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STUDY OF METHODS FOR DETERMINING THE COMPOSITION OF GAS SUPPLIED TO GAS-FIRED FURNACES AND MONITORING CO CONTENT IN FLUE GASES

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Abstract

This article investigates methods for determining the composition of gas supplied to industrial gas-fired furnaces and for monitoring the concentration of CO in flue gases in order to improve the efficiency of the combustion process. Analysis of gas composition and control of CO concentration make it possible to ensure optimal combustion conditions, reduce fuel consumption, and minimize the emission of harmful substances into the environment. The study considers the possibilities of using gas analyzers, sensors, and intelligent control methods.

Keywords: Gas-fired furnace, combustion process, CO monitoring, gas analyzer, sensor, environmental monitoring.

Introduction

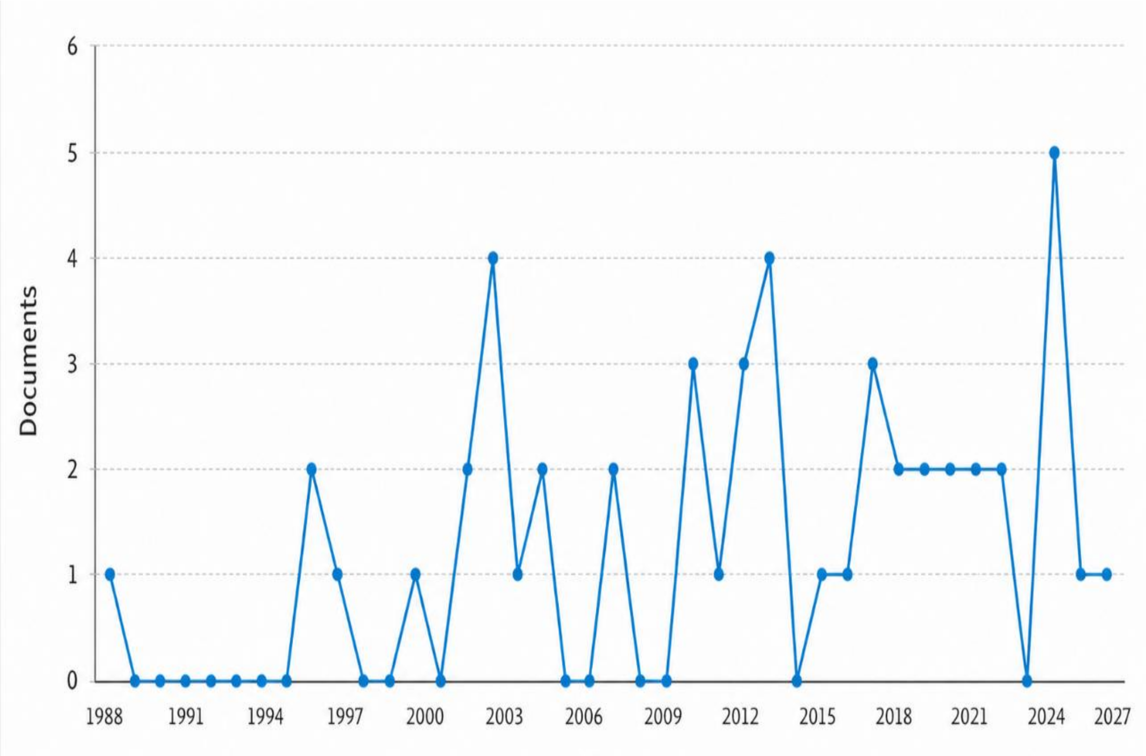
Gas-fired furnaces are widely used in industrial enterprises, particularly in metallurgy, chemical production, oil and gas industries, and the manufacturing of construction materials. The efficiency of the combustion process in such furnaces largely depends on the gas composition, the air-to-gas ratio, and the composition of combustion products.

If the gas composition is not properly controlled during combustion, incomplete fuel combustion may occur, leading to an increased concentration of CO (carbon monoxide) in the flue gases. This results in:

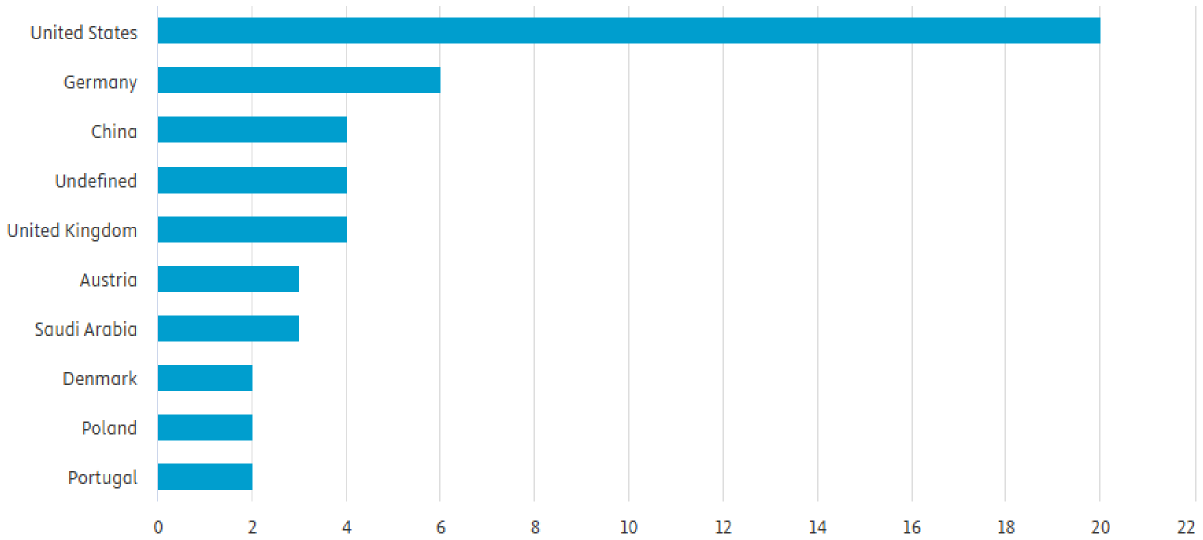
- Reduced energy efficiency
- Increased fuel consumption
- Higher emissions of harmful gases into the atmosphere

Therefore, determining the gas composition and continuously monitoring CO concentration in industrial furnaces is one of the key technical tasks [8–10].

An analysis of the literature published in internationally indexed scientific information platforms shows that over the past 30 years, the number of scientific publications devoted to gas composition measurement has been steadily increasing. This clearly confirms the high relevance of this research topic.



Yearly dynamics of scientific publications on monitoring co concentration in gas mixtures



Number of documents by country

Methods for Determining Gas Composition in Gas-Fired Furnaces

The following methods are used to determine the composition of gas in gas-fired furnaces:

Catalytic (Pellistor) Method

Catalytic (pellistor) gas analyzers are mainly used to determine the concentration of combustible gases (such as methane, propane, butane, etc.). Their operating principle is based on measuring the heat released during the catalytic oxidation process.

Basic Operating Mechanism

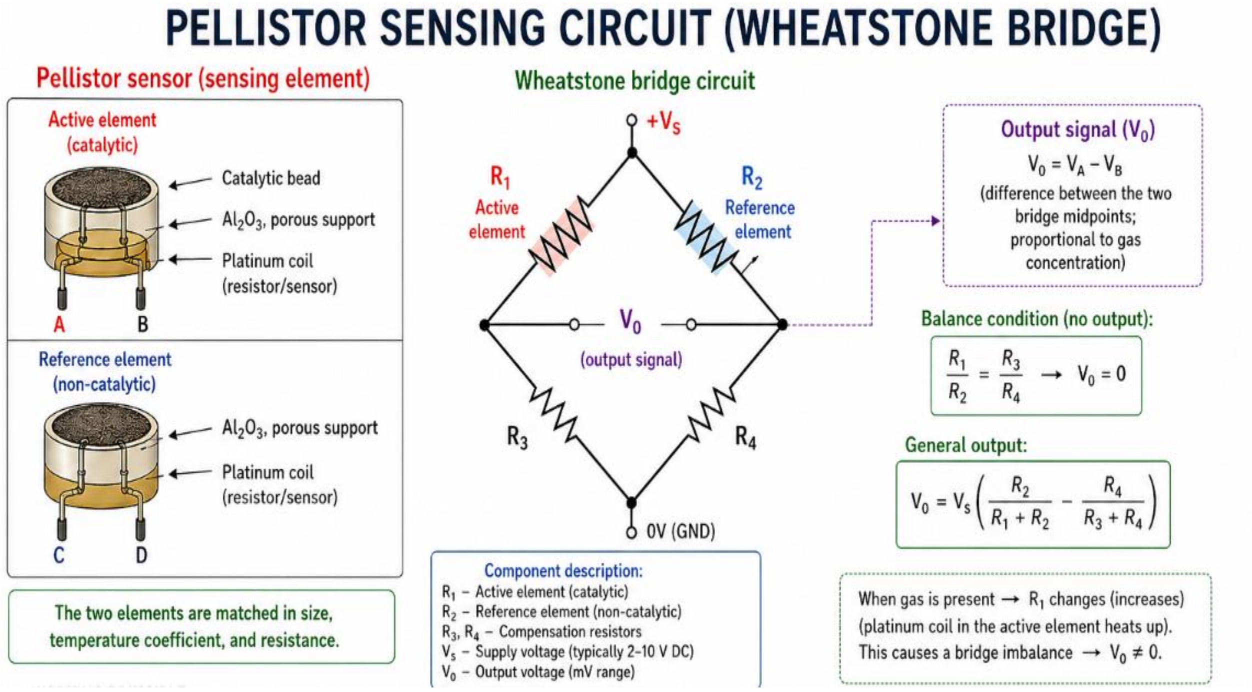
A pellistor sensor typically consists of two elements:
1. Active (catalytic) element
2. Reference element

The operating procedure is as follows:
- The sensor element is heated by an electric current
- The gas (for example, methane) reaches the sensor surface
- In the presence of a catalyst (usually platinum or palladium), the gas is oxidized (burned)
- Heat is released during this process
- As the temperature increases, the electrical resistance of the sensor changes

-This change is measured to determine the gas concentration

General Chemical Equation

Combustible gas + $O_2 \rightarrow CO_2 + H_2O$ + heat

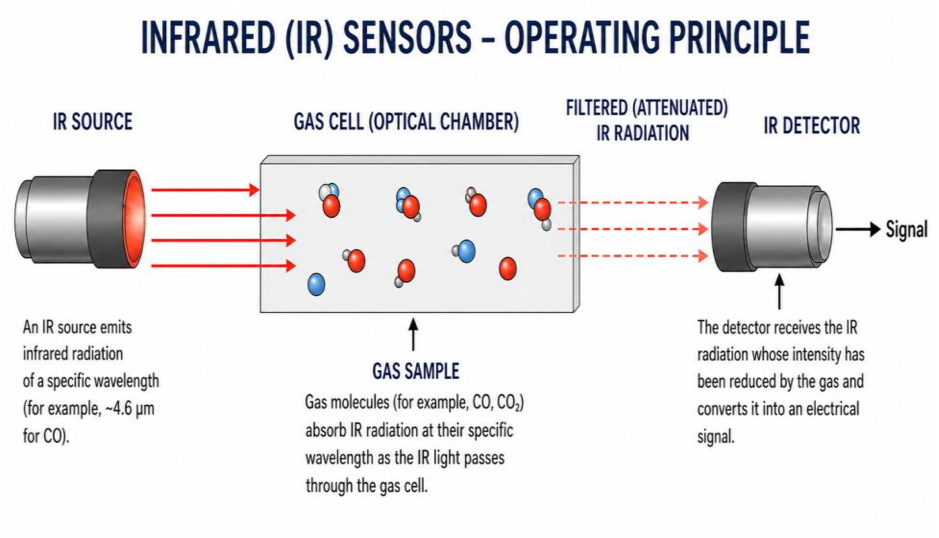


Advantages: simple and reliable design, provides fast real-time response, widely used in industry.

Disadvantages: operates only for combustible gases, requires the presence of oxygen (for oxidation) the catalyst may become “poisoned” over time (e.g., due to silicon or sulfur compounds), relatively high energy consumption.

Application Areas: oil and gas industry, chemical plants, mines, fuel storage facilities.

The catalytic (pellistor) method is one of the most reliable and widely used methods for detecting combustible gases. However, its effective operation requires the presence of oxygen and a clean sensor environment [2,3].



Infrared radiation is mainly used to measure the following gases at their corresponding wavelengths:

- CO (4.6 µm)
- CO_2 (4.3 µm)
- CH_4 (3.3 µm)
- SO_2 (7.3 µm)
- NO (5.3 µm)
- NO_2 (6.2 µm)

The absorption of infrared radiation follows the Beer–Lambert law, according to which the gas concentration is determined by the following formula:

$$I = I_0 \cdot e^{-kCL} \quad (1)$$

where: I_0 – incident light intensity, I – transmitted light intensity, I – absorption coefficient of the gas (cm^{-1}), C – gas concentration (mol/cm^3, ppm, or %), L – optical path length (cm)

Advantages (in high-temperature flue gases): non-contact measurement (optical method), high accuracy and stability, continuous (real-time) monitoring, widely used in industrial furnaces, ideal for CO and CO_2 measurement.

Disadvantages: expensive, sensitive to humidity and dust, not suitable for all gases (only ir-active gases), requires temperature compensation.

There are several difficulties in direct measurement of high-temperature flue gases:

- Gas temperature alters the absorption spectrum, leading to measurement errors

- Water vapor also absorbs infrared radiation, which introduces errors in CO concentration measurement
- Dust and soot block the optical path, reducing signal strength
- Contamination of optical elements: the sensor window becomes dirty, decreasing accuracy

Methods of Using Infrared Sensors

Infrared sensors are used in two main ways:

1) Gas Preparation System (most important)

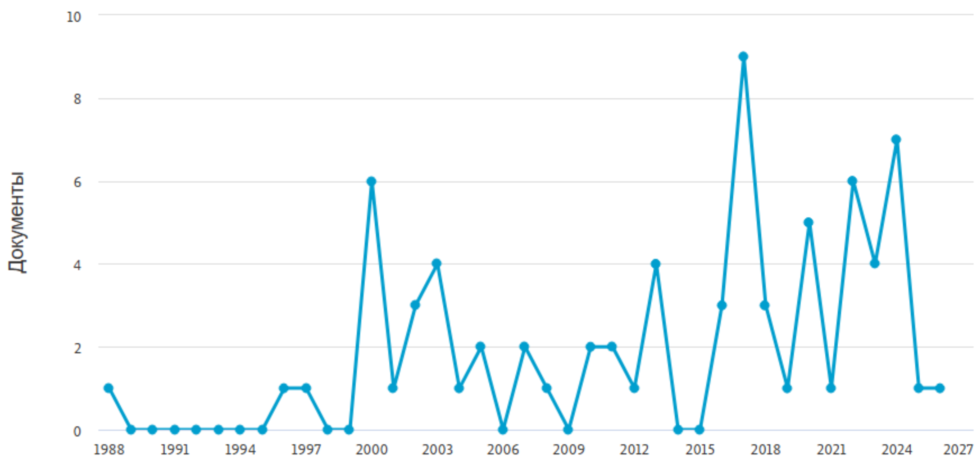
In this method, flue gases pass through a preparation stage including filters, a cooler, and a dryer before being delivered to the infrared sensor. This is considered the most reliable method (extractive method).

2) In-situ IR Sensors (direct method)

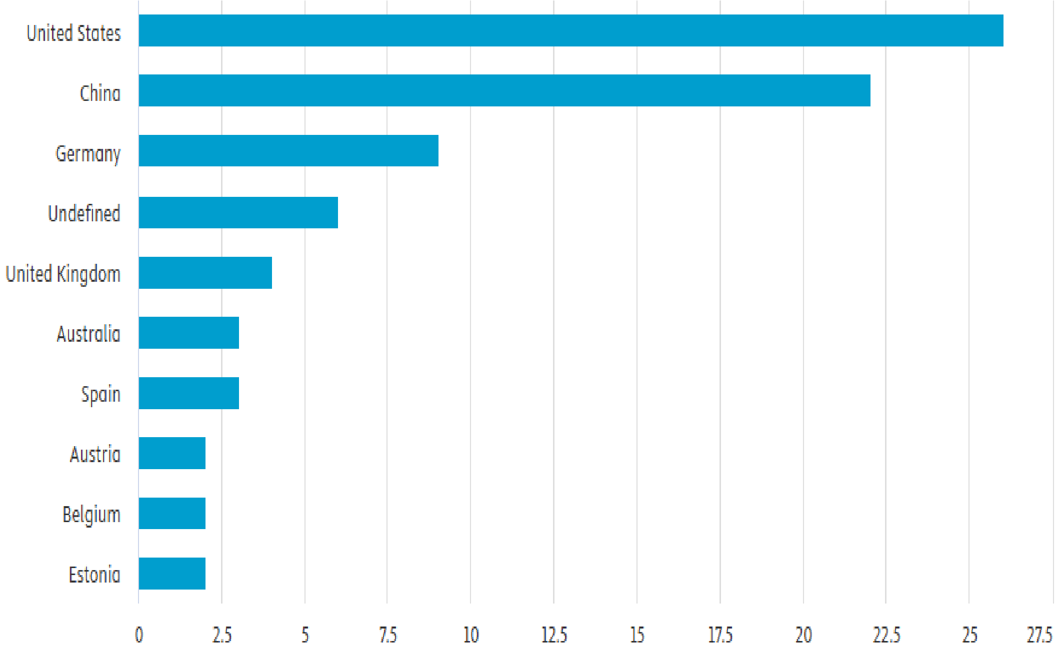
In this approach, infrared sensors are installed directly in the flue gas path. This allows very fast real-time measurements. However:

- Dust, vapor, and aerosols affect accuracy
- Cleanliness of the optical path is critical
- Calibration is more complex

Below is the dynamics of the number of scientific publications devoted specifically to optical methods and devices for gas composition monitoring.



Dynamics of scientific publications by year on optical methods for determining gas composition

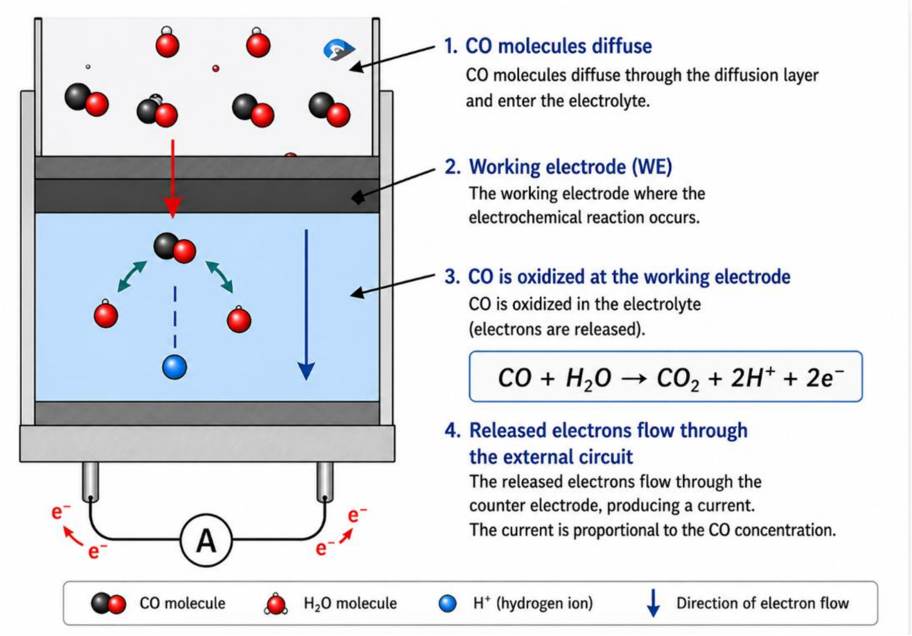


Number of documents by country

Infrared sensors are an effective method for determining CO concentration in high-temperature flue gases, offering high accuracy and stability. However, direct measurements in such environments may lead to errors due to the influence of temperature, humidity, and aerosol particles. Therefore, in practice, it is advisable to use them in combination with gas preparation systems that include cooling, drying, and filtration. Such an approach ensures accurate and stable measurement of CO concentration and enables efficient control of the combustion process [1, 6].

Electrochemical Sensors

Electrochemical sensors are devices used to detect specific components in gas mixtures—particularly gases such as CO, H_2S, NO_2, SO_2, and O_2—based on chemical-electrical reactions.



The most common reactions occurring in electrochemical sensors are as follows:

Gas	Reaction at the Working Electrode	Typical Measurement Range
CO	$CO + H_2O \rightarrow CO_2 + 2H^+ + 2e^-$	0 – 1000 ppm
H_2S	$H_2S \rightarrow S + 2H^+ + 2e^-$	0 – 100 ppm
NO_2	$NO_2 + H_2O \rightarrow HNO_2 + H^+ + e^-$	0 – 20 ppm
SO_2	$SO_2 + 2H_2O \rightarrow SO_4^{2-} + 4H^+ + 2e^-$	0 – 20 ppm
O_2	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	0 – 25 %
Cl_2	$Cl_2 + 2e^- \rightarrow 2Cl^-$	0 – 10 ppm

When gas enters the sensor, an oxidation or reduction reaction occurs at the electrode surface. The electric current generated as a result of this reaction is proportional to the gas concentration:

$$I = k \cdot C \tag{2}$$

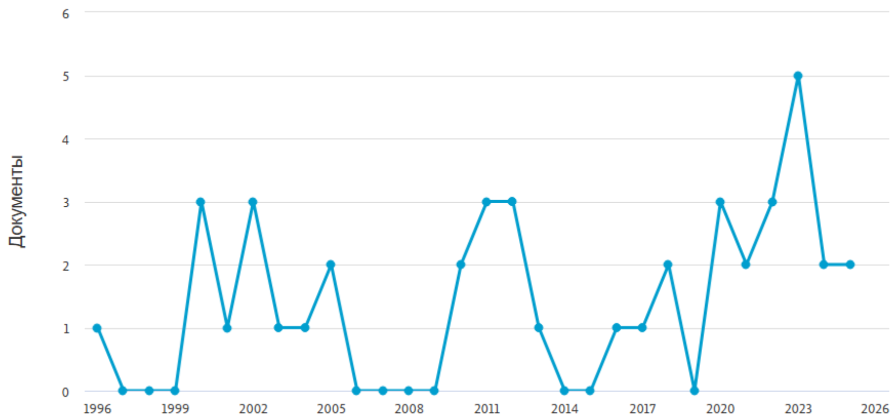
where: I – sensor current, C – gas concentration, k – sensor coefficient

Electrochemical sensors are highly suitable for detecting carbon monoxide (CO) at low and medium concentrations. Therefore, they are widely used in: gas leak detection systems, occupational safety systems, portable gas analyzers, certain industrial monitoring systems.

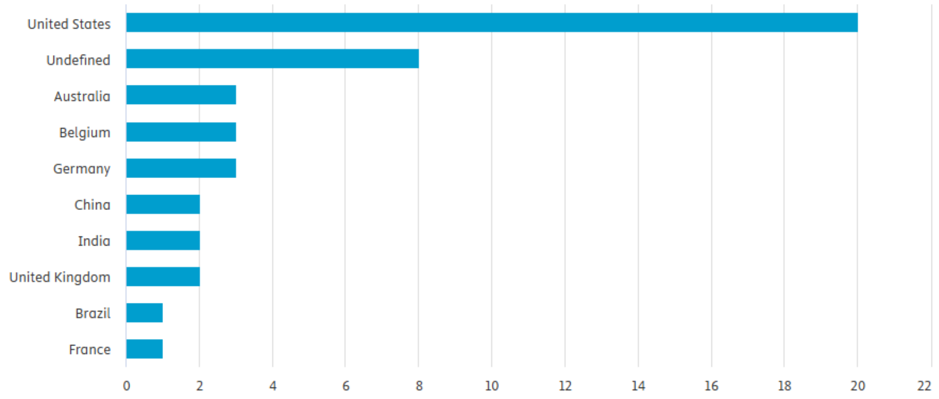
Advantages: high sensitivity, ability to detect low concentrations, compact size, low energy consumption, relatively low cost, highly suitable for portable devices

Disadvantages: limited service life, requires periodic calibration, measurement errors may increase at high temperature and high humidity, possible interference from other gases, reduced stability in contaminated and dusty environments.

In industrial furnaces, electrochemical sensors can be used to detect CO; however, it is advisable to use them not directly in high-temperature flue gases, but in cooled and conditioned gas samples. This is because high temperature, humidity, and aggressive environments negatively affect sensor reliability.



Yearly trends in scientific publications on electrochemical gas composition analysis



Number of Documents by Country

Electrochemical sensors are sensitive and cost-effective tools for monitoring CO gas. They are particularly effective in detecting low concentrations and are widely used in portable or local monitoring systems. However, for application in high-temperature flue gases of industrial gas-fired furnaces, it is necessary to pre-condition the gas sample by cooling, drying, and filtering.

Comparative Analysis of the Above Methods

Method	Accuracy	Cost	Advantages	Disadvantages
Catalytic (pellistor) method	Medium	Medium	Rapid detection of combustible gases, reliable, widely used in industry	Only for combustible gases, requires oxygen, sensor poisoning possible
IR sensor	High	Medium / High	Stable, fast, non-contact measurement, long service life	Not suitable for all gases, some gases do not absorb IR radiation
Electrochemical	Medium	Low	Compact, sensitive, low energy consumption	Limited lifespan, sensitive to temperature and humidity

Selection Criteria for Gas Composition Measurement Methods

The choice of a gas composition measurement method depends on the following factors:

- Required accuracy
- Operating environment (dust, humidity)
- Cost considerations
- Level of automation

Based on these requirements, the most effective solution is selected for industrial gas-fired furnaces. The results enable accurate CO monitoring, optimization of the combustion process, and reduction of environmental emissions [1–10].

Optimization of the Combustion Process

Optimization of the combustion process is a set of measures aimed at ensuring the most complete and efficient combustion of fuel, increasing the level of heat utilization, and reducing CO, NO_x, and other harmful emissions.

The main objective is to improve combustion efficiency through effective control of CO concentration.

An increase in CO concentration is associated with the following factors:

- Insufficient air supply
- Poor mixing of gas and air
- Low temperature in the combustion chamber

Objectives of Combustion Optimization

- Reduction of fuel consumption

- Increase in thermal efficiency
- Reduction of CO concentration
- Stabilization of technological temperature
- Improvement of environmental performance

Air–Fuel Ratio Optimization

One of the key directions in optimization is the correct selection of the gas–air ratio. This ratio is defined as:

$$\lambda = \frac{L_{real}}{L_{theor}} \tag{3}$$

where: λ – excess air ratio coefficient, L_{real} – actual air supply, L_{theor} – theoretically required air amount for complete combustion of a unit volume of gas

If the air supply is insufficient, the fuel does not burn completely, leading to increased CO concentration and fuel losses. If excess air is supplied, part of the heat is carried away with the air, reducing efficiency. Therefore, in practice, the optimal range is often considered to be:

$\lambda \approx 1.05$ to 1.15

Intelligent Control Methods

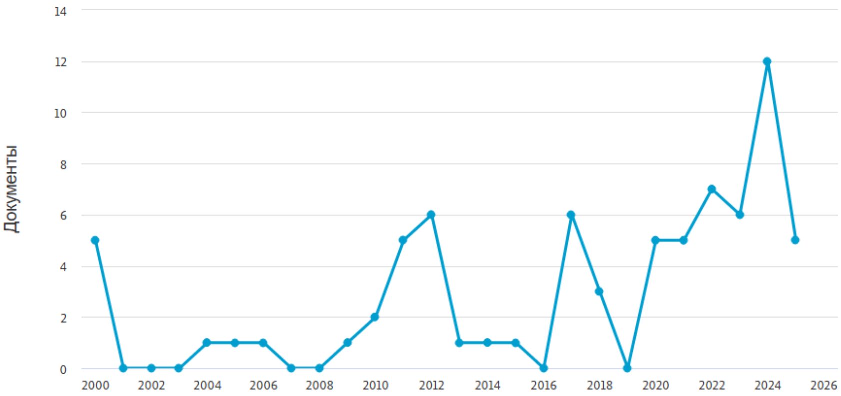
Intelligent methods for determining CO gas concentration involve the use of sensor data, mathematical models, and artificial intelligence algorithms to measure, predict, and control carbon monoxide levels.

Unlike conventional measurement methods, these approaches: take uncertainty into account, utilize multiple parameters simultaneously, enable real-time decision-making

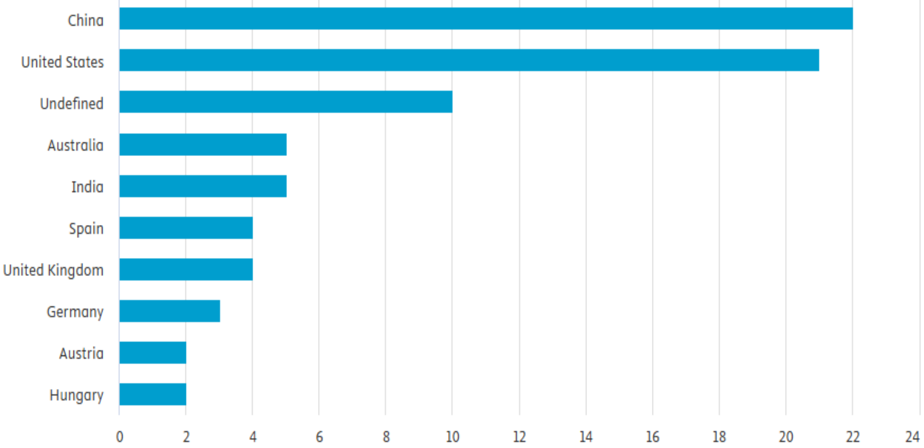
In industrial furnaces, co concentration depends on the following parameters: gas flow rate, air flow rate, temperature, pressure, oxygen (o_2) concentration, quality of mixing in the combustion chamber.

The dependence of combustion efficiency on these parameters is often nonlinear and uncertain. Therefore, analytical formulas do not always yield accurate results. For this reason, the application of intelligent methods has recently shown high effectiveness.

Below is the dynamic trend of the number of scientific and technical publications devoted to intelligent methods for gas composition determination. It can be observed that the importance and relevance of intelligent approaches are steadily increasing.



Yearly trends in scientific publications on intelligent methods for gas composition analysis



Number of Documents by Country

There are several intelligent methods for determining gas composition, some of which are described below.

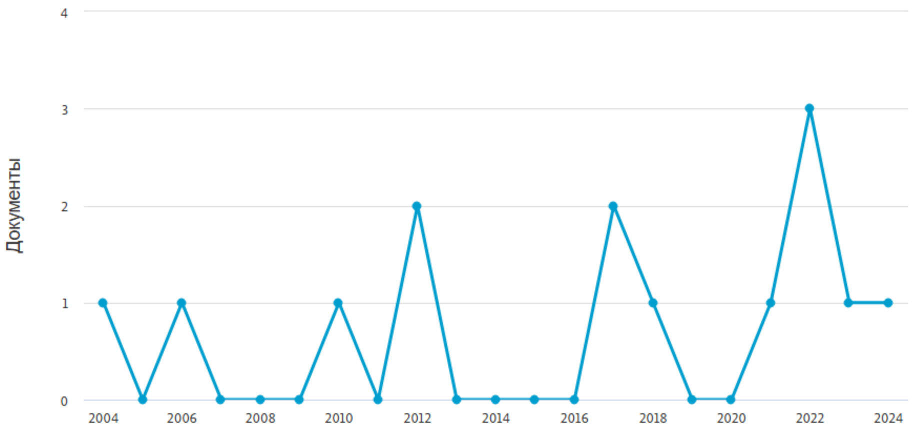
Fuzzy Logic Method

In this method, CO concentration is expressed not as precise numerical values, but in terms of linguistic variables such as *low CO*, *medium CO*, and *high CO*. The operating principle of this approach is based on rules formulated by experts. A typical rule can be expressed as follows:

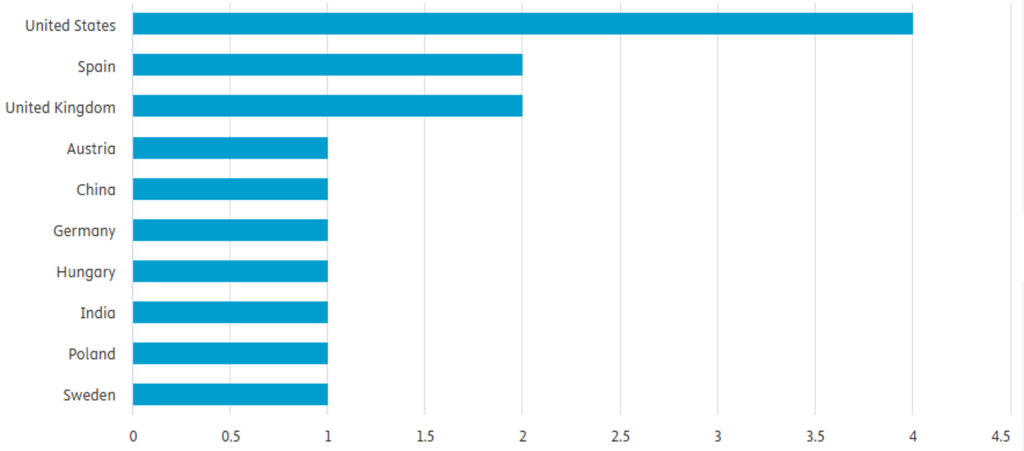
IF O_2 is low, **AND** temperature is medium, **AND** gas flow rate is high, **THEN** CO is high.

Advantages: performs well under conditions of uncertainty, allows incorporation of expert knowledge, enables representation of complex relationships that are difficult to express mathematically in the form of rules

Disadvantages: development of the rule base is complex, accuracy strongly depends on the quality of expert knowledge.
Below is the trend in the number of scientific publications devoted to determining gas composition using fuzzy logic. Statistical data indicate that this method has not lost its relevance.



Dynamics of the number of scientific publications by year on gas composition determination using fuzzy logic



Number of documents by country

Artificial Neural Networks

Artificial neural networks learn the CO concentration based on input parameters. Input parameter matrix: $x = \left[Q_{gaz}, Q_{havo}, T, O_2, P\right]$, output parameter: $y = C_{CO}$

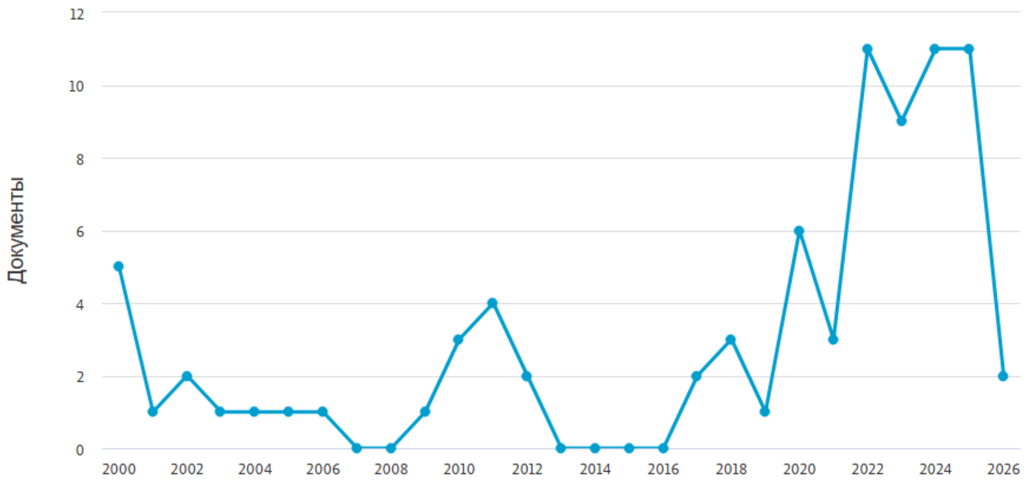
That is, $C_{CO} = f\left(Q_{gaz}, Q_{havo}, T, O_2, P\right)$

where $\boldsymbol{f}$ - is a nonlinear function learned by the neural network.

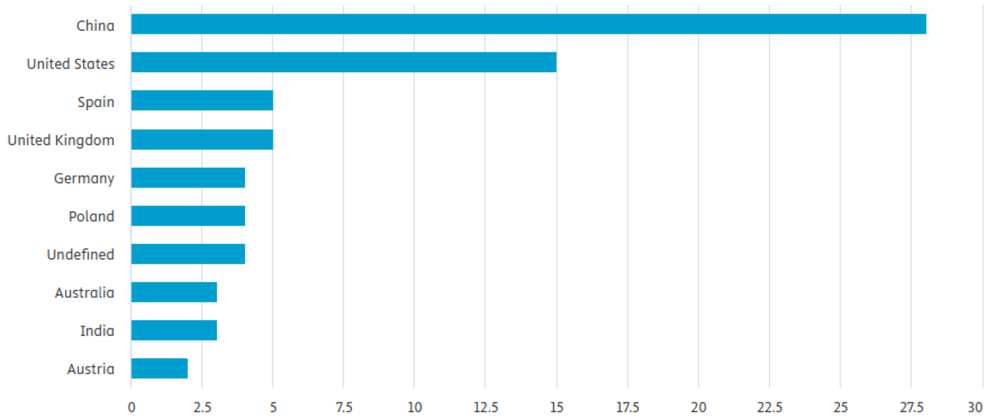
Advantages: effectively models complex nonlinear relationships, provides prediction (forecasting) capabilities

Disadvantages: requires a dataset for training the neural network, demands relatively high computational resources

Below is the increasing trend in the number of scientific publications devoted to the use of neural networks for gas composition determination. This indicates that the importance and relevance of this approach are steadily growing [11–15].



Yearly trends in scientific publications on neural networks for gas composition analysis



Number of documents by country

Neuro-Fuzzy Systems (ANFIS)

This method is a combination of an artificial neural network and fuzzy logic.

In ANFIS, fuzzy logic rules are stored, and their parameters are automatically adjusted, providing adaptive capabilities.

Advantages: Incorporation of expert knowledge through fuzzy logic, Adaptability based on neural network learning

Disadvantages: Complexity of the model structure, Requires more computational resources and time for tuning.

Today, intelligent methods are widely applied in industrial gas-fired furnaces, boiler systems, metallurgical units, flue gas monitoring, and environmental control systems, helping to ensure high efficiency.

Intelligent methods for determining CO gas concentration are considered more effective compared to traditional measurement and analytical models. In particular, fuzzy logic, artificial neural networks, and ANFIS methods make it possible to estimate CO concentration with high accuracy by taking into account the nonlinear and uncertain characteristics of the combustion process. Such approaches contribute to improving combustion efficiency in industrial furnaces, reducing fuel consumption, and lowering environmental emissions [11–15].

Conclusion

Determining the gas composition and monitoring CO concentration in gas-fired furnaces are of great importance for improving combustion efficiency. Continuous monitoring of combustion products using gas analyzers and sensors makes it possible to reduce fuel consumption and ensure environmental safety.

By implementing intelligent control systems, it is possible to optimize the combustion process and increase the energy efficiency of industrial furnaces.

The analysis of these studies shows that effective emission control in gas-fired furnaces and energy systems cannot be limited to measurement alone, but also requires adaptive control of the combustion process based on intelligent methods. The trade-off between CO and NO_x emissions, the nonlinear and non-stationary nature of the process, and the presence of external disturbances demonstrate the limitations of classical control methods. Therefore, as a modern approach, the integration of continuous emission monitoring systems (CEMS), data analysis, and intelligent control systems based on fuzzy logic and neural networks is considered the most appropriate solution.

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