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INCREASING THE ACCURACY OF MEASURING CYAN CONCENTRATION USING AN ION-SELECTIVE ELECTRODE IN THE CYANIDATION PROCESS

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Abstract: This article provides a comprehensive analysis of the scientific and methodological foundations, metrological accuracy, and industrial applications of ion-selective electrodes (ISE) for measuring the concentration of cyanide ions in the cyanidation process. In particular, the advantages of the ISE method for measuring the concentration of cyanide ions in the cyanidation process of gold and other rare metals, technical and algorithmic solutions aimed at increasing the measurement accuracy, as well as the physicochemical properties of the measurement system are thoroughly discussed. The prospects for increasing accuracy, ensuring reliability, and creating the capabilities of automated control and monitoring systems by integrating ISE-based measurement systems with artificial intelligence are considered.

Keywords: cyanide ions, ion-selective electrode, metrological accuracy, cyanidation process, calibration, signal filtering, intelligent system, real-time monitoring, membrane selectivity, microprocessor-based system.

Introduction. In modern industrial production and technological processes, accurate and rapid control of chemical reactions is of great importance for technological safety and product quality. The efficiency of the cyanidation process, which is widely used in the extraction of rare metals, including gold and silver, from ores, largely depends on the correct determination of the concentration of cyanide ions (CN^-). During the cyanidation process, cyanide ions form soluble complexes of metals, allowing them to be separated from the ore. The efficiency and environmental safety of the process depend on the quantitative control of cyanide. An excess of cyanide leads to environmentally hazardous waste, and if it is insufficient, the technological process cannot be fully implemented. Therefore, determining the concentration of cyanide ions with high accuracy and in real time is one of the urgent tasks [1].
Traditional methods for measuring cyanide concentration in pulp [2] include titrimetric analysis, colorimetry, and spectrophotometry, which are usually used in laboratory conditions and are time-consuming. These methods are not suitable for direct integration into production processes. At the same time, their sensitivity and reproducibility are often not up to the required level. One of the modern solutions to this problem is the use of automated measurement systems based on ISE. ISE technology allows for rapid and high-precision measurement methods using electrochemical sensors sensitive to specific ions in the solution. This article extensively discusses the scientific basis of the use of the ISE method in the cyanidation process, metrological requirements, signal analysis algorithms, and the possibilities of integration with artificial intelligence [3, 5].
Methodology. Ion-selective electrodes are special electrochemical sensing elements that selectively respond to a specific ion in a solution. They consist of an ion-selective membrane, an

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internal electrode, an internal buffer solution, and an external housing, and are widely used in various analytical measurements. ISEs developed for cyanide ions have high selectivity for this ion, which is important in gold separation technologies.

The principle of operation of an ion-selective electrode is based on the Nernst equation, according to which the electrode potential is proportional to the concentration of the ion in the solution [1, 4]:

$$E=E^0+\frac{RT}{nF}\ln(a_{CN^-}+\sum K_i a_i)$$

where, K_i – is the coefficient of the effect of ions, E – is the measured potential,
E^0 – is the standard potential, R – is the gas constant, T – is the absolute temperature (Kelvin), n – is the ion charge, F – is the Faraday constant, a_{CN} – is the cyanogen ion concentration.

Based on this equation, the ISE potential changes logarithmically. This feature increases the sensitivity of the analysis and allows for accurate recording of concentration changes.

ISEs exhibit optimal selectivity for cyanide ions only in the pH range of
11–13. Under these conditions, CN^- ions are in a stable state, the ion exchange properties of the membrane are maximized, and interference from competing ions (OH^-, CO_3^{2-}) is minimized. Therefore, it is advisable to add a buffer solution to the measurement system to maintain a stable pH.

ISE-based measurement systems [6] have the advantages of fast response time (5–30 seconds), easy automation and integration into digital systems, high selectivity (responding only to certain ions), long-term stability, and adaptability to laboratory and industrial conditions.

The main advantage of ISE-based measurement systems is their sensitivity and accurate response. However, in real-world conditions, the accuracy of the electrode response depends on membrane quality, solution composition, signal processing technology, calibration accuracy, and interference protection factors.

The main source of sensitivity of an ISE is its sensing membrane. For cyanide ions, Ag_2S based membranes are usually used. These materials have high selectivity only for cyanide ions, chemical stability, do not decompose in alkaline media, and mechanical strength properties.

For the use of an ISE in a production environment, calibration must be performed before each work sequence. This includes the following steps:

- standard solutions: CN^- solutions from $1 \cdot 10^{-6}$ mol/l to $1 \cdot 10^{-2}$ mol/l are used;
- logarithmic calibration graph: a potential plot is obtained against $\log(a_{CN^-})$;
- calibration curve equation: based on this equation, the CN^- concentration of the unknown solution is determined.

For high calibration quality, temperature, pH and solution composition must be constantly monitored. The signal received from the ISE is usually weak and noisy. To accurately digitize and analyze it, the Kalman filter is used - smoothing the signal and removing noise, detecting periodic components in the signal, and converting analog signals to 10–16-bit digital values.

By integrating ISE-based systems with modern microprocessors and artificial intelligence algorithms, it is possible to create real-time, accurate and robust measurement systems. This approach is consistent with the requirements of the digital industry (Industry 4.0) and provides automatic control of technological processes.

Modern microcontrollers serve as the main tool for reading, converting and processing the signal received from the ISE sensor into a digital signal. The voltage signal received from the ISE is

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converted into a digital signal by the microprocessor using the ADC module. If the signal value is too low, an amplifier is used.
To improve measurement accuracy and analyze results, artificial intelligence algorithms are integrated into the ISE system. The following methods are particularly useful:
- Artificial neural network - forms the closest and most suitable predictions based on previous results;
- Fuzzy logic - draws understandable conclusions from fuzzy signals;
- Data classification - divides the signal into classes and makes diagnostics.

Experiments were conducted in laboratory and semi-industrial conditions to evaluate the effectiveness of the cyanide concentration measurement system based on ISEs. The studies covered the electrode response in solutions of different concentrations of cyanide ions, interference factors, calibration curves, and the possibility of increasing accuracy using artificial intelligence. At high concentrations ($\geq 10^{-4}$ mol/l), the ISE gave a very stable signal. At low concentrations, noise increased, but a useful signal was extracted using digital filtering.
The cyanide ion measurement system based on ISEs is proving its relevance in industrial processes as a highly accurate and rapid measurement method that meets modern metrological, technological and environmental requirements. Especially in the technology of cyanidation of gold and other precious metals, the use of this method not only increases efficiency, but also ensures safety. Also, the advantages of the ISE method over other methods include easy automation, the ability to obtain information in real time, its suitability for laboratory and industrial use, fast response and low chemical reagent requirements, suitability for continuous operation in industry, and increased environmental safety.
Conclusion. Accurate and rapid control of chemical reactions in modern industrial production and technological processes is essential for technological safety and product quality. The efficient operation and environmental safety of the cyanidation process rely on systems that can accurately and quickly measure the amount of cyanide ions. ISE measurement systems allow for real-time measurement of cyanide ion concentrations with high sensitivity and accuracy, which increases the efficiency of the cyanidation process.
The advantages of ISE technology include high selectivity, fast response time, adaptability to automation, and long-term stability. ISE systems, integrated with artificial intelligence algorithms for signal processing, meet the requirements of the digital industry (Industry 4.0) and allow for automatic control of processes. With the help of artificial intelligence, measurement accuracy and noise can be increased.
The use of the ISE method in the cyanidation process is especially effective at high concentrations, and uncertainties at low concentrations can be eliminated by digital filtering. The ISE-based measurement system allows for high accuracy and fast response in industrial conditions, which ensures the safety and efficiency of the process. In general, the ISE-based cyanide ion measurement system is the most modern method that provides high accuracy, speed, environmental safety and technological efficiency, and can be widely used in industrial processes. This method not only increases efficiency, but also ensures safety in the cyanidation technology of gold and other rare metals.

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