: χ_t, ε_r and t to the amplitude and phase components of the MFP signals: ε, ε_r and t to the amplitude and phase components of the MFP signals: with the emf E_2, due to the magnetic flux F_2 passing through the wastewater sample and the phase angle φ between the emf E_0 MFP (without sample) and the EMF E_2. The normalised generalised characteristics were introduced: the specific normalised magnetic flux G_t passing through the liquid (the liquid is placed in a glass tube) and a generalised parameter x_t, which expresses the ratio of the radius a of the glass tube to the depth of penetration of the magnetic field δ into the sample. Thus, by measuring the magnetic fluxes F_2 and F_0 or their corresponding EMFs E_2 and E_0 and the phase angle φ, it is possible to determine three parameters of a sample of electrolytic fluid: χ_t, ε_r and t, either together or separately. It is necessary to note that any change in the specific electrical conductivity χ_t, the relative permittivity ε_r and the temperature t leads to a change in the generalised parameter x and, consequently, to a change in the amplitude and phase components of the thermal MFP signals with the wastewater sample, i.e. to a change in the normalised and measured MFP signal components: G_t, φ, E_0, E_2, that is why conversion functions are universal for weak electrolytic liquid media when implementing informative non-contact electromagnetic methods based on MFP.

Thus, as a result of preliminary measurements of the phase angle ϕ, in accordance with the dependence $\phi = f(x_t)$, we determine the electrical conductivity χ_t:

$$\chi_t = \frac{4 \cdot x_t^2 \cdot E_0 \cdot G_t}{\mu_0 \cdot d^2 \cdot \Delta E_t \cdot \pi \cdot f}. \quad (6)$$

The dependence χ of a wastewater sample on temperature t has the following form [14]:

$$\chi_t = \chi_0 \cdot \left(1 + \alpha \cdot (t - t_0)\right), \quad (7)$$

where χ_0 is the electrical conductivity at the initial temperature, t_0= 12°C.

The value of permittivity ε_{rt}, at a constant frequency of the electromagnetic field probing the sample, is found from the expression:

$$\varepsilon_{rt} = \frac{f}{2 \cdot \chi \cdot \varepsilon_0 \cdot 10^{-8}}, \quad (8)$$

where ε_0 is an electrical constant.

The temperature coefficient of resistance α is determined experimentally by measuring two values of electrical conductivity χ, at known temperatures t_1 and t_2 from the temperature range under study [14]:

$$\alpha = \frac{\chi_t - \chi_1}{\chi_1 \cdot (t_2 - t_1)}. \quad (9)$$

The temperature of the controlled wastewater sample is found from the expression:

$$t = \frac{1}{\alpha} \cdot \left(\frac{4 \cdot x_t^2 \cdot E_0 \cdot G_t \cdot \chi_0}{\mu_0 \cdot d^2 \cdot E_t \cdot \pi \cdot f} - 1\right) + t_0. \quad (10)$$

Since the wastewater discharged into the municipal sewage system is mainly acidic in composition, the authors propose the addition of alkaline reagents based on aluminates $mCaO \cdot nAl_2O_3$ and calcium silicates $CaSiO_3$ as the most promising method of treatment, reagents used to bind hydrogen ions formed as a result of hydrolysis of coagulants based on acid salts.

Table 2 shows the results of determining the physicochemical parameters of a wastewater sample.

Table 2.
The results of joint measurements of electrical and temperature parameters of wastewater samples
$\alpha = 1{,}89\cdot10^{-2}$ 1/°C; $t_0 = 12$ °C; $a = 55\cdot10^{-3}$ m; $\mu_0 = 4\pi\cdot10^{-7}$ H/m; $t = [12 \ldots 33°C]$, $I = 37{,}11$ mA; $f = 18$ MHz

t',°C	t,°C	γ_t, %	ε'_{rt}	ε_{rt}	$\gamma_{\varepsilon r}$, %	$\chi'_t\cdot10^{-1}$, Sm/m	$\chi_t\cdot10^{-1}$, Sm/m	$\gamma_{\chi t}$, %
12	12.29	1.93	65.58	65.45	1.29	14.27	14.58	3.34
14	14.16	0.94	60.13	60.60	0.76	14.89	14.63	-2.69
16	16.85	-0.79	55.23	55.98	-0.43	13.95	13.15	2.01
18	18.84	-0.76	48.16	48.01	-0.29	12.23	12.41	1.76
20	20.95	-0.22	46.22	46.13	-0.19	11.57	11.68	1.04
22	22.08	0.32	40.69	40.76	0.17	10.87	10.95	0.74
24	24.03	0.11	39.51	39.57	0.15	10.20	10.15	-0.45
26	26.01	0.03	37.84	37.90	0.16	9.51	9.47	-0.34
28	28.97	-0.09	36.11	36.16	0.14	8.86	8.83	-0.25
30	30.99	-0.03	35.26	35.24	0.06	8.10	8.11	0.08

Analysing the data in Table 2, we can say that the results of measurements of the parameters χ, ε_r, and t are in good agreement with the data of the control methods χ', ε'_r and t'. As control methods for measuring specific electrical conductivity χ', relative dielectric permittivity ε'_r and temperature t', the conductometric method, the method of measuring electric capacitance, and the thermoelectric method (chromel-kopel thermocouples THC) have been implemented. The ranges of change in the measurement errors of the proposed method in relation to the control ones, taken in modulus, amounted to $\gamma_{\chi t}$= [3.34….0.08%], γ_t= [1.93….0.03%], $\gamma_{\varepsilon r}$ = [1 .29….0.06%].

Thus, the contactless electromagnetic method of joint measurements of specific conductivity, relative permittivity ε_r and temperature t of a sample of liquid electrolytic medium (wastewater sample from apple juice production) has been proposed. The technique of defining the universal functions of the transformation connecting the dependence of the amplitude and phase components of the multiparameter signal MFP with the physical and chemical parameters of the sample of the electrolytic liquid medium is at the centre of such research. It should be noted that the acidic environment of wastewater due to the presence of sulphuric acid H_2SO_4, hydrochloric acid HCl, nitric acid HNO_3 and orthophosphoric acid H_3PO_4. Since the wastewater discharged into municipal sewerage systems is mainly acidic in composition, the authors propose the addition of alkaline reagents based on aluminates $mCaO\cdot nAl_2O_3$ and calcium silicates $CaSiO_3$ as the most promising and inexpensive method of treatment.

5. Results and discussion

Nowadays, the most important task of environmental protection is the sewerage and treatment of wastewater from food and processing plants; this helps to prevent systematic harm to public health and regulates the environmental situation in residential areas where mini-mills and small production lines are located. At the same time, the development of production and consumption systems leads to the degradation of ecosystems in populated areas. When choosing new treatment methods and the equipment to implement them, it is necessary to consider the specific characteristics of the effluents caused by production technologies, water consumption and wastewater treatment methods in the food and processing industries. For small capacity enterprises (mini-factories, fruit juice production lines), wastewater treatment issues are important and relevant, as most of these enterprises are located in the territory of residential areas, often in the centres of large metropolitan areas. Their wastewater flows directly into the sewerage system and into open natural and artificial water bodies. The negative external effects of such production arise when the enterprise pollutes the local environment without adequate compensation, both for the ecosystem and for the population of the district, city, or metropolitan area. However, a number of measures can be recommended to improve the situation:

1) Implementation of new information methods and expansion of the functional and technical capabilities of measuring instruments to perform environmental monitoring tasks as a result of an integrated environmental monitoring system;
2) Processing the results of joint measurements of physicochemical parameters of wastewater samples;
3) Transition of mini factories to a closed water cycle;
4) Selection of promising methods and treatment equipment for their implementation based on the results of measurements of physicochemical parameters of wastewater samples.
5) Accounting for external environmental costs.

This set of measures implies efficient use of production resources and, in the framework of preventing negative consequences, development and improvement of measuring methods and devices for their implementation to improve the accuracy of determination of parameters of wastewater samples, which allows to determine the composition and to choose a rational treatment method.

In this connection, there is an important scientific and practical problem connected with the creation of new informative methods of joint multi-parameter measurements of normative parameters of electrolytic liquid samples (wastewater of food and processing production) with the purpose of further selection of inexpensive rational methods of wastewater treatment of mini-factories and fruit juice production lines, which are located in residential areas.

Recently, a number of works devoted to the determination of physicochemical parameters of electrolytic liquids have appeared. First of all, it is necessary to note scientific works in which methods of measurement of specific electric conductivity χ and relative permittivity ε_r at fixed temperature t, based on the phenomenon of electric impedance, are studied. Thus, in the work [19], within the limits of research of processes of electro-oxidation at the removal of organic substances from hard sewage of breweries, frequency spectra of dielectric permittivity $\varepsilon_1(\nu)$ and dielectric losses $\varepsilon_2(\nu)$ of water solution NaCl are considered. A limitation of the method proposed in [19] is the determination of the corresponding solutions coefficients at a fixed temperature value. At the same time, it would be interesting to obtain values of the relative permittivity ε_r and the corresponding coefficients at different temperatures.

In the work [20], research were carried out connected with application of an oscillatory circuit as a comparison standard, when implementing the method for measuring the parameters of electrolyte solutions, in which realisation is carried out by means of non-contact measuring cells and consists in allocation of components of the impedance of a measuring cell with the investigated solution. Limitations of the method described in [20] are the complicated algorithm of measurement procedures and the occurrence of methodological errors associated with the inaccuracy of the description of conversion functions.

Within the framework of solving those mentioned above important scientific and practical problems, a new three-parameter informative electromagnetic method of joint measurement control of the parameters of apple juice production effluents (generally electrolytic liquids) is considered in the present work.

The advantages of the informative method proposed in this work are the possibility of using only one measuring device – a transformer-electromagnetic transducer (MFP), which allows measuring of three parameters of electrolytic liquid samples χ, ε_r and t simultaneously. As a rule, the information signal of the electromagnetic transducer is an AC signal whose components include the amplitude of the magnetic flux F, the phase angle of shift φ between the (reference) magnetic flux and the normalised conventional magnetic flux, and the frequency of the magnetic field f probing the sample under the control of the liquid medium. The implementation of the proposed three-parameter electromagnetic method is based on the analysis of the interaction of an external homogeneous magnetic field with the magnetic field of eddy currents induced by an excitation coil in a glass tube with the studied sample of electrolytic liquid (wastewater sample). At the same time, in order to establish universal conversion functions that relate the parameters of the electrolytic fluid sample to the components of the MFP signals, normalised generalised characteristics were introduced: the specific normalised magnetic flux G_t that passes through the fluid (the fluid is placed in the glass tube) and the generalised parameter x_t that expresses the ratio of the radius a of the glass tube to the depth of penetration of the magnetic field δ into the sample. Thus, by measuring the magnetic fluxes F_2 and F_0 or their corresponding EMFs E_2 and E_0, as well as the phase angle φ, it is possible to obtain information on the specific electrical conductivity χ, relative permittivity ε_r and temperature t of the electrolytic liquid medium. It is necessary to note that any change in the specific electric conductivity χ, relative permittivity ε_r and temperature t leads to a change in the generalised parameter x and, consequently, to a change in the amplitude and phase components of the thermal MFP signals with a wastewater sample, i.e. to a change in the normalised and measured components of the MFP signals: G_t, φ, E_0, E_2.

Prospects of further research relate to increase of accuracy of joint measurements of normative parameters of wastewater samples, based on statistical stability of measured characteristics of wastewater samples from food and processing industries. The need to expand research on methods for processing measurements results is associated with development of measurement methodology and improvement of mathematical methods for presenting data, as well as the development of perspective algorithms for measuring and computing procedures at realisation of multi-parameter electromagnetic methods. In turn, determination of errors of joint multiparameter measurements of wastewater parameters allows to establish rational modes of operation of measuring equipment, to increase the accuracy of measurements of physical and chemical parameters of electrolytic liquid media, and then, based on the obtained experimental data, to significantly improve the efficiency of purification process and to make a choice of rational method of purification of wastewater samples.

6. Conclusions

The measurement of physical and chemical quantities is now increasingly used not only in engineering and industry but also in biology, medicine, agriculture, and environmental protection. Developing new informative measuring methods makes it possible to account for material resources, determine product quality, choose new rational methods of wastewater treatment, improve treatment technologies and automate the relevant processes. The existing methods of measurement of normative parameters of wastewater (weak electrolytic liquid media) [11-18], do not provide the necessary accuracy of measurements. To determine many parameters of samples of controlled liquids, it is necessary to use additional measuring instruments. Therefore, within the framework of the solution of the scientific and practical problem presented in the work, which is connected with the creation of new informative methods of joint multi-parameter measurements of normative parameters of electrolytic liquid samples (wastewater of food and processing industry) in order to choose further cheap rational methods of wastewater treatment of mini-factories and fruit juice production lines, which are located in residential areas, the three-parameter informative electromagnetic method for the joint measurement of the specific electrical conductivity χ, the relative permittivity ε_r and the temperature t of wastewater samples from the production of apple juice has been studied. Until now, the theory of multi-parameter electromagnetic transducers has not been sufficiently developed in relation to the control of electrolytic liquid media, probably due to the complexity of electromagnetic processes occurring in conductive liquid media associated with the diffusion of the alternating magnetic field in them, so that it was necessary to perform complicated calculations and design pass-through electromagnetic transducers with controlled liquid sampling. It should be noted that in the measurement control of electrolytic liquid media, it is advisable to use pass-through electromagnetic transducers with two windings, the coils of which cover the controlled object - liquid sample (located in a glass tube), according to the popular classification these transducers refer to electromagnetic transformer transducers [21-27].

The possibility of applying the MFP operating theory to the realisation of an informative three-parameter electromagnetic method of joint measurements of the parameters of specific conductivity χ, relative permittivity ε_r and temperature t of wastewater is studied within the framework of solving the presented problem. An algorithm for modelling the process of joint multi-parameter measurements of specific conductivity χ, relative permittivity ε_r and temperature t on the basis of MFP has been developed. The basic relations describing a three-parameter method of joint measurements of specific conductivity χ, relative permittivity ε_r and temperature t of controlled wastewater samples have been given. The implementation of the proposed three-parameter method allows increasing in the accuracy of identification of wastewater samples due to the obtained multi-parameter information, as well as indirectly determines the composition of wastewater samples, using only one transducer with certain physical properties; all this leads to increased accuracy of measurements of parameters of wastewater samples in comparison with the reference methods and measuring tools. The analysis of the research results, which are presented in Table 2, shows that the results of the measurements of the parameters χ, ε_r and t agree well with the data of the reference methods χ', ε'_r and t' described in the works [11-18]. The ranges of change in the measurement errors of the proposed method in relation to the control ones (taken in modulus) amounted respectively to $\gamma_{\chi t}$= [3.34….0.08%], γ_t= [1.93….0.03%], $\gamma_{\varepsilon r}$ = [1.29….0.06%]. The development of new informative measurement methods makes it possible to improve the cleaning and automation technologies of the processes involved. The originality of the article is that the theory of operation of a thermal transformer electromagnetic converter (MFP) has been further developed with a sample of a weak electrolytic liquid having an acidic composition (a sample of wastewater from apple juice production).

The essence of the realisation of the electromagnetic method consists in that due to the probing of the wastewater sample by the magnetic field of the thermal MFP, using two universal transformation functions connecting amplitude and phase components of the multi-parameter signal, i.e. $G = f(x)$ and $\varphi = f(x)$ with physicochemical characteristics of a wastewater sample χ, ε_r, t, it is possible to determine three parameters together at one frequency of magnetic field f without using complex hardware methods of compensation of air gap effects, which lead to complication of the measuring device and occurrence of large measurement errors related to under- and over-compensation. Implementing the proposed method leads to an extension of the functional and technical possibilities of the three-parameter electromagnetic device – the thermal transformer electromagnetic converter (MFP). The data obtained indicate an acidic composition of the wastewater, so it is proposed to carry out neutralisation of the effluent at the outlet of the finished product. In comparison with the known methods of measuring the normative parameters of liquid media, the non-contact three-parameter electromagnetic method studied in this article will allow, in the long term, to carry out measurements of the specific electrical conductivity χ and the relative permittivity ε_r in a wide range of temperatures during the control of heated, aggressive, toxic liquid media. As the most perspective and inexpensive way of wastewater treatment for low-capacity production, the authors of the paper propose the addition of alkaline reagents based on aluminates $mCaO\text{-}nAl_2O_3$ and calcium silicates $CaSiO_3$, which are used for binding hydrogen ions formed because of hydrolysis of coagulants based on acid salts.

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