Технічні науки

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FIBER-OPTIC SENSORS FOR MONITORING GAS LEAKS AND TEMPERATURE IN INDUSTRIAL FACILITIES

Summary. *The article discusses the theoretical foundations and practical application of fiber-optic sensors (FOS) for detecting gas leaks and monitoring temperatures at industrial facilities. A comprehensive analysis of the operating principles of FOS, their classification, signal modulation methods, and distributed sensing is carried out. Particular attention is paid to their application in aggressive environments, including in the oil and gas, chemical, and energy industries. The advantages and limitations of the technology are presented, as well as the prospects for its development within the framework of industrial digitalization and the implementation of IoT solutions. Directions for further research, including intelligent signal analysis, increased selectivity, and standardization of application are considered separately.*

Key words: *fiber optic sensors, gas leak, temperature monitoring, industrial safety, DAS, DTS, FBG, distributed sensors, IoT, digitalization.*

Relevance of the study. Modern industry is faced with increasing demands for safety and environmental responsibility. Gas leaks and equipment overheating at industrial facilities such as pipelines, chemical and power plants pose a serious threat to the environment, personnel health and the sustainability of technological processes. Traditional monitoring methods, including point electrical sensors and visual inspections, often do not provide the necessary accuracy and efficiency in detecting anomalies, especially in long or hard-to-reach areas.

Fiber optic sensors (FOS) are a promising technology for monitoring temperature and gas leaks. They have high sensitivity, resistance to electromagnetic interference, the ability to work in aggressive environments and are capable of providing continuous monitoring over long distances. Distributed systems based on FOS allow detecting temperature changes and acoustic signals associated with leaks with high spatial resolution and accuracy. Despite the progress in the development of VOS, issues related to the optimization of data processing algorithms, increasing the accuracy of leak localization, and adapting systems to various industrial conditions remain unresolved. This emphasizes the need for further research in this area.

Purpose of the study. The purpose of this study is to analyze and evaluate the effectiveness of fiber optic sensors for gas leak detection and temperature monitoring at industrial facilities.

Materials and methods of the study. The methodological base of the study includes an analytical review of scientific and technical literature, data from industry reports, regulatory documents, and the results of a comparative analysis of the characteristics of sensor technologies.

The work uses a structural and functional approach to describing the types of optical optical systems, a classification method based on technical characteristics, and a comparative analysis of distributed and point systems. The principles of optical fiber physics, signal modulation, spectroscopy, and interferometry were used as an analysis tool.

Research Results. Until now, electrical, piezoelectric, acoustic, thermal, electromagnetic and other sensors attached to various points of the controlled structure have been used as sensor elements in embedded control systems. The quality of sensor attachment, the presence of high levels of noise and vibration during flight, strong electromagnetic fields, and additional mass made embedded control systems on attached sensors extremely unreliable. In this regard, the question arose of using sensor elements embedded in the material from which the controlled structure was made. In this case, it becomes possible to significantly reduce the dependence of the sensor signal on noise and vibration. Thus, a new class of materials appears - intelligent materials with sensory functions that respond to changes in external influences - loads, temperatures, etc. [3, p. 90].

A fiber-optic sensor is a small device in which optical fiber is used both as a data transmission line and as a sensitive element capable of detecting changes in various quantities [4]. Due to their unique properties, such as resistance to electromagnetic interference, the ability to work in aggressive environments and high sensitivity, optical fiber optical systems are widely used in various industries, including oil and gas, energy, construction and transport. Optical fiber optical systems operate based on changes in the characteristics of light propagating through an optical fiber under the influence of external physical factors. The main principles of operation include:

1. Amplitude modulation: changing the intensity of light in response to external stimuli.

2. Phase modulation: changing the phase of a light wave, which allows for the detection of deformations and vibrations.

3. Frequency modulation: shifting the frequency of light in response to changes in temperature or pressure.

Examples of analog modulated signals are shown in the figure below [5].

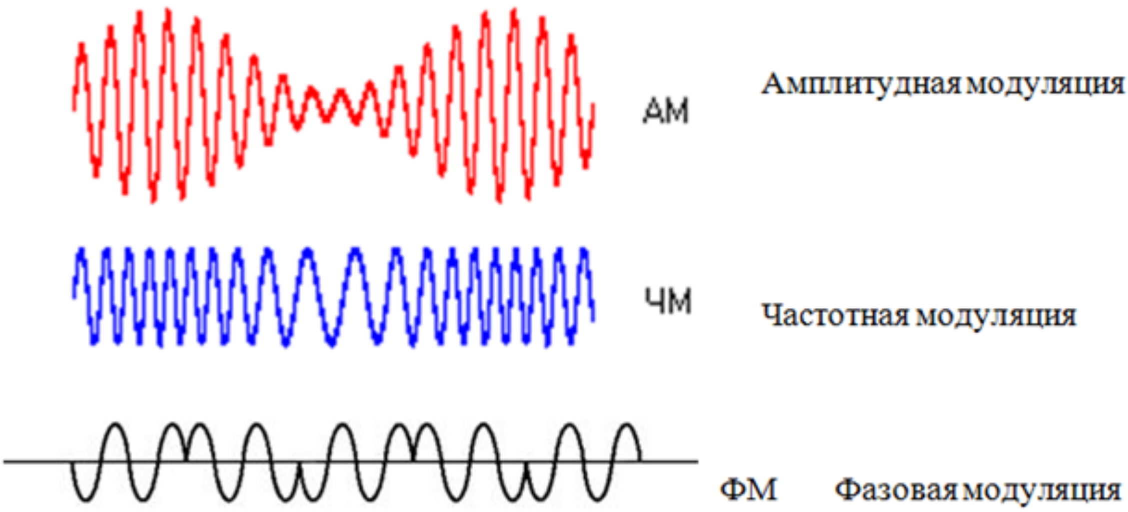

Fig. 1. Examples of analog modulated signals

VOS are classified according to various criteria (Table 1). Each type of sensor has its own characteristics and areas of application, which allows choosing the optimal solution for specific monitoring tasks.

Table 1

Classification of fiber optic sensors

Classification criterion	Types of sensors	Description / Features
By operating principle	- Interferometric; - Bragg gratings (FBG); - Distributed (DTS, DAS, DVS); - Polarization	Use phase, spectral, acoustic and temperature effects to detect external influences
By type of measured value	- Temperature; - Pressure; - Deformations; - Vibrations; - Gas analyzers	Allows you to monitor key parameters in real time
By placement method	- Point sensors; - Distributed sensors	Point sensors are fixed in a certain area, distributed sensors are sensitive along the entire length of the fiber.
By the method of signal modulation	- Amplitude; - Frequency; - Phase; - Polarization	Provide different ways of processing data with different sensitivity and accuracy
By fiber type	- Single-mode (SMF); - Multi-mode (MMF);	Single-mode cables are used when high precision is required, multi-mode

	- Photonic crystal	cables are used when transmitting large amounts of data.
By type of interaction environment	- Gas sensors; - Liquid sensors; - Solid sensors	Depends on the application: from gas leak monitoring to monitoring the condition of structures
By method of nutrition	- Passive; - Active	Passive ones do not require external power supply (use reflected/transmitted light), active ones contain built-in sources
By resistance to external conditions	- For standard environment; - For aggressive environment (acids, petroleum products, etc.)	Sensors can have protective coatings and shells adapted to operating conditions

Optical fiber optic systems operate based on changes in the characteristics of light passing through an optical fiber under the influence of external factors. The main technologies include:

1. Distributed acoustic sensing (DAS) - these are "virtual" microphones along an optical fiber. Standard single-mode fiber and Rayleigh scattering are used, where acoustic vibrations cause small changes in the refractive index, which are captured by this scattering. The fiber literally "hears" events occurring in the environment. The number of such microphones is a combination of spatial resolution, distance, and pulse duration. Modern systems can operate at distances of up to 80 km. Combining several devices into a single network allows for the creation of thousands of kilometers of monitoring lines [2, p. 382].

2. Diode laser absorption spectroscopy (DLAS) - used to measure the concentration of gases such as methane with high sensitivity and accuracy. The method is based on measuring the absorption of light of a certain wavelength by the target gas. 3. Fiber Bragg gratings (FBG) – respond to changes in temperature and pressure, which allows them to be used to detect leaks accompanied by such changes.

A fiber-optic system for monitoring the temperature state of power elements of power supply systems receives data on the operating temperature in real time, provides the necessary information on when maintenance and repairs are required. Equipment at power plants is switching from the "periodic maintenance" mode to "maintenance according to the real state", and this in turn is dictated by the current requirements in the electric power industry, where the principle of increasing efficiency and reducing costs is the basis for everything [1, p. 67].

The main advantages of using fiber-optic sensors (FOS) for monitoring gas leaks are presented in Table 2.

Table 2

Advantages of using VOS

Advantage	Description
High sensitivity	Detection of the slightest changes in environmental parameters, including micro gas leaks
Precise localization of leaks	Possibility of determining the location of a leak with an accuracy of up to a meter (in distributed systems)
Work in aggressive environments	Resistance to chemicals, moisture, high temperatures and pressure
Electromagnetic compatibility	Complete immunity to electromagnetic interference, which is especially important in energy and petrochemical facilities
Remote monitoring	Monitoring the condition of objects at a distance of up to tens of kilometers without active electronics at the measurement site
Minimal maintenance	The absence of moving parts and power supply in the sensing element reduces the need for maintenance
Long service life	Fiber optic sensors can operate for up to 30 years without degradation of performance
Compact and flexible installation	Small fiber diameter allows integration into hard to reach or narrow areas of structures
Data multiplexing	Possibility of combining several sensors into one line without deteriorating the quality of measurements
Environmental safety	The absence of sparks and metal components makes the technology safe for use in hazardous areas

The limitations of fiber optic sensors (FOS) are due to both physical, technical and economic factors, despite their numerous advantages.

First, the high initial installation cost remains a limiting factor. This includes not only the cost of the equipment itself (fiber optics, lasers, spectrometers and reading modules), but also the costs of design, integration into the infrastructure and personnel training. Distributed high-resolution systems are especially expensive.

Second, the complexity of signal interpretation requires a qualified approach to analyzing the data obtained. In some cases, false alarms are possible due to vibrations, temperature changes or external noise, especially in DAS systems. This necessitates the availability of filtering and multiparametric analysis algorithms, as well as experienced operators.

The third limitation is sensitivity to mechanical damage. Despite its resistance to chemical and climatic influences, the optical fiber itself remains a fragile material, susceptible to microcracks and deformations during careless installation, especially under vibration or pressure.

Also, one should take into account the limited compatibility with some types of industrial controllers and software. This requires additional integration and interfacing with SCADA systems or other industrial control platforms, which can be technically and organizationally difficult.

In addition, the temperature and chemical limits of individual sensor components (e.g., reflective gratings or adhesive joints) limit the use of optical fiber in extreme conditions, such as areas with high concentrations of aggressive gases or ultra-high temperatures.

Finally, time delays in data transmission and processing in some types of systems (especially with long fiber lengths and when using spectroscopy) can limit the use in tasks that require an immediate response to a leak.

Optical fiber is widely used to monitor gas leaks in various industries:

- Oil and gas industry: monitoring the condition of pipelines, tanks and other facilities for timely detection of leaks and prevention of accidents.
- Chemical industry: ensuring safety during production and storage of chemicals sensitive to gas leaks.
- Power engineering: monitoring the condition of gas turbines, generators and other installations where gas leaks are possible.

The prospects for the use of fiber optic sensors in industry and critical infrastructure are rapidly expanding due to global trends in digitalization, the implementation of the Internet of Things (IoT), automation of monitoring, and increasing requirements for industrial safety. The key areas for future development and implementation of fiber optic sensors are presented below.

1. Integration into digital ecosystems and IoT.

One of the priority areas is the integration of VOS into digital monitoring platforms. Modern VOS systems are becoming part of distributed sensor networks that connect to industrial IoT platforms, SCADA systems and cloud solutions. This allows for intelligent data analysis, predictive equipment maintenance and automatic response to critical events.

2. Miniaturization and cost reduction.

Modern research is focused on reducing the size of sensor modules, switching to new materials (e.g. photonic crystal fiber), and reducing production costs. This will allow scaling the implementation of fiber-optic sensors even in small businesses, agriculture, and housing and communal services.

Example: projects for the implementation of small-sized fiber sensors in smart home and smart city systems.

3. Increasing sensitivity and selectivity.

The development of spectroscopy, interferometry, and machine learning technologies can improve the accuracy of gas recognition (e.g. methane, hydrogen, ammonia) and differentiate signals from different sources. Future fiber-optic sensors will be able to distinguish the type of leak, its direction, and gas concentration in real time.

4. Expansion of application areas

Although at present VOS are most actively used in the oil and gas, energy and transport industries, the prospects for their implementation also cover other areas:

- Mining industry (monitoring gas contamination in mines);
- Nuclear and thermal energy (monitoring overheating of cooling systems);

- Pharmaceutical and food production (hygienic clean control systems);
- Logistics and storage of hazardous substances (monitoring of tanks and reservoirs).

5. Development of self-diagnostics and self-healing.

Modern prototypes of fiber-optic systems include elements of self-diagnostics and intelligent failure notification. Solutions for the use of materials with a self-healing effect for the fiber cladding are being explored.

6. Global regulatory recognition and standardization.

International organizations (IEC, ISO, ANSI) are gradually introducing standards for the use of fiber-optic technologies in security tasks. This contributes to the formation of a unified methodological base, mandatory use at strategic facilities and the inclusion of fiber-optic systems in tender requirements for the design of facilities.

7. Use of AI and machine learning.

Artificial intelligence algorithms are used to analyze complex signals coming from distributed fiber-optic systems. The direction of the so-called cognitive sensorics is developing, when the system is trained to recognize specific leak patterns, acoustic "signatures" or temperature anomalies.

Conclusions. Thus, the conducted study confirmed the high efficiency of fiber-optic sensors in the tasks of gas leakage control and temperature monitoring at critical facilities. Due to their high sensitivity, electromagnetic compatibility and the ability to operate in extreme conditions, FOS provide more reliable and accurate monitoring compared to traditional sensors. However, the implementation of this technology is accompanied by a number of limitations, including high cost, the need for qualified interpretation of signals and the complexity of integration into the existing industrial infrastructure. The prospects for the development of FOS are associated with miniaturization, intellectualization, cost reduction and regulatory standardization, which opens the way to their mass implementation in the digital industry of the future.

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