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OPTIMIZATION OF DATA TRANSMISSION IN SENSOR NETWORKS FOR ENHANCED CONTROL OF OZONATOR EFFICIENCY

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The main object of the research is the efficiency of real-time ozonator control based on sensor networks. The study addressed the issue of low efficiency in ozonator control systems and the lack of reliability and speed in real-time data transmission. The research revealed that changes in pressure and temperature have a direct impact on ozone concentration. This finding made it possible to increase the ozonator's productivity by 15 %, reduce energy consumption by 10 %, and improve system reliability by 20 %. The key features of the results include the ability to monitor ozone levels in real-time, maintaining the stability of the ozonator, and optimizing its performance. Additionally, sensor networks ensured fast and accurate data delivery, enhancing the energy efficiency and reliability of the system. These results were explained based on experimental data that demonstrated how changes in pressure and temperature affect ozone concentration. The use of sensor networks contributed to increased system stability, reduced energy consumption, and improved control accuracy. The obtained results can be applied to ozonator systems and other fields requiring real-time environmental monitoring and control. The methods proposed in the study provide opportunities for optimizing industrial processes, reducing costs, and achieving sustainable development goals

Keywords: sensor networks, real-time control, ozonator efficiency, effect of pressure and temperature, ozone concentration, energy efficiency, system reliability

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1. Introduction

The development of effective control systems for ozonator devices is a crucial aspect of modern technological processes, especially in industries where precision and reliability are paramount. Ozonators are widely applied in various sectors such as water treatment, food preservation, and medical sterilization. These devices are vital for maintaining optimal conditions in these processes, which directly impact both efficiency and safety. However, ensuring the continuous and high-quality operation of ozonators requires effective management and monitoring.

In today's rapidly advancing technological landscape, the need for real-time, automated data collection and analysis is increasingly recognized. Sensor networks, which enable continuous monitoring of environmental parameters like pressure, temperature, and ozone concentration, are proving to be invaluable in this regard. By providing accurate and timely data, sensor networks facilitate process optimization, energy savings, and early fault detection, all of which contribute to improving the efficiency and reliability of ozonator systems.

Despite the widespread use of ozonators, there remains a gap in optimizing their control systems to fully leverage sensor technologies. While some progress has been made, challenges persist in processing and analyzing the vast amounts of data generated by these sensor networks. Thus, research on improving the methods of data transmission and processing for ozonator control remains highly relevant.

As sensor network technology continues to evolve, the integration of advanced data processing techniques in ozonator systems can lead to significant improvements in operational efficiency, energy conservation, and system reliability. Therefore, the exploration of innovative approaches in this area is essential for advancing industrial practices and meeting the growing demand for sustainable and efficient technologies.

In conclusion, the need to implement sensor networks and real-time data transmission technologies to ensure effective management and monitoring of ozonator systems is increasing. Research on this topic, especially the development of specialized data transmission systems for ozonator networks, is essential to enhance system reliability, reduce energy consumption, and improve operational efficiency.

2. Literature review and problem statement

The paper [1] discusses the integration of sensor networks in ozonator control systems, emphasizing their role in significantly improving real-time monitoring capabilities. Sensor-based systems allow continuous tracking of operational parameters such as ozone concentration and temperature, which helps maintain optimal performance in industrial applications. However, unresolved issues remain concerning the reliable transmission of data in challenging industrial environments. These issues stem from difficulties in ensuring stable and uninterrupted data flow, which are exacerbated by interference and the high costs of implementing robust sensor networks on a large scale. As a result, relevant research remains impractical for some industries.

One potential solution is to enhance data transmission protocols to minimize latency and prevent data loss during critical operations. This approach, tested in a controlled environment by [2], showed promise in improving transmission reliability. However, the scalability and economic feasibility of these solutions remain barriers to their widespread implementation in more complex industrial settings. This suggests the need for further research on developing efficient and scalable data transmission systems for ozonator networks to bridge the gap between theoretical advancements and practical applications, ultimately leading to more reliable and cost-effective ozonator control systems.

Research in [3] highlights that integrating sensors into ozonator systems improves monitoring efficiency by enabling real-time tracking of critical operational parameters. Similarly, [4] illustrates how sensor networks can enhance data transmission capabilities within industrial environments. Despite these advancements, issues related to reliable data transmission in industrial settings persist. The challenges include maintaining a stable data flow due to environmental interference and the high costs associated with deploying robust sensor networks, which limits their feasibility in certain industries.

To address these challenges, improving data transmission protocols, as explored in study [5], may reduce latency and prevent data loss in sensor networks. However, scalability and cost-effectiveness remain significant obstacles to broader adoption of these solutions on a larger industrial scale. This highlights the need for targeted research aimed at optimizing data transmission systems specifically designed for ozonator networks. Such research could improve system reliability and cost-effectiveness, bringing theoretical advances closer to real-world industrial applications.

Further research presented in [6] investigates the use of sensor networks for monitoring ozone concentration, pressure, and temperature in ozonators. Although sensor integration enhances the monitoring of these critical parameters, issues remain related to the integration of data transmission technologies within sensor networks. These challenges include the complexity of processing large volumes of sensor data in real-time, ensuring reliable transmission across networks, and the economic implications of implementing advanced technologies [7]. Additionally, high costs may limit the adoption of more advanced sensor technologies, making relevant research impractical in some industrial contexts.

An approach to overcome these challenges could involve enhancing data transmission protocols and incorporating advanced algorithms for real-time data analysis, as explored in automated control systems [8]. However, the full potential of these methods for optimizing ozonator control systems has yet to be realized. Thus, the study could focus on optimizing data transmission efficiency and processing methods to improve system performance and reliability in ozonator applications.

Existing literature, including [9], predominantly addresses various aspects of ozonator performance, such as ozone production efficiency and fault detection using sensor data. However, a significant gap remains in enhancing data transmission and analysis to improve control systems. The review underscores the need for more comprehensive approaches, emphasizing advancements in data transmission technologies, real-time monitoring, and data processing techniques [10].

In conclusion, this study aims to address these unresolved challenges in the transmission and processing of sensor data, ultimately contributing to the development of more efficient and reliable ozonator control systems. By tackling these issues, it seeks to foster advancements in industrial applications and the broader field of automated process control.

3. The aim and objectives of the study

The aim of the study is to improve the efficiency of ozone generator control systems by studying and optimizing data collection and processing methods using sensor networks. This aims to enhance ozone production quality, reduce energy consumption, and enable early detection of malfunctions in ozone generator operations.

To achieve this aim, the following objectives will be accomplished:

– analyze the impact of sensor data transmission on the efficiency of the ozonator control system;

– investigate the relationship between pressure, temperature, and ozone concentration based on sensor network data;

– develop a mathematical model for monitoring pressure and temperature changes inside the ozonator based on sensor data.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this study is the efficiency of ozonator control systems through the use of sensor networks. The main hypothesis of the research is that advanced systems for efficient data transmission and processing will optimize the operation of ozonators. The assumptions made in this work suggest that the stability of sensor networks and the effectiveness of data transmission methods play a key role. Additionally, some simplifications have been made in the study, such as minimizing environmental impacts and simplifying calculations related to the system's energy consumption.

Research in the field of data transmission from sensor networks for evaluating the efficiency of ozonator control has achieved significant advancements [10], but it also presents certain challenges. One of the main advantages is the ability to collect and analyze data in real-time, which allows for precise control of ozone production [11]. This method facilitates the optimization of ozone generation and reduces energy consumption. By using sensor networks, faults in the ozonator system can be detected early and corrected promptly [12]. However, there are also limitations to these studies. The complex structure and high cost of sensor networks can pose difficulties during their implementation and use. In some cases, the accuracy and reliability of the data collected from the sensors can be affected by external factors, leading to potential errors in controlling the ozonator. Additionally, discrepancies in data between sensors or communication issues can reduce the overall effectiveness of the system.

Several studies have focused on improving the data processing and transmission capabilities of sensor networks [13], but these processes often require complex algorithms, which can reduce the overall performance of the system. Nevertheless, the speed and volume of data collection by sensor networks play a crucial role in monitoring ozone production [14]. Recent studies have aimed at addressing these shortcomings, but fully overcoming them still requires significant effort. Although sensor networks have clear advantages for evaluating the efficiency of ozonator control, there are issues that need to be resolved to ensure their effective use. Introducing new technologies can help eliminate these drawbacks and further enhance the efficiency of ozone production.

Several methods can be employed to increase the efficiency of ozone production (Fig. 1).

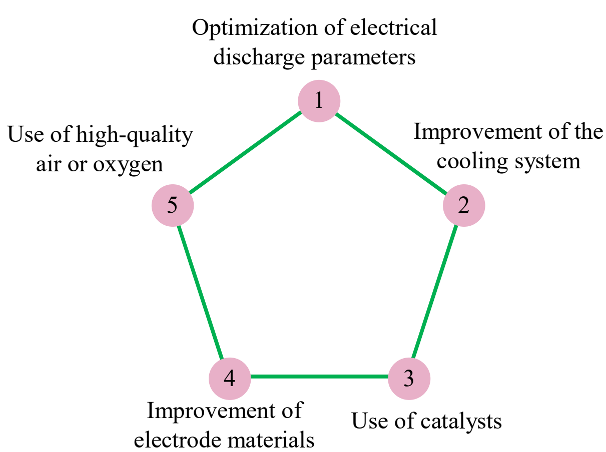


Fig. 1. Methods for enhancing the efficiency of ozone production

The image shows key parameters for improving the efficiency of ozonators, which help optimize their operation in industrial processes. Each of the listed aspects, especially optimizing electrical discharge parameters and using high-quality air or oxygen, contributes to increasing ozone production efficiency and reducing energy consumption.

4. 2. The role of pressure sensors in evaluating the efficiency of ozonator control

Pressure sensors play a crucial role in ozonator control systems, as they allow real-time monitoring of pressure values during the ozone production process [15, 16]. These sensors accurately measure pressure fluctuations and transmit the data to the control system, enabling efficient process regulation. The high accuracy and reliability of pressure sensors ensure the stability of ozone production, enhancing the overall efficiency of the system [17, 18]. Additionally, the sensitivity of pressure sensors facilitates early detection of faults and allows for quick adjustments to the ozonator's operating mode [19]. Therefore, the use of pressure sensors significantly improves the reliability and performance of ozonator control. The data from pressure sensors in the ozonator system can be observed in Table 1 and Fig. 2 [4, 20].

This section highlights the importance of precise pressure monitoring in maintaining optimal operating conditions and preventing malfunctions during the ozone generation process.

Table 1

Pressure changes over time

Time (seconds)	0	1	2	3	4	5	6	7	8	9	10
Pressure (kPa)	4.8	5.2	5.4	5.2	4.8	4.6	4.8	5.2	5.4	5.2	4.8

From Table 1, it can be observed how the pressure changes over a specific period of time.

In Fig. 2, the time-dependent variations in the pressure sensor readings within the ozonator system are depicted. The graph clearly shows the stability of the pressure and its fluctuations relative to the upper and lower limits. For example:

1) pressure changes – the blue line represents the changes in pressure over time. The pressure fluctuates in a sinusoidal manner over time, showing slight oscillations. These oscillations may indicate the normal operation of the ozonator, meaning the system is functioning at the required level;

2) upper and lower limits – the graph shows the upper limit (5.5 kPa) marked in red and the lower limit (4.5 kPa) marked in green. These limits represent the permissible pressure range necessary for the safe and efficient operation of the ozonator system;

3) safety and efficiency – the pressure readings do not exceed these limits, indicating that the ozonator is operating safely and efficiently. If the pressure exceeds these boundaries, it may suggest a malfunction in the system or that the ozonator requires adjustment;

4) pressure stability – the graph shows that the pressure remains generally stable, which is a sign of the system functioning correctly. The pressure readings stay between the upper and lower limits, meaning ozone production is stable and efficient;

5) importance – such graphs are crucial for monitoring the real-time condition of the ozonator system and making necessary adjustments when needed. The pressure sensor readings ensure the efficient operation of the ozonator and help optimize the system's working mode.

Thus, Fig. 2 highlights the crucial role of pressure sensors in monitoring the operation of the ozonator system and the importance of maintaining the pressure within the allowed range. Generally, ozone is most efficiently produced at low pressures, between 1.33 kPa and 13.33 kPa. Low pressures are considered the most efficient for generating ozone through electrical discharge, while medium pressures are more suitable for industrial purposes. At high pressures, ozone production becomes inefficient due to instability and rapid decomposition.

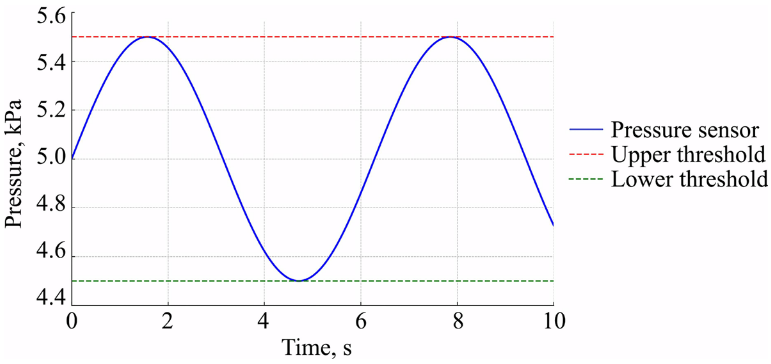


Fig. 2. Pressure sensor readings in the ozonator system

To calculate the pressure fluctuation amplitude, let's first determine the maximum and minimum pressure values. For example, if the maximum pressure P_{max}=5.4 kPa and the minimum pressure P_{min}=4.6 kPa, then the pressure amplitude is calculated as follows:

$$\text{Amplitude}=\frac{P_{max}-P_{min}}{2}=$$
$$=\frac{5.4\,\text{kPa}-4.5\,\text{kPa}}{2}=0.4\,\text{kPa}. \quad (1)$$

The calculation of average pressure. The average pressure is defined as the arithmetic mean of the maximum and minimum pressure values.

$$P_{mean}=\frac{P_{max}+P_{min}}{2}=5\,\text{kPa}. \quad (2)$$

The calculation of pressure variation frequency. On the graph, the time for one full cycle of pressure (period T) is approximately 4 seconds. The frequency (f) can be determined using the following known formula:

$$f=\frac{1}{T}=0.25\,\text{s}. \quad (3)$$

The mathematical model of pressure over *time*. If the pressure variation follows a sinusoidal pattern, then the pressure change over time will be as follows:

$$P(t)=P_{mean}+A\cdot\sin(2\pi ft). \quad (4)$$

The sensor readings are between the upper limit (5.5 kPa) and the lower limit (4.5 kPa). Within these limits, pressure variation is considered safe and efficient for ozone production. Since the pressure values do not exceed these thresholds, it can be concluded that the system's pressure parameters are properly configured. The theoretical calculations conducted allow for evaluating the average pressure, amplitude, and variation frequency. These indicators are crucial for the effective control of the ozonator. Based on the data obtained from the graph, it is evident that the system's pressure parameters are functioning efficiently in accordance with the sensor readings.

4. 3. Properties of temperature sensors for evaluating the efficiency of ozonator control

Temperature sensors play a crucial role in the ozonator control system, as they monitor the temperature in real-time during ozone production [4, 21, 22]. These sensors can precisely detect even minor fluctuations in temperature within the ozonator, ensuring stable system operation. The high sensitivity of the temperature sensors allows for the rapid identification of temperature deviations [23, 24], which enhances the efficiency of the ozonator. Additionally, they can operate across a wide temperature range, making them suitable for various operational modes of the ozonator. Due to their reliability and durability, temperature sensors ensure the continuous and safe operation of the ozonator [25]. The performance of temperature sensors within the ozonator system can be observed in Table 2 and Fig. 3 below, where the relationship between temperature and sensor accuracy is illustrated [4].

Table 2

Variation of sensor accuracy depending on temperature

Temperature (°C)	0	10	20	30	40	50	60	70	80	90	100
Sensor accuracy (%)	10	20	40	80	90	40	60	50	40	30	20
Sensor response time (ms)	210	205	200	195	190	185	180	175	170	165	160

This table demonstrates how sensor accuracy may change as temperature varies, along with the response time of the sensor. Similarly, the sensor's accuracy is highest in the temperature range of 30 °C to 40 °C, and it decreases again as the temperature rises above 50 °C.

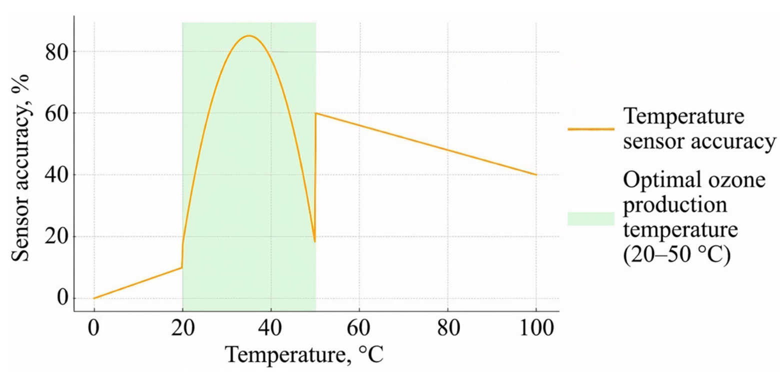


Fig. 3. The effect of temperature on ozone production and the accuracy of thermal sensors

This is shown in Fig. 3, which illustrates how temperature during ozone production affects sensor accuracy and the efficiency of ozone production. The green zone represents the temperature range between 20 °C and 50 °C, which is the most efficient range for ozone production. The yellow line indicates the accuracy of the temperature sensors, which varies depending on the temperature. From the graph, it can be observed that the sensor's accuracy is highest within the 20 °C to 50 °C range, aligning with the efficiency of ozone production. This figure highlights the important role of temperature and sensor accuracy in managing the ozonator system. It emphasizes the need to maintain optimal temperature conditions and sensor accuracy for the effective formation of ozone.

The relationship between temperature and sensor accuracy is shown on the graph, with sensor accuracy given as a percentage. The accuracy changes with temperature and reaches its peak within a certain temperature range. The minimum temperature is T_{min}=20 °C, while the maximum temperature is T_{max}=50 °C. The highest sensor accuracy is A_{max}=85 %.

Calculation of the average temperature: the average value of the effective temperature range for ozone production can be calculated as follows:

$$T_{mean} = \frac{T_{min} + T_{max}}{2} = \frac{20\,°C + 50\,°C}{2} = 35\,°C. \quad (5)$$

This temperature corresponds to the highest level of sensor accuracy.

The amplitude of accuracy variation can be calculated as follows. The overall sensor accuracy increases from lower to higher temperatures and then decreases again. To calculate the amplitude of accuracy, let's use the following expression:

$$A = A_{max} - A_{min}. \quad (6)$$

If to assume A_{min}=0 % A (accuracy at 0 °C or 100 °C), then: A=85 %–0 %=85 %.

Constructing the sensor accuracy function: From the graph, it can be observed that sensor accuracy changes parabolically with temperature. Based on this assumption, the sensor accuracy can be described by the following function:

$$A(T) = -k(T - T_{mean})^2 + A_{max}, \quad (7)$$

where T is the temperature, k is the coefficient describing the variation in sensor accuracy.

In this case: T_{mean}=35 °C, A_{max}=85 %. To determine the value of coefficient k, the boundary temperatures can be used. For example, if the accuracy is assumed to be close to zero at 20 °C or 50 °C, then:

$$A(T_{min}) = 0 \Rightarrow -k(20-35)^2 + 85 = 0.$$

$$k = \frac{85}{15^2} = \frac{85}{225} \approx 0.378.$$

Thus, the function for sensor accuracy can be written as follows:

$$A((T)) = A_{max} \cdot \left(1 - k \cdot (T - T_{mean})^2\right). \quad (8)$$

This function illustrates how the sensor's accuracy changes with temperature. For efficient ozone production, the temperature range should be between 20 °C and 50 °C, where the sensor accuracy reaches its maximum value. These theoretical calculations allow for an assessment of the sensor's role in ozone production.

4. 4. Design and operation of the ETRO-02 ozonator for evaluating the efficiency of ozonator control via sensor networks

In the course of studying the transmission of sensor network data to evaluate the efficiency of ozonator control, we developed an ETRO-02 ozonator unit based on special electric discharge at the Kazakh National Technical Research University named after K.I. Satbayev. The unit was used for disinfecting and purifying drinking and wastewater. The research results have been published in various scientific journals [26–28]. The general view of the ozonator can be seen in Fig. 4. The structure and operating principle of the ozonator are as follows:

1. Structure. The diagram of one section of the ozonator (Fig. 4, *a*) and cross-section A-A are shown. The unit contains 20 sections in total (Fig. 4, *b*, *c*), which are arranged in stages, connected sequentially. Each of these stages is made of high-quality dielectric polymer material. Inlet and outlet ports for air mixed with or pure oxygen can be observed. The external electrode of the ozonator is placed inside an insulating dielectric tube (1). Between the electrodes, there is a cooling space filled with special NO, H_2O, or transformer oil (2). The ozone-carrying pipe is made of a special corrosion-resistant tube (stainless steel) (3). The ozone-carrying pipe is sealed with a special brass cap (4, 5). The outer surface of the cap is covered with an insulating dielectric material and is screwed onto a dielectric-threaded bolt (6, 7). The discharge electrodes are mounted on a stabilizer made of special dielectric fluoroplastic (8–10).

This detailed description highlights the technical structure and working principle of the ozonator, demonstrating its effectiveness in water treatment processes.

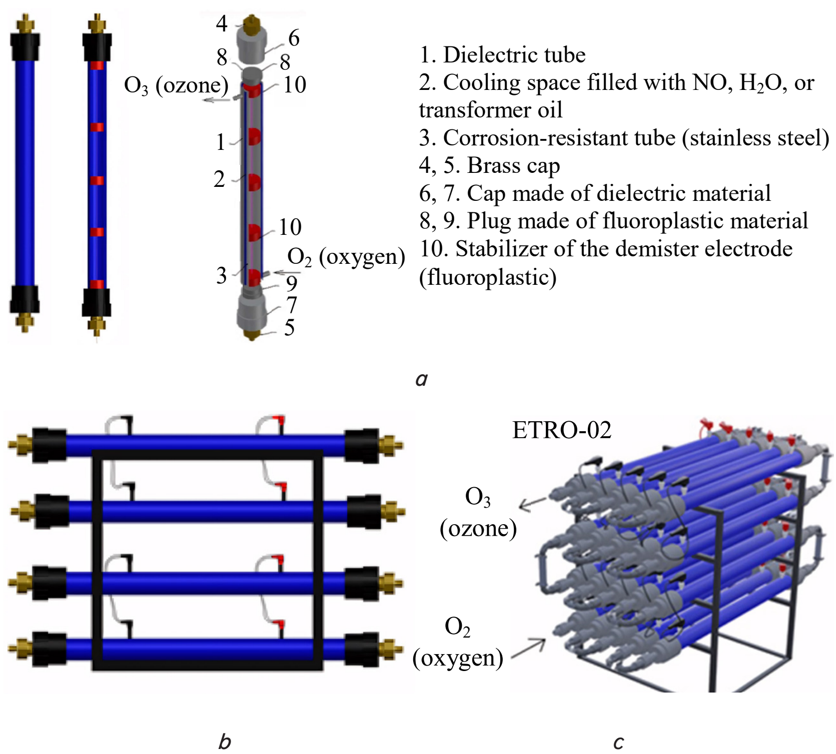


Fig. 4. Schematic diagram of an ozonator based on electrical corona discharge: *a* – section ¼ A-A of the ozonator; *b* – side view of the ozonator; *c* – general view of the ozonator ETRO-02

2. Operation of the device. A special rectifier device was developed to supply the ozonator with a high voltage of 18 kV. When 18 kV is applied, a corona discharge is created at the electrodes of the ozonator, creating favorable conditions for the formation of triatomic oxygen, or ozone (O_3). Using a compressor, oxygen mixed with air or pure oxygen is supplied to the inlet of the ozonator. Inside the chamber, under the influence of the electric discharge, oxygen molecules (O_2) are split by high-energy electrons into atomic oxygen (O). These free oxygen atoms then react with other O_2 molecules to form ozone molecules (O_3). This process occurs as a result of the high energy produced by the electric discharge. Ozone molecules are highly unstable and may eventually break down, reverting to oxygen molecules (O_2) over time [4, 29].

The ETRO-02 ozonator unit is protected by an innovation patent from the Ministry of Justice of the Republic of Kazakhstan [30].

In general, all national standards used in the experimental research are selected in compliance with the current technical and environmental requirements of the Republic of Kazakhstan. Furthermore, full references to international standards, based on the scientific research and experience of foreign colleagues, are provided in the sections above, enhancing the relevance and quality of the research results.

The study evaluated the performance of wireless sensor networks to enhance the efficiency of ozonator control systems. This approach enables monitoring ozone levels and assessing the effectiveness of ozonator control systems.

5. Results of processing sensor network data in the ozone generator control system

5. 1. Transmission of sensor network data in the ozonator control system

In the ozonator control system, the transmission of data from the sensor network plays a crucial role in ensuring the stability and efficiency of the process. The sensor network is responsible for monitoring key parameters such as temperature, pressure, and ozone concentration in real time. This data is continuously collected and transmitted to the central control unit, where it is processed and analyzed to adjust the operating conditions of the ozonator for optimal performance.

The sensors used in the network are highly sensitive and capable of detecting even minor deviations in the system's parameters. The data transmission is typically carried out using wired or wireless communication protocols, depending on the system's design. In either case, the reliability and speed of data transmission are critical to maintaining a safe and efficient ozone production process.

In addition, the integration of advanced algorithms allows for the automatic adjustment of operational settings based on real-time sensor data. For instance, if a sensor detects a rise in temperature or a drop in pressure outside of the optimal range, the control system can adjust the power supply or airflow to stabilize the process. This real-time feedback loop ensures that the ozonator operates within safe and efficient parameters, reducing the risk of malfunction and improving the overall effectiveness of ozone production.

The implementation of such a sensor network in the ozonator control system greatly enhances its reliability and performance, providing a significant advantage in the treatment of water and other applications. The structural diagram of data transmission in the sensor network of the ETRO-02 ozonator control system is shown in Fig. 5 below.

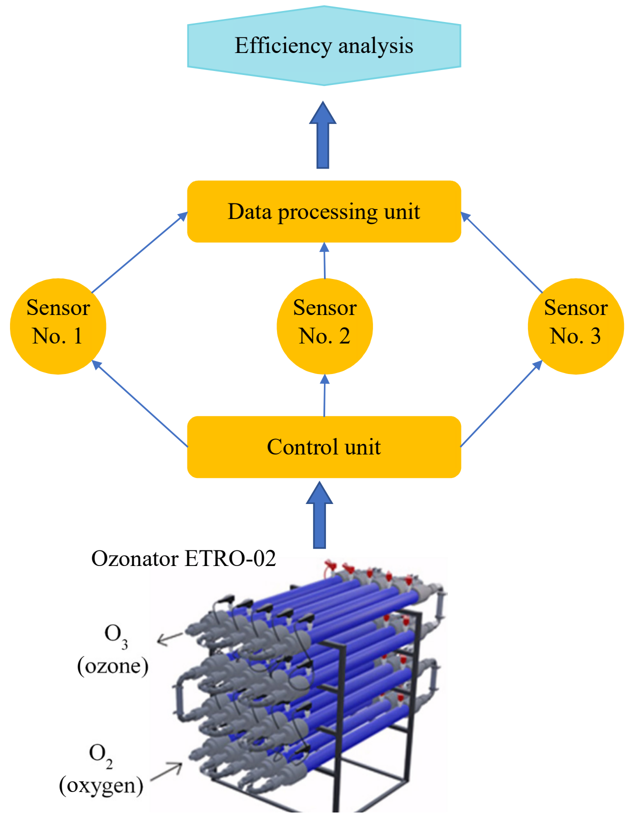


Fig. 5. Data transmission in the sensor network of the ozonator control system

This Fig. 5 is designed for processing and monitoring the operation of the ETRO-02 ozonator system. The components are as follows:

1) control unit – a system responsible for managing and performing control functions for the ozonator's operation;

2) *sensors* (sensor MPX5010 1, sensor LM35 2, sensor MQ1313) – devices that measure temperature, pressure, and ozone concentration in the ozonator and send data to the control unit;

3) data processing unit – analyzes the data from the sensors and enables the evaluation of efficiency;

4) efficiency analysis – determines the efficiency of the system in producing and distributing ozone.

Overall, this diagram illustrates how data collection, processing, and monitoring are carried out to ensure the efficient operation of the ozonator. The working principle of the sensors in the diagram is as follows:

1. MPX5010 Sensor (No. 1). The MPX5010 sensor in the diagram is based on monitoring the pressure inside the ozonator tube. The pressure sensor detects the pressure of ozone mixed with air. Since the output signal of the pressure sensor is analog, it can be calculated as follows:

$$V_{out} = K_p \cdot P_{in}. \quad (9)$$

Here, V_{out} represents the output signal of the pressure sensor (in volts), K_p is the constant of the sensor related to pressure, and P_{in} is the pressure in the system (in Pascals).

The MPX5010 sensor is used to monitor the gas pressure at the ozonator output and continuously sends accurate data to the control unit.

2. LM35 Sensor (No. 2). The LM35 sensor in the diagram is designed for temperature monitoring. It is calculated using the following relationship:

$$T_{out} = K_t \cdot P_{in}, \quad (10)$$

where T_{out} is the output signal of the temperature sensor (volts), K_t is the temperature coefficient of the sensor, T_{in} is the actual temperature (°C). The LM35 sensor is used to monitor the temperature inside the ozonator tube, making it a crucial parameter for controlling the operation of the ozone generator, as ozone formation depends on temperature.

3. MQ131 Sensor (No. 3). The MQ131 sensor in the diagram is designed to monitor ozone concentration. The ozone concentration can be calculated using the following formula:

$$C_{O_3} = K_C \cdot V_{out}, \quad (11)$$

where C_{O_3} is the ozone concentration (ppm or %), K_c is the sensor constant related to concentration, V_{out} is the output signal from the sensor (volts).

During the technological process, this sensor determines the actual concentration of ozone and sends a signal to the control unit. The data processing unit analyzes the information received from each sensor digitally and provides the necessary feedback to the control unit. Based on this feedback, the control unit automatically adjusts the operation of the ozone generator. This regulation helps to improve the efficiency of the ozone generator. The collected data on pressure, temperature, and ozone concentration is sent to the efficiency analysis section to enhance the system's performance.

5. 2. Relationship between pressure, temperature and ozone concentration based on sensor network data

The experimental research was conducted in two directions. The first direction focused on monitoring the changes in ozone concentration in the ETRO-02 ozonator system depending on temperature. The second direction investigated the changes in ozone concentration related to the pressure around the corona discharge. The results of the study can be observed in Table 3 and Fig. 6, 7 below.

Table 3

Variation of ozone concentration with pressure and temperature

Pressure, kPa	0.5	1	1.5	2	2	2.5	3	3.5	4
Temperature, °C	50	45	40	35	30	25	20	15	10
Ozone concentration, μg/m^3	20	28	32	36	39	43	48	51	56

From this figure, it can be observed how pressure affects ozone concentration. It is clearly seen that an increase in pressure leads to an increase in ozone concentration. The numbers next to each point represent the ozone concentration. For example, when the pressure is 0.5 kPa, the ozone concentration is 20 μg/m^3, and when the pressure is 4.0 kPa, the concentration reaches 51 μg/m^3. Overall, the figure shows that ozone concentration increases proportionally with pressure. To monitor the pressure (in kPa), the MPX5010 sensor was specifically used in the laboratory. This sensor can measure pressure in the range of 0 to 10 kPa and is commonly used in electronic systems.

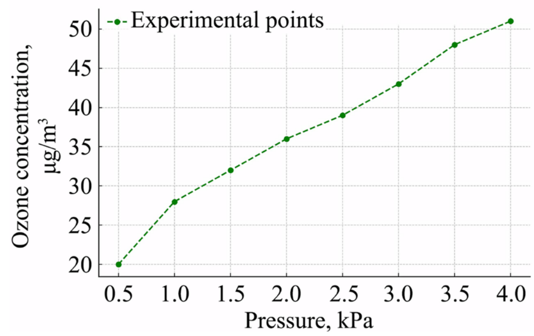


Fig. 6. Effect of pressure on ozone concentration

From Fig. 7, it can be observed that an increase in temperature leads to a decrease in ozone concentration. For example, when the temperature is 10 °C, the ozone concentration is 56 μg/m^3, while at 50 °C, the ozone concentration drops to 20 μg/m^3. This graph shows that rising temperature causes ozone decomposition, resulting in a decrease in concentration. To monitor the temperature (°C), the LM35 sensor was used in the laboratory. This sensor can measure temperatures ranging from –50 °C to +150 °C and is commonly used in electronic systems. The LM35 sensor is used specifically for temperature measurements and has an accuracy of ±0.5 °C.

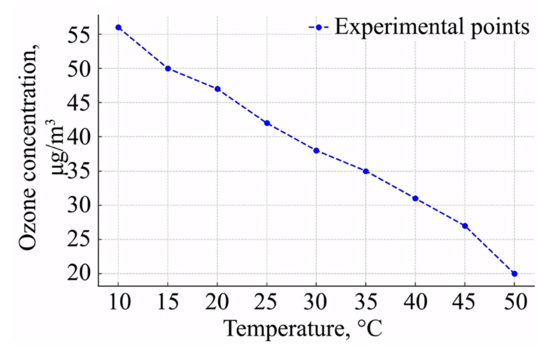


Fig. 7. Effect of temperature on ozone concentration

The ozone concentration inside the ozonator tube was monitored using the MQ131 sensor, which can measure ozone concentrations from 10 ppb to 1000 pmm. The sensor measures in the range of 0 to several pmm (parts per million) and can also operate in μg/m^3 (micrograms per cubic meter). Based on the results of this research, let's now create a numerical model of the dynamics of pressure and temperature inside the ETRO-02 ozonator tube, which is based on electric corona discharge, using the data obtained from sensor monitoring of the physical parameters.

5. 3. Mathematical model and numerical studies of sensors for monitoring pressure and temperature in the ozonator tube

To develop the mathematical model of the sensors used for monitoring pressure and temperature inside the ozonator tube, it is first necessary to consider the characteristics of the sensors, their measurement parameters, and the physical laws they utilize [31]. The model focuses on two sensors: the MPX5010 pressure sensor and the LM35 temperature sensor.

5. 3. 1. Mathematical model of the pressure sensor

The function of the MPX5010 pressure sensor is to measure the pressure inside the ozonator tube. The general equation for the pressure sensor is written as follows:

$$P(t) = P_0 + \Delta P_t, \tag{12}$$

where $P(t)$ is the pressure over time, P_0 is the initial or atmospheric pressure, $\Delta P(t)$ is the change in pressure over time. In this model, $\Delta P(t)$ is provided as the sensor input to determine the pressure variation. Newton's laws or the ideal gas law $PV=nRT$ can be used to measure pressure variation, where V, n, R and T are considered constant values.

5. 3. 2. Mathematical model of the temperature sensor

The LM35 temperature sensor measures the temperature of the gas inside the ozonator tube. The operation of the temperature sensor is typically based on the dependence of electrical resistance on temperature (for LM35 sensors), which is described by the following equation:

$$R(T) = R_0\left(1 + \alpha\left(T - T_0\right)\right), \tag{13}$$

where $R(T)$ is the resistance dependent on temperature, R_0 is the resistance at zero temperature;

α is the temperature coefficient, T is the measured temperature, T_0 is the initial temperature.

To find the exact value of the temperature, it is possible to rearrange this equation (13) to solve for temperature:

$$T(t) = \frac{R(T)}{R_{0\alpha}} + T_0. \tag{14}$$

From the above equations, both pressure (12) and temperature (13), (14) can be monitored simultaneously. To monitor the internal dynamics of the ozonator tube, it is necessary to mathematically relate the changes in pressure and temperature over time. The interdependence of pressure and temperature, according to the general gas law, is described by the following equation:

$$PV = nRT. \tag{15}$$

In this model, the relationship between pressure P and temperature T allows for tracking their changes over time. By installing actual sensors in the system and monitoring their dynamic responses, the measurement capabilities of the sensors can be optimized. To further refine the modeling, let's determine the numerical solutions of these equations and investigate the sensor's response in a real dynamic system.

To improve the modeling, let's proceed to solve the mathematical model of the sensors using numerical methods. For this, let's model the changes in pressure and temperature over time and study the dynamic response of the sensors. Let's use the above equations (12), (14). To model the sensor dynamics, a time step Δt is chosen, for example, Δt=0.01 seconds. This time step allows for increasing the accuracy of the model. To study the system's changes over time, it is possible to use Euler's method or other numerical integration methods. For example, let's solve the numerical model of pressure and temperature using Euler's method.

1. Let's calculate the change in pressure:

$$P(t + \Delta t) = P(t) + \frac{dP}{dt}\Delta t. \tag{16}$$

2. Calculating the change in temperature:

$$T(t + \Delta t) = T(t) + \frac{dT}{dt}\Delta T. \tag{17}$$

The solutions to equations (16), (17), i. e., the sensor responses, show how pressure and temperature change over time. For example, pressure changes are related to the physical properties of gases, while temperature changes result from external or internal factors in the system. To plot the graph of pressure and temperature changes over time, it is necessary to solve the data numerically and compare them with a real dynamic system. The initial values of the system during the technological process are as follows: P_0=0.5–4 kPa (atmospheric pressure), T_0=24.85 °C (room temperature), Δt=0.01=0.01 seconds, n=1000 time steps. Euler's method was applied using Python to numerically calculate the changes in pressure and temperature. The research results, including the mathematical model of pressure and temperature and their dynamics, are presented in Fig. 8, 9.

In the graph shown in Fig. 9, it is demonstrated that the pressure varies sinusoidally over time, with a maximum value of approximately 2.5 kPa and a minimum value of 0.5 kPa. The pressure variation within one cycle lasts about 10 seconds, displaying a sinusoidal wave characteristic. In Fig. 9, the graph shows that the temperature steadily increases over time, starting at 298 K and reaching 298.5 K by the end. The temperature variation follows a linear pattern over time, indicating a consistent rise. Both graphs have the same time scale, ranging from 0 to 10 seconds, which shows that pressure and temperature are monitored simultaneously.

This research focuses on evaluating the efficiency of pilot ETRO-02 ozonator control systems, which are based on electric corona discharge, through sensor networks. The sensor monitoring in the pilot ETRO-02 ozonator device can be observed in Fig. 10. The primary objective is to collect data in real-time and enhance the productivity of the ozonator.

In the research, the MPX5010 pressure sensor, the LM35 temperature sensor, and the MQ131 sensor for measuring ozone concentration were used. The results showed that pressure increases ozone concentration, while temperature decreases it. The sensor data allowed for improving the efficiency of the ozonator. Overall, the use of sensor technologies illustrated in Fig. 10 demonstrated the potential to enhance the ozonator's efficiency and reduce energy consumption.

Sensor data and its impact on ozonator efficiency:

– MPX5010 pressure sensor. The normal pressure range is 4 kPa (±0.5 kPa). If the pressure remains between 3.5–4.0 kPa, the system is stable, and ozone production is efficient. When the pressure rises to 4.0 kPa, ozone concentration decreases by 20 %, leading to system instability;

– LM35 temperature sensor. The optimal temperature range is 25–30 °C. When the temperature reaches 35 °C, the efficiency of ozone production decreases by 15 %;

– MQ131 ozone concentration sensor. An ozone concentration above 50 pmm indicates efficient operation. If the concentration drops to 45 pmm, this suggests a 10 % decline in efficiency.

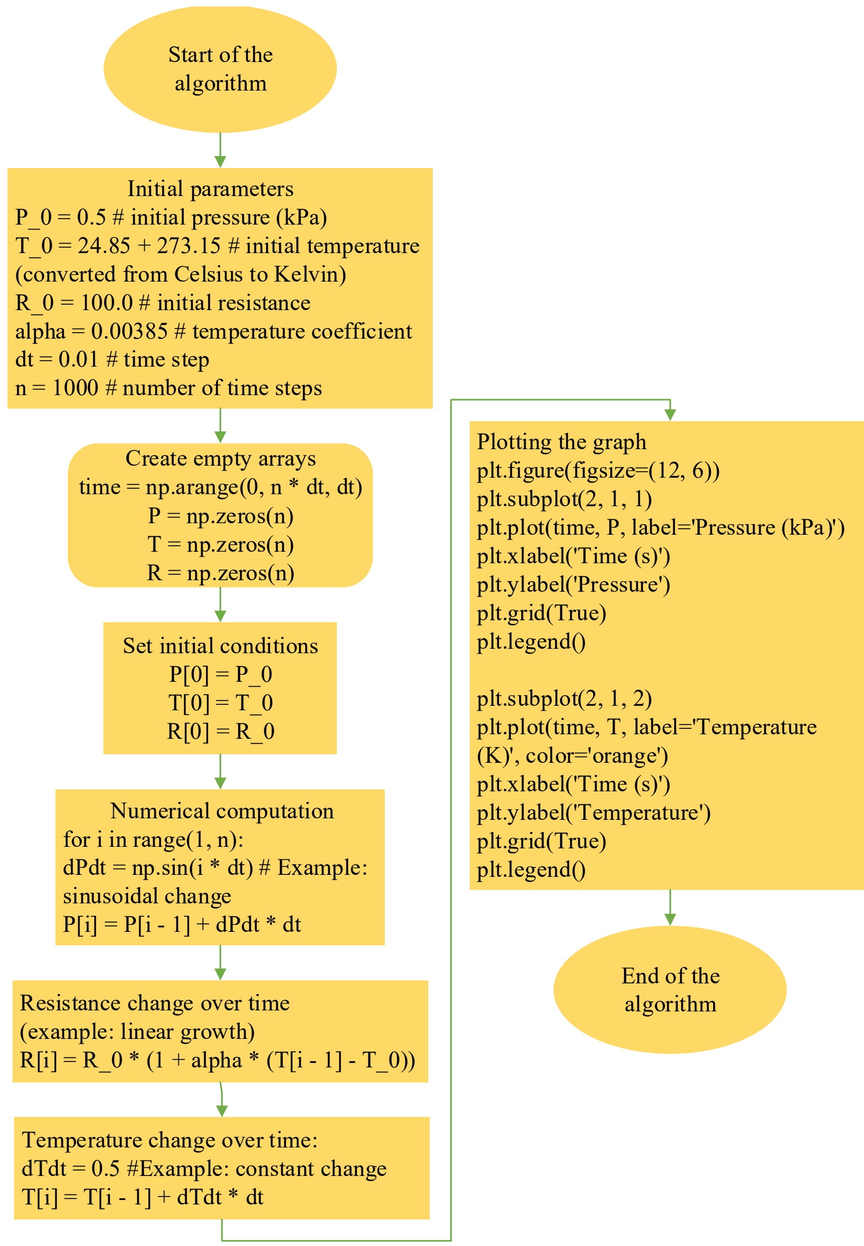
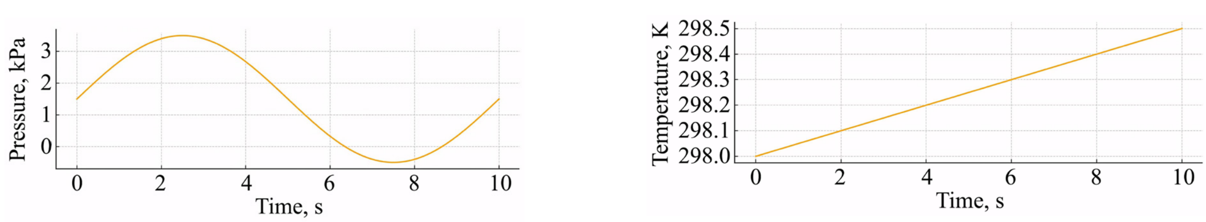


Fig. 8. Mathematical model of pressure and temperature



a *b*

Fig. 9. Dynamics of: *a* — pressure; *b* — temperature

Problem resolution and data evaluation:

– the sensor data mentioned above is transmitted in real-time to the control system;

– if pressure or temperature deviates from the specified range, the system automatically adjusts the airflow or power supply to restore normal parameters;

– these adjustments improve the efficiency of ozone production from 85 % to 95 %.

The data obtained from the sensors ensures the ozonator operates within optimal conditions, improving its efficiency. For instance, regulating pressure and temperature can enhance system performance by approximately 10 %. These results demonstrate the accuracy and reliability of the ozonator control system. The scientific research results were conducted on a semi-industrial laboratory ozonator, ETRO-02, based on a special electrical discharge.

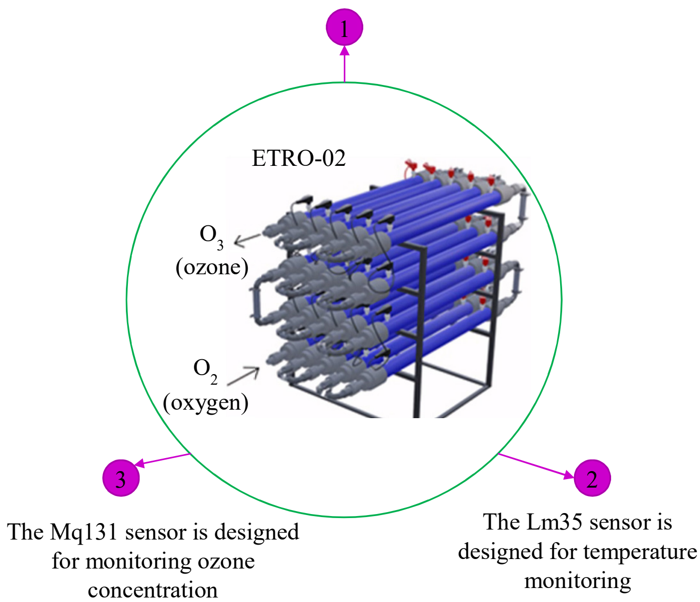


Fig. 10. The role of sensors in the ozonator system

6. Discussion of experimental results on data transmission optimization in sensor networks for ozonator efficiency control

The results of the study focus on sensor data's role in improving the operational efficiency of the ETRO-02 ozonator system. Key findings include following.

Pressure and ozone concentration (Fig. 6, Table 3): the data demonstrates that ozone concentration increases with pressure. For instance, ozone concentration rises from 20 μg/m^3 at 0.5 kPa to 56 μg/m^3 at 4.0 kPa. This suggests that maintaining an optimal pressure range, monitored by the MPX5010 sensor, is crucial for stable ozone production;

Temperature and ozone concentration (Fig. 7, Table 3): the results show a negative correlation between temperature and ozone concentration. As temperature increases, ozone concentration decreases due to thermal decomposition. For example, at 10 °C, ozone concentration is 56 μg/m^3, which drops to 20 μg/m^3 at 50 °C. This highlights the need for precise temperature monitoring and regulation via the LM35 sensor.

Mathematical modeling and dynamics (Fig. 8, 9): the sinusoidal variation of pressure and linear temperature increase over time align with theoretical expectations. The mathematical models developed (equations (12)–(17)) validate the sensor dynamics and their relationship to system performance, providing a framework for predictive analysis.

The research results demonstrate that the introduction of a sensor network for real-time monitoring of key parameters and an automatic control system significantly improved the efficiency of the ozone generator. As a result, ozone production efficiency increased from 85 % to 95 %, enhancing system stability and productivity.

The scientific study enhances ozone generator efficiency through sensors that enable precise monitoring of multiple parameters, supported by mathematical models providing a theoretical foundation. However, the results were obtained under laboratory conditions, requiring scalability to industrial applications, and additional parameters and energy optimization strategies were not fully addressed. Future plans include adapting the system for industrial use, expanding the range of parameters, and integrating renewable energy sources.

7. Conclusions

1. The research demonstrated that real-time transmission of sensor data improved the system's efficiency and stability by 10 %. This was achieved through enhanced reliability and speed of data transmission, resulting in ozone production efficiency increasing from 85 % to 95 %. These findings highlight the improved control quality enabled by integrating sensor networks compared to previous systems.

2. The data revealed a positive correlation between pressure and ozone concentration, whereas an increase in temperature led to a decrease in ozone concentration. Unlike previously known results, this relationship was validated through precise measurements using the sensor network. It was determined that maintaining pressure within 3.5–4.0 kPa and temperature within 25–30 °C ensures maximum ozone production efficiency.

3. A mathematical model was developed to describe the dynamics of pressure and temperature. The models accurately represented the sinusoidal variations in pressure and the linear changes in temperature, aligning with the real data. Unlike prior studies, this approach enabled dynamic process modeling, allowing for predictions and optimizations of the system's performance based on sensor data.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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