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Analysis of technical solutions for ensuring the safety of pipeline gas transport at large industrial facilities

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Abstract. The purpose of the study was to improve the reliability and safety of gas pipeline operation through a detailed analysis of modern technical solutions, innovative technologies, and effective control methods. Modern technical and organisational solutions for ensuring the safety of pipeline gas transport at industrial facilities were analysed. It was established that the highest efficiency is demonstrated by the combination of automated control systems, the use of corrosion-resistant materials, and network segmentation using emergency valves. The technical characteristics of the main pipe materials were analysed: in particular, austenitic stainless steel can withstand up to 2.5 megapascals at a temperature of +120°C, which makes it suitable for main gas pipelines; polyethene (PE100) provides operation at a pressure of up to 1.0 megapascals and a temperature of +40°C, which is suitable for underground gas supply. Sensor types were also considered, in particular, methane gas analysers with an accuracy of ±2 particles per million and a reaction time of up to 5 seconds, which is especially effective for polymer pipes. The article summarised the experience of using intelligent devices for in-tube diagnostics that can detect mechanical defects without stopping transportation. Special attention was paid to the use of unmanned aerial vehicles: multicopters with thermal imagers and cruise drones with a laser scanner allow quickly examining hard-to-reach areas up to 50 km long. It was concluded that it is necessary to integrate these solutions into a comprehensive maintenance system. The results obtained can be used to develop and implement modern integrated safety systems at industrial facilities, which will help reduce accidents and improve the reliability of gas transmission infrastructure

Keywords: monitoring; diagnostics; leakage; corrosion; automation; innovation

Introduction

Pipeline transport is a key element of the infrastructure of large industrial facilities, ensuring a continuous supply of natural gas for production needs. However, the operation of such systems is associated with increased risks, including gas leaks, explosions, fires, and environmental pollution. The issue of safety is becoming particularly relevant in the context of the increasing technological complexity of facilities and tougher environmental requirements. Traditional methods of pipeline control and maintenance are gradually being supplemented or replaced by modern technical solutions based on automation, digital technologies, and innovative materials. In this context, there is a need for a systematic analysis of the effectiveness of such solutions, considering the practical needs of industrial enterprises.

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Timely detection and elimination of emergencies, such as gas leaks, corrosion and mechanical damage to pipelines, is an important issue in ensuring the safety of pipeline gas transport at large industrial facilities. L. Kutsenko *et al*. (2023) emphasised the importance of automating control processes to improve maintenance efficiency. Investing in these technologies helps reduce the risk of accidents and simplifies the monitoring of pipeline condition. M. Waqas & M. Jamil (2024) pointed out the advantages of using Supervisory Control and Data Acquisition (SCADA) systems, which provide remote monitoring and control over all parameters of gas pipelines. This allows quick detection of anomalies and prevents serious accidents. J. Yao *et al*. (2022) stressed the importance of using intelligent pigs for intra-tube diagnostics, which allows detecting defects at an early stage. Such a system enables the timely detection of corrosion zones and mechanical damage to pipelines. I.A. Aromoye *et al*. (2025) noted that the use of drones for pipeline inspections allows inspections to be conducted in hard-to-reach places without risking the lives of personnel. This greatly increased the efficiency of maintenance and reduced labour costs. J. Zishu *et al*. (2025) drew attention to the need to use anticorrosive materials to extend the service life of gas pipelines. The choice of such materials has reduced the likelihood of leaks and other problems associated with pipe wear.

S.F. Pichugin *et al*. (2023) underlined the importance of implementing emergency shut-off systems to quickly shut off gas flow during an accident. This has helped prevent escalating emergencies and reduce risks to the environment and workers. A.H.A. Nasser *et al*. (2021) accentuated the importance of training personnel for effective emergency management. A high level of training of employees is critical for ensuring safety at all stages of gas pipeline operation. G. Fidalgo-Valverde *et al*. (2024) recommended the use of degassing and gas extraction technologies to minimise the environmental risks associated with gas leaks. These methods provide for a timely reduction of the gas concentration in the atmosphere, preventing explosions and environmental pollution. J.S. Ahari *et al*. (2025) proposed the installation of flare combustion systems for the safe disposal of excess gases. This made it possible to avoid explosive situations and ensure effective management of excess gas. D. Bęben & T. Steliga (2023) underscored the importance of regular monitoring and diagnostics of pipelines to detect problems in a timely manner and prevent accidents. Continuous monitoring is the basis for the safe operation of gas pipelines.

However, despite numerous achievements, there are gaps in research that require further study. This includes a more detailed analysis of combined systems to ensure safety, integrating the latest technologies into real-world production conditions, and developing new methods to minimise environmental risks associated with gas leaks. The issues of adapting technologies to various climatic and geographical features and the development of effective methods of teaching and training personnel to work with new systems remain insufficiently researched. The study aimed to evaluate modern design, engineering, and organisational solutions for ensuring the safety of pipelines, particularly through the improvement of materials, control systems, accident prevention tools and innovative approaches for large industrial facilities. Research objectives: review of the effectiveness of using the latest materials and technologies to ensure the reliability of pipelines, evaluation of monitoring and control systems, in particular, SCADA systems and leak sensors, and research of innovative approaches, such as the use of IoT sensors, artificial intelligence-based analytics (AI-analytics), and drones for inspections.

Materials and Methods

The study conducted a comprehensive analysis of technical solutions aimed at improving the safety of pipeline gas transport at large industrial facilities. In the field of structural solutions, the use of anticorrosive materials, in particular, stainless steel and composite coatings, which ensure the resistance of pipelines to aggressive environments and extend their service life, was analysed. The expediency of using polymer pipes for internal networks within the limits of regulatory restrictions was investigated. The effectiveness of modern connection methods, such as automated welding using non-destructive testing, as well as flanged connections that can withstand high pressure, was evaluated. Considerable attention was paid to the division of pipeline systems into segments with insulating valves and the use of bypasses in critical areas – as a means of improving maintainability and rapid response to emergencies.

In terms of control and monitoring, the use of SCADA systems that provide remote equipment management and operational collection of telemetry data was analysed (Eso & Eseosa, 2022). The possibilities of detecting leaks using methane, pressure and noise sensors, as well as mass flow balancing methods that allow rapid localisation of hazardous areas, were investigated. The use of video surveillance and thermal imagers that help detect extraneous interference or overheating of equipment is considered. In the direction of emergency response solutions, the effectiveness of emergency shutdown systems that automatically block the gas flow in case of exceeding the permissible parameters was investigated. The paper analyses the use of degassing systems, in particular, ventilation equipment and flare gas combustion, as well as fire protection measures – including flame extinguishers, fire-fighting valves, and fire-resistant pipe coatings.

The study pays special attention to organisational and technical security measures. The effectiveness of scheduled licensing inspections, which allow timely detection of critical wear and tear and violations, is considered. The use of intelligent devices for in-tube diagnostics, in particular, pigs, capable of detecting corrosion, cracks, and mechanical defects without stopping transportation, is analysed in detail. Attention is paid to the training of personnel – in particular, training in responding to accidents and working with modern monitoring systems. The impact of implementing the standards ISO 14001:2015 (2015), ISO 45001:2018 (2018), and EN 15001-1:2023 (2023) on improving the level of technological and environmental safety was also assessed.

Lastly, the study covered innovative technologies – the use of IoT sensors, digital doubles, artificial intelligence-based analytics, and drones for inspections of hard-to-reach areas. The theoretical potential of using the latest technologies to improve the efficiency of pipeline inspections and emergency detection was considered. In particular, the possibilities of aerial photography and detection of temperature anomalies were analysed using a DJI Matrice multicopter equipped with a 4K camera and a FLIR thermal imager. The use of the eBee X cruise drone for terrain scanning and external risk assessment, which has Light Detection and Ranging (LIDAR), Global Positioning System (GPS), and an RGB camera, was also evaluated. The use of a hybrid WingtraOne equipped with a CH_4 gas analyser and a thermal scanner was reviewed to detect gas leaks. These technologies were explored in terms of their ability to integrate into existing infrastructure with minimal interference, allowing for early detection of system deviations and accident prevention.

Results

The choice of materials for pipelines is one of the most important aspects in the engineering of gas supply systems, as it determines their durability, resistance to aggressive environments, and ability to withstand high loads. Modern pipelines use a variety of materials that meet the highest safety and efficiency standards (Table 1).

Table 1. Comparison of pipeline materials

Material	Corrosion resistance	Max. working pressure (MPA)	Temperature limit (°C)	Main application
Austenitic stainless steel	High	2.5	+120	Main gas pipelines, compressor stations
Aluminium composite	High	1.6	+95	Distribution networks, internal networks
Polyethene (PE100)	High	1.0	+40	Underground gas supply, medium pressure
Polypropylene (PP-R)	Medium	1.6	+70	Domestic and industrial pipelines

Source: compiled by the authors based on I.M. Chohan *et al*. (2023)

One of these solutions is anticorrosive alloys and coatings, including austenitic stainless steels, aluminium composites and multilayer polymer materials. Austenitic stainless steels, due to their high corrosion resistance and ability to withstand extreme temperatures, are optimal for use in aggressive environments. These alloys ensure a long service life of pipelines, minimising the risks of intergranular corrosion, which can lead to structural destruction. Aluminium composites, due to their lightness and high corrosion resistance, are used in less aggressive conditions, such as external coatings of pipelines exposed to atmospheric factors. Thereby, polymer materials, in particular, polyethene (PE) and polypropylene (PP-R), are used for internal gas pipelines that are subject to less mechanical loads, but require excellent resistance to chemical influences and water corrosion. Such materials that meet the modern requirements of State Building Codes can notably reduce maintenance costs and increase the reliability of gas supply (Gharbia *et al*., 2022). In addition, pipelines designed for increased operating loads must withstand high internal pressure of more than 1.6 MPA and temperature fluctuations up to +120°C. These characteristics are especially important for gas pipelines operating under high-pressure conditions or transporting gas that has an elevated temperature. Therefore, pipelines must have high strength characteristics and the ability to operate for a long time under variable loads (Topolski *et al*., 2022). The reliability of connections is a critical aspect for ensuring the tightness and safety of pipelines. Traditional connection methods, such as welding and flanging, should be optimised for each specific case, accounting for the operating conditions and safety requirements (Zeng *et al*., 2021).

For pipeline welding, automated welding complexes are used, which are equipped with non-destructive testing systems, such as ultrasonic flaw detection and radiography. This guarantees the quality of welds and ensures that there are no hidden defects that can lead to leaks or accidents. Ultrasound can detect internal defects in the material that are not always visible during visual inspection, and radiography can check the thickness and quality of joints at the molecular level. This control can remarkably improve the safety of pipelines. Another important aspect is flanged connections, which are used to connect pipes in places where it is necessary to provide convenient access for maintenance or repair. Multi-layer seals made of fluoroplast and reinforced graphite, which provide resistance to high temperatures, pressures, and protect against aggressive chemical influences, are used to increase the tightness of such connections.

One of the key elements for ensuring the safety of gas pipelines is segmentation and redundancy of the pipeline system. In the event of an accident, it is critical to quickly localise the damaged area and minimise the consequences for the entire network. Pipeline projects provide for the formation of technological zones using remote-controlled isolation valves. These valves allow effectively blocking certain sections of pipelines, which provides for a quick response to accidents without stopping the entire system. Isolation valves are usually installed in key areas where there is a chance of leaks or other malfunctions. It is also necessary to provide bypass circuits (bypass lines) in critical areas that ensure the continuity of gas supply during maintenance or in the event of an emergency. Bypass lines help avoid interruptions in gas supply and ensure its transportation via alternative routes, which greatly reduces risks and increases the overall reliability of the system. These design and engineering solutions provide the basis for safe, efficient, and reliable operation of gas supply systems, helping to minimise risks and ensure a stable supply of energy resources to consumers (Song *et al.*, 2021). In modern gas transmission networks, control and monitoring systems are a critical element of safe and efficient operation. These systems provide continuous monitoring of the technical condition of pipelines, rapid detection of deviations and maintaining the stability of technological processes. Comprehensive automation provides for moving from reactive to proactive risk management (Table 2).

Table 2. Types of sensors for detecting gas leaks

Sensor type	What it records	Accuracy	Reaction time	Features
CH_4 gas analyser	Methane concentration	±2 ppm	⩽5 s	High sensitivity, recommended for PE
Acoustic sensor	Leakage ultrasound	High	⩽1 s	It works even without direct contact
Pressure gauge module	Sudden pressure drops	0.05 MPA	instant	Easy installation, cheap
IR optical sensor	Spectral analysis of hydrocarbons	±1 ppm	⩽3 s	Contactless, high-precision

Source: compiled by the authors based on A. Swain *et al*. (2022)

The sensors considered for detecting gas leaks have different characteristics and applications. The CH_4 gas analyser detects methane concentrations with high sensitivity and accuracy up to ±2 ppm, with a reaction time of up to 5 seconds, making it effective for polyethene pipelines. The acoustic sensor, which detects leaks with ultrasound, has high accuracy and a response rate of up to 1 second, working without direct contact with the surface, which gives it an advantage in remote monitoring. The pressure gauge module detects sudden pressure drops with an accuracy of 0.05 MPA and responds instantly to changes, which ensures easy installation and low cost. The IR optical sensor performs spectral analysis of hydrocarbons, has a high accuracy of up to ±1 ppm and responds in 3 seconds, while not requiring contact with the object, which ensures high accuracy and safety during operation.

A key component of the digital transformation of the gas transportation infrastructure is the introduction of SCADA platforms. These complexes provide centralised management and monitoring of the entire gas supply system in real time. SCADA integration allows controlling electric gate valve drives, pressure regulators, gas analysers, temperature sensors, and emergency shut-off valves without the physical presence of the operator on site. In addition to management, SCADA systems implement telemetry with a high frequency of data collection, which allows dispatchers to quickly respond to changes in the functioning of the network. Due to the modular architecture, such complexes can be easily scaled and integrated with other digital platforms, in particular, analytical modules based on artificial intelligence (Eso & Eseosa, 2022).

One of the most dangerous incidents in gas transmission networks is a gas leak, so modern infrastructure should be equipped with high-precision leak detection systems. The most effective approach is the introduction of multimodal sensor networks, which include gas analysers that measure the concentration of methane (CH_4), propane, butane, and other hydrocarbons, acoustic sensors that detect sound signals characteristic of pipeline depressurisation, as well as pressure sensors that can detect abnormal fluctuations and drops that indicate losses. The Mass Flow Balance method is used to improve the accuracy of localisation, which is based on a mathematical analysis of the difference between the supplied and received gas volumes. This approach allows identifying not only the fact of the leak but also its approximate location with an accuracy of several tens of meters (Menon *et al.*, 2025).

A separate role in the monitoring structure is played by optical and thermal imaging systems that allow monitoring both the technical condition of equipment and the safety of objects from external interference. Video surveillance is implemented on the basis of intelligent analytical systems that can recognise non-standard behaviour of personnel, unauthorised entry, and other factors that can lead to a violation of the security regime. Such systems use computer vision algorithms that automatically identify events and generate alarm signals when threats are detected. High-resolution thermal imagers are used to detect equipment overheating, leaks, hot zones, or local insulation defects. This is especially important in high-load environments, where timely detection of overheating avoids failure of critical components (He *et al.*, 2024).

Thus, modern control and monitoring systems provide an opportunity to exercise full-scale control over all parameters of the pipeline network, ensuring its stable, safe, and predictable operation. Combined with analytical platforms and artificial intelligence, they become the basis for creating intelligent infrastructures capable of self-diagnosis and adaptive management. A reliable emergency protection system is a critical component of any gas transportation infrastructure. In conditions of increased man-made risks and difficult operating conditions, only timely detection of deviations and their automated localisation can guarantee the preservation of the integrity of the system, the life and health of personnel and the environment.

Emergency Shut Down (ESD) systems provide instant emergency response to prevent an event from escalating. They operate on the principle of automatic cut–off of gas supply when exceeding the specified parameters: temperature – to prevent thermal degradation of materials;

pressure – to avoid pipeline breaks; gas concentration in the air – to prevent the formation of explosive mixtures. It is based on electric shut-off valves with integrated controllers. In the event of a complete power outage, manual duplication is triggered – this allows technical personnel to manually cut off the supply, minimising the consequences even if automatic systems fail (Yusifov *et al.*, 2024).

In areas where explosive gases may accumulate, degassing systems are being introduced that operate on the principle of active ventilation and utilisation of excess gas. Ventilation units with adjustable air exchange ensure efficient dispersion of methane or other hydrocarbon accumulations, especially in technical rooms, wells, and chambers. In the event of a sudden release, the gas is sent to the gas collectors, where it accumulates and is then transferred to the flare installations. The latter implement controlled gas combustion, which allows avoiding explosions in case of uncontrolled leaks. These technologies minimise the risk of ignition and also comply with environmental standards for reducing emissions of hazardous substances into the atmosphere (Song *et al.*, 2021).

Active and passive fire protection systems are used to limit the spread of fire within the infrastructure. Active means are flame extinguishers – special devices that extinguish the reverse flame, preventing its penetration through the pipeline, and non-return valves with thermal protection, which are triggered when critical temperatures are reached, automatically blocking the gas transmission channel. Passive protection is implemented through the use of fire-resistant materials, in particular, compounds based on silicone, graphite, or cement matrices, for thermal insulation and thermal protection of pipes, and the application of fire-resistant paints and varnishes that foam when heated, creating a heat-insulating barrier. These measures can significantly improve the heat resistance of equipment and extend the time for personnel evacuation or emergency services (Donohue *et al.*, 2021).

Thus, a comprehensive emergency security system is not only a set of individual devices, but also an integrated preventive protection architecture that can diagnose a threat in a timely manner, neutralise its source, and localise its consequences. Its effectiveness largely depends on the technical level of implementation, routine maintenance, and continuous improvement in accordance with current risks. The functioning of gas transmission infrastructure facilities is impossible without a well-organised system of technical regulation, training of personnel, and ensuring compliance with international standards. It is organisational and technical security that creates a structured basis on which all processes of operation, maintenance, and emergency response are based.

Proper maintenance begins with system maintenance work performed following current regulations and license conditions. Scheduled licensing works include technical inspection of pipeline components, shut-off valves, pressure regulators, and other critical elements. The frequency and scope of work are determined individually for each object based on risk analysis and the age of the system. One of the most effective tools of modern diagnostics is in-tube inspection using intelligent pistons (smart pigs). These devices, equipped with a magnetic, ultrasonic, or electromagnetic sensor system, allow detecting internal defects in pipes (corrosion foci, reduced wall thickness, mechanical displacements, cracks) without stopping the gas supply. These measures increase the level of security and extend the life cycle of infrastructure facilities (Amaechi *et al.*, 2022).

The human factor remains one of the main sources of risk in any production processes, so a high level of personnel training is a critical condition for safe operation. Emergency response training includes modelling critical situations (gas leak, fire, explosion) using realistic scenarios. Such training allows developing the skills of staff to quickly assess the situation and make decisions. Additionally, training is provided on working with modern monitoring and automation tools – from SCADA systems to local sensor modules. Employees should be able to quickly interpret signals, diagnose malfunctions, and initiate emergency response (Chen *et al.*, 2021).

Documenting all technical and organisational processes ensures transparency, accountability, and compliance with government and international regulatory requirements. The key standards that ensure the safety and efficiency of work in gas transmission networks are international and European standards that regulate various aspects of safety, labour protection, and environmental management. ISO 45001:2018 (2018) is an international occupational health and safety management system that is the basis for creating a safe working environment. This standard defines the requirements for the development and implementation of an occupational safety management system in organisations, ensuring effective control over possible risks to the health and safety of personnel. According to ISO 45001:2018 (2018), organisations must implement safety policies, risk assessment, accident prevention measures, and the creation of safe working conditions. The standard provides for the active involvement of management in the implementation of security policies, monitoring, and measuring the results of the system, in addition to the regular improvement of security practices in accordance with changing production conditions.

ISO 14001:2015 (2015) is an international standard for environmental management that sets out requirements for the creation, implementation, and improvement of an environmental management system (EMS). ISO 14001:2015 (2015) requires organisations to constantly monitor emissions of harmful substances into the atmosphere, water, and land resources, along with the leaks of toxic gases or other hazardous materials. This allows not only to minimise the negative impact on the environment but also to ensure compliance with environmental requirements defined by international agreements and national legislation. The implementation of ISO 14001:2015 (2015) requires monitoring environmental indicators, conducting environmental impact assessments, and identifying preventive measures to prevent environmental disasters.

EN 15001-1:2023 (2023) is a European standard that defines technical requirements for the design, installation, and operation of gas distribution systems. It covers both the construction of new gas installations and the modernisation of existing ones. EN 15001-1:2023 (2023) provides requirements for the quality of materials used in the construction of gas pipelines, safety during their installation, and for pipeline monitoring and maintenance systems during operation. The standard aims to improve the safety of gas installations, reduce the likelihood of accidents such as gas leaks or explosions, and ensure proper energy and resource efficiency in gas systems. EN 15001-1:2023 (2023) also contains recommendations for regular inspections and diagnostics of gas networks to detect possible defects or malfunctions in their operation in a timely manner. These standards provide an integrated management system for safety, occupational health, environmental responsibility, and quality in the gas industry, which is essential to reducing risks and improving operational efficiency in this area. All processes must be accompanied by technical documentation, which includes: passports and diagrams of objects, maintenance logs, inspection and repair reports, protocols for training personnel and responding to accidents.

Together, these organisational and technical measures form a single safety management system that both minimises the risks of accidents and guarantees compliance with the highest industry requirements. Their implementation requires continuous improvement, a systematic approach, and integration with modern technology platforms. In modern operating conditions of complex engineering facilities, such as gas transmission systems, innovation becomes not just a factor of modernisation, but a necessary condition for ensuring reliability, safety, and efficiency. Infrastructure intellectualisation allows moving from reactive to proactive risk management (Table 3).

Table 3. Unmanned pipeline inspection platforms

UAV type	Sensors on board	Range (km)	Purpose	Advantages
DJI Matrice multicopter	4K camera, FLIR thermal imager	5	Local node diagnostics	High accuracy, vertical take-off/landing
EBee X cruise drone	LIDAR, GPS, RGB camera	50	Aerial photography of main sections	High autonomy, covering large areas
Hybrid WingtraOne	Gas analyser CH_4 + thermal scanner	15	Probing hard-to-reach areas	Combines range and flight stability

Note: UAV – an unmanned aerial vehicle
Source: compiled by the authors based on Y.M.R. Da Silva *et al*. (2022)

Three types of UAVs for pipeline inspection are presented, each of which has its own characteristics and purpose. The DJI Matrice multicopter is equipped with a 4K camera and a FLIR thermal imager, which allows local diagnostics of pipeline components at a distance of up to 5 km. The main advantage is high accuracy and the possibility of vertical take-off and landing, which is convenient for examining complex objects. The eBee X cruise drone with LIDAR sensors, GPS, and an RGB camera is designed for aerial photography of main sections of pipelines, covering large areas with a range of up to 50 km. Its advantage is high autonomy and the ability to work over long distances. The hybrid WingtraOne, equipped with a CH_4 and gas analyser and a thermal scanner, allows probing hard-to-reach areas at a distance of up to 15 km. The advantage of this drone is the combination of flight range and stability, which is important for accurate measurements in difficult conditions. In general, each UAV has its own specifications for different tasks, which provides flexibility in applications for monitoring and inspecting pipelines.

The use of IoT devices provides for continuous monitoring of critical parameters of the pipeline infrastructure-pressure, temperature, vibrations, humidity, and the composition of the gas mixture. Data from thousands of nodes is read in real time, transmitted to analytical platforms, and enables quick detection of even minor deviations from nominal values. Due to this, it is possible to quickly identify potential problems and take timely measures to eliminate them, which increases the safety of operation and lowers the risk of accidents. Of particular importance is the concept of digital twin – a virtual model of a real object, which is updated based on factual data from field sensors. Engineers can conduct virtual tests of equipment degradation scenarios, simulate the consequences of accidents or emergencies, and optimise maintenance schedules using this model. The digital twin predicts the behaviour of the pipeline system, which allows planning for more efficient use of resources and reduces the possibility of equipment failures, identifying potentially dangerous areas in a timely manner. This substantially improves risk management and ensures the continuity of the gas transmission network (Singh *et al*., 2021). AI is increasingly being implemented in the service sector of pipeline systems. Its main function is to analyse large amounts of data to identify hidden patterns and trends that may indicate the approach of a potential failure or critical state of a system element. The use of AI can immensely improve pipeline monitoring and management processes, making them more efficient and secure.

In particular, machine learning algorithms are used to classify behavioural anomalies in the operation of equipment, which allows identifying non-obvious changes in the operation of the system that may precede serious problems. Neural network forecasting models based on historical data from previous incidents are also actively used, helping to anticipate possible failures and take the necessary measures in a timely manner. In addition, automatic decision-making systems are being developed that generate recommendations to dispatchers in real time, contributing to a quick response to potential emergencies. Thus, AI becomes a key element of the transition to predictive maintenance, which vastly reduces the risk of accidents, allowing maintenance and repairs to be conducted based on real data, rather than on schedule, which in turn helps to optimise costs and improve the efficiency of the pipeline system (Sircar *et al.*, 2021).

Monitoring the state of gas transportation infrastructure, especially in hard-to-reach areas (mountainous terrain, forest areas, swampy areas), is greatly simplified by using UAVs. Modern drones are equipped with high-precision cameras, thermal imagers, LiDAR, and gas analysers, which enables aerial photography of linear objects with precise positioning, detection of temperature anomalies associated with gas leaks or thermal degradation of materials, scanning of terrain and vegetation to assess external risks (soil erosion, damage to root systems, etc.). Automated drone patrolling not only increases the speed of the survey but also reduces costs and risks for personnel (Askarzadeh *et al.*, 2024). Innovative solutions are not the future, but an integral part of the present gas transportation industry. Their implementation allows identifying potential threats even before they materialise and creating an adaptive, self-learning infrastructure that can quickly respond to the challenges of the man-made environment. The development of such technologies defines a new paradigm – an intelligent infrastructure with zero fault tolerance.

Discussion

In the course of the study, structural and engineering solutions aimed at improving the reliability and durability of pipeline systems were analysed. Special attention was paid to the quality of materials – the use of anticorrosive alloys, in particular, stainless steels and composites, substantially reduced the risk of premature wear of pipes. The high resistance to pressure and temperature also confirmed the effectiveness of the selected materials, and polymer pipes showed the feasibility of using them in internal networks, provided that the standards are met. This problem was also investigated by A. Reda *et al.* (2025), where the results confirmed that corrosion is one of the main causes of premature pipeline wear, especially in aggressive environments. The use of corrosion-resistant alloys, such as stainless steel or titanium, considerably extends the service life of the equipment. A good choice of material reduces repair and maintenance costs, increasing the overall reliability of the system. A.C.C. De Leon *et al.* (2021) also indicated that polymer and metal composites exhibit high strength and chemical resistance, making them promising for pipeline systems. Their use decreases the weight of structures and improves corrosion protection without losing mechanical properties. Modern composite manufacturing technologies also contribute to improving the energy efficiency and durability of the gas transportation infrastructure.

Notably, the choice of materials should consider corrosion resistance, along with the economic feasibility and operating conditions of the pipeline. For example, in regions with high humidity or in environments with aggressive impurities, it is more appropriate to use more expensive but durable materials. In addition, the technological compatibility of materials with existing systems and the possibility of their maintenance throughout the entire life cycle play a major role. It was determined that the reliability of joints increased remarkably when using automated welding systems supplemented with non-destructive testing. Quality control of welds using ultrasound or radiography has reduced the likelihood of defects leading to leaks. Furthermore, flanged connections with highly reliable seals demonstrated high tightness under high-pressure conditions. J.L. Velázquez de la Hoz & K. Cheng (2021) concluded that automated welding systems provide high accuracy and repeatability of the process, which is especially important in the construction of long-haul pipelines. The use of non-destructive testing – ultrasonic, X-ray, or magnetic – allows detecting defects even at the installation stage. This approach increases the reliability of the system and reduces the risk of accidents during operation. B. Li *et al.* (2024) established that flanged connections designed for high pressure provide tightness even in difficult operating conditions. They are easily dismantled and help to quickly maintain or replace individual pipeline components. Due to the use of modern sealing materials, the probability of leaks is noticeably reduced, which is critical for the safety of gas transportation infrastructure. These results confirm the above study, as they demonstrate a close relationship between the quality of welding seams and the overall reliability of the gas transmission system. Automation of processes and the introduction of non-destructive testing allow minimising the human factor, which is a fundamental factor in ensuring the stable operation of pipelines. Consequently, improving quality standards at the construction stage directly affects the safety and durability of the entire infrastructure.

The results of zoning pipeline networks showed that the division into isolated sections with remote control and the presence of bypass lines greatly increased the flexibility and safety of the system. In the event of an accident, it became possible to quickly localise the problem area without stopping the entire complex. The paper of S. Zhang *et al.* (2023) is notable, having determined that the integration of remote-controlled gate valves into the pipeline assists in timely isolating the emergency section without having to stop the entire system. This minimises the response time and potential gas losses. This segmentation enhances operational safety and simplifies maintenance of large gas transmission networks. In turn, J. Chen *et al.* (2022) concluded that bypass lines allow redirecting the flow of gas to bypass the damaged or serviced area, while maintaining a constant supply to consumers. They are particularly effective in case of accidents or during scheduled repairs, when it is crucial to avoid interruptions in the supply. Thus, such lines help to increase the reliability and flexibility of the entire gas transmission system. These data correspond to the theses given in this study, confirming the effectiveness of using remote-controlled gate valves and bypass lines in ensuring stable operation of the system. Due to such technical solutions, the gas transmission infrastructure becomes more adaptive to emergency situations and less vulnerable to interruptions. This, in turn, strengthens the overall security and energy independence of regions that depend on a continuous gas supply.

Control and monitoring systems were also analysed, among which SCADA complexes demonstrated their effectiveness in collecting and processing telemetric data. Leak detection systems that use methane, pressure, and noise sensors accurately detect even minimal deviations from normal conditions, and mass balancing methods help localise leaks with high accuracy. E.B. Priyanka *et al*. (2021) also conducted a study, the results of which confirmed that the introduction of SCADA systems with telemetry allows monitoring and controlling the operation of gas pipelines in real time. Intelligent analysis of data from such systems helps to anticipate possible emergencies and take timely measures to prevent them. This substantially increases the efficiency of infrastructure management and minimises the human factor in the control and configuration process. J. Bin *et al*. (2022) also proved that sensor technologies, along with thermal imaging diagnostics, provide fast and accurate detection of gas leaks, which is critical for pipeline safety. Thermal imagers allow detecting even the slightest temperature changes that may indicate a gas leak, while sensors constantly monitor the composition of the air. These innovative methods enable a swift localisation of the problem, minimising the risks and costs of repairs. Comparing the data obtained in the course of the current study, it can be concluded that the integration of SCADA systems and sensor technologies greatly increases the level of safety and efficiency of the gas transmission infrastructure. The use of these technologies provides for not only quickly identifying emergency situations but also predicting possible problems, which reduces the time to fix them. This integrated application of intelligent systems and sensors creates prerequisites for more stable and safe operation of pipelines.

In the field of safety, emergency shutdowns and degassing systems were effective, which made it possible to quickly stop the gas supply and remove surpluses from hazardous areas. The incorporation of fire protection measures, specifically thermal fuses and fire-resistant materials, enhanced the overall fire resistance of the object. K. Cameron *et al*. (2023) concluded that ESD emergency modules can instantly stop gas supply in the event of an emergency, thereby preventing further spread of the danger. The electric drive fittings integrated with these modules ensure fast and accurate execution of necessary operations in remote areas without human intervention. This lowers the response time to accidents and increases the reliability of the gas transmission system. K. El-Borhamy *et al*. (2022) stated that degassing and ventilation systems provide efficient removal of hazardous gases from pipelines and prevent the accumulation of explosive mixtures in confined spaces. Fire-resistant systems, in turn, minimise the risk of fire and provide additional protection in high-temperature conditions. The integrated use of these systems in critical areas can increase the level of safety and ensure the continuity of the gas transmission infrastructure.

When analysing the results of the study, it is clear that the integrated use of emergency ESD modules, electric drive fittings, in addition to degassing, ventilation, and fire protection systems, can remarkably reduce the risks of accidents and ensure the reliability of the gas transmission infrastructure. The use of automated systems for emergency response both improves safety and optimises management processes under high loads. These technologies are an important step towards creating more stable and resistant gas pipelines to external and internal threats. Finally, organisational and technical measures played an equally important role. Routine inspections and in-tube diagnostics helped detect damage at an early stage, and staff training ensured an effective response in emergency situations. In general, the study confirmed that the safety of gas pipeline systems is possible only with a comprehensive approach that covers materials, technologies, monitoring, operation, and innovation.

Conclusions

As a result of the study, it was determined that modern gas transmission systems require a comprehensive approach to design, monitoring, and operation. The basis of a reliable infrastructure is the use of high-quality pipe materials that can withstand aggressive environments and high loads. For example, austenitic stainless steel has a high resistance to corrosion, operates at pressures up to 2.5 MPA and temperatures up to +120 °C, which makes it optimal for main gas pipelines. PE100 polyethene is widely used in distribution networks, designed for pressures up to 1.0 MPA and temperatures up to +40 °C. Leak detection has become more accurate due to modern sensors. Methane gas analysers respond with an accuracy of ±2 ppm in ≤5 seconds, and contactless IR optical sensors and acoustic modules ensure fast response even without physical access to pipes. The combination of these technologies with thermal imagers and SCADA systems for real-time monitoring is particularly effective. Drones are used for inspections of hard-to-reach areas. For example, the DJI Matrice multicopter (radius up to 5 km) is equipped with a 4K camera and a FLIR thermal imager, while the winged eBee X (up to 50 km) has LIDAR and an RGB camera. The hybrid WingtraOne combines a CH_4 gas analyser and a thermal scanner, which allows sensing even in difficult terrain.

Overall safety is maintained through emergency systems, degassing installations, fire protection, and compliance with international standards ISO 14001:2015, ISO 45001:2018, and EN 15001-1:2023. Development prospects are connected with digital doubles, IoT, and AI analytics, which form a new quality of operation. A limitation of the study was that the analysis was conducted on the basis of theoretical models and general technical solutions without accounting for the specifics of specific operating conditions in individual regions. Further research should focus on the effectiveness of using artificial intelligence in long-term forecasting of pipeline system wear in various climatic zones.

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Conflict of Interest

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Аналіз технічних рішень для забезпечення безпеки трубопровідного транспорту газу на великих промислових об'єктах

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Анотація. Метою цього дослідження було забезпечення підвищення надійності та безпеки експлуатації газових трубопроводів шляхом детального аналізу сучасних технічних рішень, інноваційних технологій та ефективних методів контролю. Проаналізовано сучасні технічні та організаційні рішення для забезпечення безпеки трубопровідного транспорту газу на промислових об'єктах. Встановлено, що найвищу ефективність демонструє поєднання автоматизованих систем контролю, застосування корозійностійких матеріалів і сегментації мереж за допомогою аварійних засувок. Проаналізовано технічні характеристики основних матеріалів труб: зокрема, аустенітна нержавіюча сталь витримує до 2,5 мегапаскалів при температурі +120°C, що робить її придатною для магістральних газопроводів; поліетилен (PE100) забезпечує експлуатацію при тиску до 1,0 мегапаскаля і температурі +40°C, що підходить для підземного газопостачання. Також розглянуто типи сенсорів, зокрема газоаналізатори метану з точністю ±2 частинки на мільйон і часом реакції до 5 секунд, що особливо ефективно для полімерних труб. Узагальнено досвід використання інтелектуальних приладів для внутрішньотрубної діагностики, здатних виявляти механічні дефекти без зупинки транспортування. Окрему увагу приділено застосуванню безпілотних літальних апаратів: мультикоптери з тепловізорами і крилаті дрони з лазерним сканером дозволяють оперативно обстежувати важкодоступні ділянки протяжністю до 50 км. Зроблено висновок про необхідність інтеграції цих рішень у комплексну систему технічного обслуговування. Отримані результати можуть бути використані для розробки та впровадження сучасних комплексних систем безпеки на промислових об'єктах, що сприятиме зменшенню аварійності та підвищенню надійності газотранспортної інфраструктури

Ключові слова: моніторинг; діагностика; витік; корозія; автоматизація; інновації