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Ismayilov G.G.[1], *Doctor of Technical Sciences, Professor, ORCID: 0000-0002-5849-2488,* ***Ismayilova F.B.***[1], *PhD Technical Sciences, ORCID: 0000-0002-5849-2488,* ***Nagizadeh A.***[2], *ORCID: 0009-0003-6716-1626*

[1] ***Azerbaijan State Oil and Industry University***
16/21, Azadlig Ave., AZ1010 Baku, Azerbaijan, e-mail: fidan.ismayilova2014@mail.ru
[2] ***Oil and Gas Scientific Research Project Institute***
88A, H. Zardabi Ave., AZ1122 Baku, Azerbaijan, e-mail: nagizadeanar26@gmail.com

Advanced resource operation of main natural gas pipeline using CFD modeling methods

Abstract. The possibility of future operation of pipelines, that are under exploitation, is one of the most important issues of the oil and gas industry. Therefore, it is necessary to periodically check (diagnose) the technical condition of pipelines. Taking into account the severe operation conditions of the pipelines, the thickness losses may occur during the operation period. The paper investigates the residual operating resources of various elements of the pipeline as a result of diagnostic work, as well as, calculation of wall thickness of the main gas pipeline by using an OLYMPUS 27 MG Ultrasonic Thickness Gauge. Based on the actual data obtained in the studies, the minimum allowable thicknesses corresponding to the existing internal pressure in the pipeline were calculated and compared with the actual minimum thicknesses. Thus, the possibility of safe operation of the gas pipeline was studied on the basis of gauge measurements, minimum thicknesses and operational loads. Both analytical methods and modern software were used during the calculations. A physical model created in the structural design software can be transformed into an analytical model for structural analysis. A three-dimensional spatial model of the pipeline was created via the software and the strength and stability of the pipeline under the influence of various forces was calculated. Subsequently, as a result of technical diagnostics of the pipeline, the possibility of further operation of the pipe element was determined. *Bibl. 20, Fig. 3, Tab. 5.*
Keywords: main gas pipeline, strength, design resistance, yield strength, reliability coefficient, allowable stress.

Introduction

Natural gas has become a fundamental part of daily life, recognized as the most reliable energy carrier due to its universal application, environmental friendliness, and resource efficiency. The ecological purity and high efficiency of natural gas have significantly increased its role in the energy balance and economic development.

The issue facing the gas industry is not a shortage of gas reserves and production, but the inadequacy of transportation infrastructure to deliver gas to consumers. Natural gas currently accounts for over 25 % of the global energy supply. Analysis indicates that global gas reserves exceed those of oil, making gas suitable for a broader range of applications, primarily in electricity generation and heating. The high likelihood of using natural gas is also attributed to its ecological cleanliness, especially when compared to oil and coal [1–3].

The primary method of transporting natural gas is through pipelines. Pipeline transport involves moving gas through a network of pipelines equipped with instruments and devices like meters, valves, compressors, and safety mechanisms. This method is the most established and widely utilized technology for gas transportation globally. Pipelines are classified into three categories based on their size and functionality [4, 5]:

– Gathering pipelines. These short-distance pipelines collect various products within a field and transport them to processing facilities. Typicalcally, they have a small diameter less than 300 mm;

— Main pipelines. These pipelines serve as the primary channels for transporting gas. They can have very large diameters (1000–1400 mm), and extend over great distances. Natural gas main pipelines lines typically deliver gas to industrial facilities or distribution systems;

— Distribution pipelines. These pipelines enable local low-pressure distribution from the transmission system. While some distribution lines may have large diameters, the majority are less than 150 mm in diameter.

This paper focuses on steel main pipelines. The wall thickness of the main pipelines is determined based on calculation, taking into account the design pressure in the pipeline. If gas pipelines traverse large bodies of water, they are weighed down with special loads or encased in concrete and buried at the bottom. Simultaneously with the main pipeline, a reserve pipeline of the same diameter is installed. At intersections with railways and major highways, the gas pipeline is encased in a pipe with a diameter 100–200 mm larger than that of the pipeline [6–8].

As an integral part of gas production facilities, main gas pipelines have been exposing to a number of external and internal factors from the moment they are put into operation. Loads and impacts on gas pipelines have a wide range and include, gas pressure and temperature, vibration loads on pipelines from compressor stations, wind loads on aboveground pipelines, hydrodynamic loads on underwater passages and etc. These effects cause losses in various elements of the pipeline, especially in the wall thickness of the pipeline. Defects in the welding elements that connect the various components of the pipe (linear section, elbow, transition, etc.) can lead to reduction in the pipeline's service life or even shutdown the pipeline. In order to keep all these effects under control and to avoid negative consequences it is important to carry out periodic inspection of pipelines.

Currently, a number of periodic inspection and monitoring methods are implemented in practice to solve the stated problems and to increase the structural reliability of the pipelines. Conducted diagnostic measures play an important role in detecting potential hazards that may occur in the pipeline due to the influence of a number of static and dynamic loads. The purpose of carrying out the inspection is to determine the possibility of future operation of oil and gas pipelines [9–11].

Pipelines undergo inspections using both internal and external methods. Common inspection processes include pigging, hydrotesting, and corrosion assessments. Pigging, which began in the 1960s, is utilized for cleaning and monitoring the internal condition of long pipelines. The pig, a cylindrical electronic device, is equipped with condition monitoring systems and is also known as a smart pig or inline inspection tool. Smart pigs are the most frequently used instruments in the pipeline industry [7, 12]. Additional types of smart pigs include magnetic flux leakage (MFL) and ultrasonic pigs. These devices consist of a drive pack that moves the pig through the pipeline, a flux loop that generates magnetic flux, and a recorder pack equipped with sensors to detect variations in flux and location. MFL pigs are utilized to identify metal loss, cracks, pit shapes, lengths, maximum pit depths, and wall thicknesses affected by corrosion and erosion. Crack detection pigs represent the latest advancement in inspection methods, with ultrasonic crack detectors, transverse magnetic flux leakage tools, and elastic wave pigs employed to identify both circumferential and longitudinal cracks. Besides pigging, pipeline conditions can be evaluated through operational parameters like pressure, flow rate, and physical dimensions. Geometry tools, such as caliper and pipe deformation tools, assess the physical shape and geometric conditions of pipelines. Mapping tools with integrated global positioning systems (GPS) are used to locate valves, equipment positions, and create pipeline maps. Additionally, low-frequency long-range guided wave inspection techniques are employed to map corrosion and erosion in pipelines [13, 14].

Research methodology

Taking into account abovementioned, the purpose of the study is to determine the residual operating resources of various elements of the pipeline as a result of diagnostic work. In the study, the process was modeled using the STAAD.Pro 3D Structural Analysis and Design Software, and the wall thickness of the gas pipeline was determined as a result of mathematical calculations.

The analysis of the state of operation of the studied main pipeline was carried out in the following order.

Determination of pipeline resistance to tension (compression)

To determine the structural reliability of the main pipelines in operation, as a first step, the minimum value of the pipe resistance to tension R_1^n and compression R_2^n (tensile strength and yield strength) must be determined [15, 16]:

$$R_1 = \frac{{R_1}^n \times m}{k_1 \times k_e};\ R_2 = \frac{{R_2}^n \times m}{k_2 \times k_e}; \qquad (1)$$

$$R = min\{R_1;\ R_2\},$$

where R_1^n — normative resistance, MPa; R_2^n — yield strength, MPa; m — pipeline operating condition coefficient; k_1, k_2 — reliability factors for material; k_e — the reliability factor for the purpose of the pipeline.

The values of the coefficient of operating conditions, that are used in calculating the strength, stability and deformation of the pipeline and depend on the category of the pipeline, are given in Table 1 [17, 18]. The reliability coefficients for the material depending on the purpose of the pipeline are selected according to Tables 2–4 [19, 20].

Table 1. Coefficient of operating conditions *m*

Category of pipeline and its area	N^* when calculating deformation, m
In more important areas, inside buildings, compressor stations, in underground gas storages, in water passages of oil pipes with a diameter of 1200 mm	0.60
Water crossings of main pipelines, railway crossings, highways, difficult-to-cross swamps, intersections with compressor stations, pigging launcher and receiver points:	0.75
I and II	–
III	0.90
IV	0.90

N^* — Pipeline strength, stability and coefficient of working conditions when calculating deformation.

Table 2. Reliability factor according to the material k_1

Pipe specifications	R^*, k_1
100 % controlled rolling steel and thermally strengthened welded pipelines with whole process seam safe method	1.34
Double-sided arc welding, rolled and forged seamless pipes with hole process seam safe method	1.40
Pipes welded from low alloy or carbon steel, 100 % controlled, safe or non-destructive, made by double-sided electric arc welding	1.47
Welded pipes and other seamless pipes of low alloy or carbon steel, double arc welded	1.55

R^* — Reliability factor according to the material.

Table 3. Reliability factor according to the material k_2

Pipe specifications	R^*, k_2
Low carbon, seamless	1.10
According to $R_2^n/R_1^n \le 0.8$ low-carbon and low-alloy straight seam and spiral seam, welded	1.15
Made of high-strength steel $R_2^n/R_1^n > 0.8$	1.20

R^* — Reliability factor according to the material.

Table 4. Reliability factor for the purpose of the pipeline k_r

Reliability factor for the purpose of the pipeline, k_r	Nominal pipe diameter, mm			
	up to 500	600–1000	1200	1400
For gas pipeline:				
$P \le 5.4$ MPa	1.00	1.00	1.05	1.05
$5.4 < P \le 7.4$ MPa	1.00	1.00	1.05	1.10
$7.4 < P \le 9.8$ MPa	1.00	1.05	1.10	1.15
For oil and oil product pipelines	1.00	1.00	1.05	–

Determination of the pipeline wall thickness

The calculated thickness δ (mm) of the pipeline, which provides the necessary strength at a given working (standard) pressure P, is calculated using the following formula [16, 17]:

$$\delta = \frac{n \cdot P \cdot D}{2(R + n \cdot P)}, \qquad (2)$$

where n — reliability factor due to load; P — operating pressure, MPa; D —external diameter of the pipe, mm; R — allowable stress for steel, MPa.

Conducting technical inspection studies of the underground main gas pipeline "Astara-Gazimammad" (Azerbaijan)

he main purpose of technical inspection is to identify potentially dangerous sections of the pipeline, assess the degree of danger of defects, determine the priority of dangerous sections and carry out preventive repairs [19, 20].

According to the current technical task [20]:

— length of the pipeline L = 210 km;

— external diameter of the pipeline D = 1220 mm;

— design pressure of the pipeline P_{design} = 5,5 MPa;

— maximum allowable operating pressure $P_{operating}$ = 1,8 MPa;

— type of steel — 17Г1С-У.

During the technical diagnostics, gauge measurements were performed by using an OLYMPUS 27 MG Ultrasonic Thickness Gauge [19]. Based on the actual data obtained in the studies, the minimum allowable thicknesses corresponding to the existing internal pressure in the pipeline were calculated and compared with the actual minimum thicknesses. Thus, the possibility of safe operation of the gas pipeline was studied on the basis of gauge measurements, minimum thicknesses and operational loads.

Results and discussion

The assessment of the safe operating reserves of the studied pipeline was determined, taking into account the surface defects observed in them, as a result of direct measurements. The actual minimum cross-sectional thicknesses were based on the results of the stress calculation under internal pressure.

As a result of measurement carried out at pressure of P = 1.8 MPa at L = 187.74th km of the "Astara-Gazimammad" underground main gas pipeline, the wall thickness of the pipeline was determined in different places:

— on the top 12.18; 12.24; 12.36; 12.45; 12.40; 12.58; 12.65 mm (δ_{min} = 12.18 mm);

— on the side 11.96; 11.95; 11.80; 11.91; 11.96; 11.93; 11.98 mm (δ_{min} = 11.80 mm);

— on the bottom 9.85; 9.64; 9.49; 9.19; 9.25; 9.30; 9.38; 9.48 mm (δ_{min} = 9.19 mm).

Also, corrosion pits with a depth of 5–6 mm and layered corrosion products were found on the side and bottom surface of the pipe.

The calculated value of the required minimum thickness of the pipe cross-section at given conditions is determined, mm:

$$\delta = \frac{n \cdot P \cdot D}{2(R + n \cdot P)} = \frac{1.1 \cdot 1.8 \cdot 1220}{2(260.87 + 1.1 \cdot 1.8)} = 4.6\,.$$

As a result of the comparison of the result obtained in the measurement performed on the bottom surface of the pipe (taking into account the corrosion pits) with the calculated value, it was determined that this section of the pipeline is no longer suitable for operation.

Creating a constructive model

The strength and durability analysis of the pipe was performed using the standard STAAD.Pro Connect Edition software. STAAD is a popular structural analysis application known for analysis, diverse applications of use, interoperability and time-saving capabilities. STAAD helps structural engineers perform 3D structural analysis and design for both steel and concrete structures. A physical model created in the structural design software can be transformed into an analytical model for structural analysis. Many design code standards are incorporated into STAAD to make sure that the structural design complies with local regulations.

A simple diagram of a simulated main gas pipeline with a diameter of 1220 mm is shown in Figure 1.

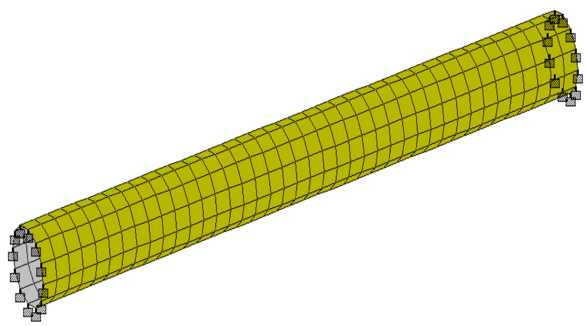

Figure 1. Simplified model of the gas pipeline.

Table 5. The properties of the steel

Indicators	Actual Dimensions
Density, kg/m^3	7849
Modulus Elasticity, E, MPa	200,000
Shear modulus, G, MPa	77220
Poisson's ratio	0.3
Yield stress, MPa	245

The characteristics of the steel used at the 187.74th km section of the "Astara-Gazimammed" underground gas pipeline are given in Table 5.

Distribution of applied loads

The applied mathematical modelling took into account the operating pressure generated in the pipeline, including the mass of the metal. The load distribution scheme is shown in Figure 2.

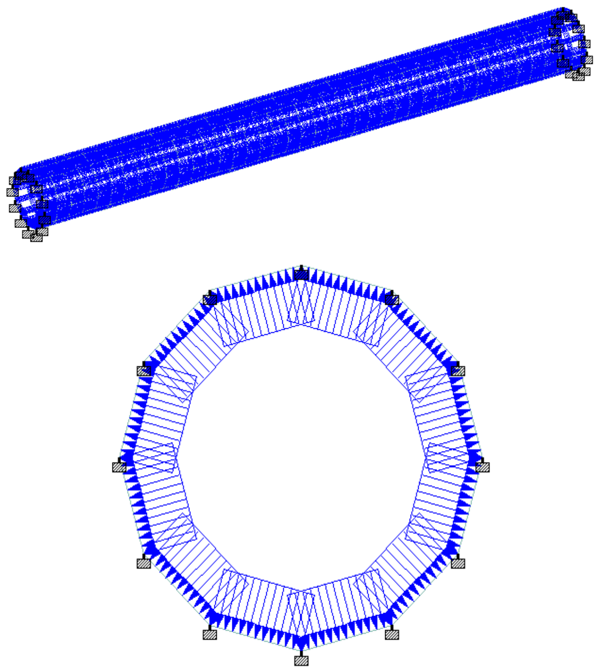

Figure 2. Distribution of applied loads along the surface of the pipe.

Determination of the stress concentration zone

It was determined that the maximum value of the yield stress in the pipeline, due to the effect of the applied load combination, is 379 MPa (Figure 3).

According to the selected load combination, the color diagram shows the increase of the yield stress from top to bottom according to the model.

The structural model of the pipe was modeled in the STAAD.Pro software, and analyzed taking into account the metal weight and the working pressure generated in the pipe. Since the yield strength on the bottom of the pipeline (379 MPa) is greater than the yield strength (350 MPa) corresponding to the physical properties of the metal, the resulting stress in the pipe is greater than the allowable stress.

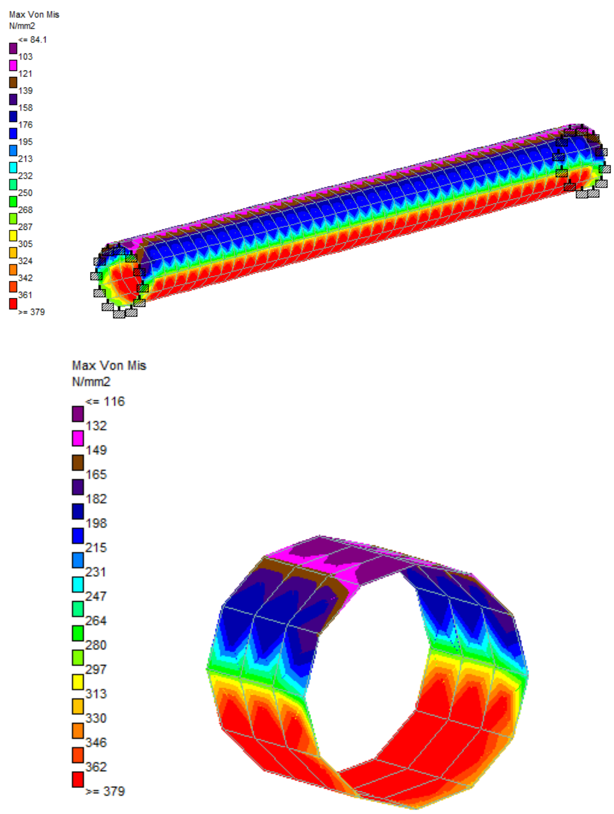

Figure 3. Evaluation of stress limit generated in pipeline elements.

Conclusion

Defectoscopy was carried out with an OLYMPUS 27 MG ultrasonic thickness gauge on the 187.74th km section of the underground main gas pipeline "Astara-Gazimammad" of the "Gas Export" Department (SOCAR, Azerbaijan). During the monitoring process, measurements were taken on the surface of the pipeline in the annular direction, and it was determined that the actual wall thicknesses were 12.18 mm on the top surface of the pipe, 11.80 mm on the side surface, and 9.19 mm on the bottom surface. Since corrosion pits sized 5–6 mm were found on the bottom surface of the pipe, the actual value of the thickness in this part turned out to be 3.19 mm.

By comparing the estimated thickness of the pipeline by mathematical calculation with the actual thickness (3.19 < 4.60), it was concluded that the pipeline was unsuitable for operation.

The structural model of the pipeline was modeled in STAAD.Pro software and analyzed taking into account the metal weight and the operating pressure generated in the pipeline. Since the yield stress (379 MPa) is greater than the stress corresponding to the physical properties of the metal (350 MPa), the resulting stress in the pipe is determined to be in excess of the allowable stress limit.

References

1. Ismayilov G.G., Iskandarov E.K., Ismayilova F.B., Hacizade S.G. (2021). Analysis of the Gas Pipelines Operation Based on Neural Networks. *Advances in Intelligent Systems and Computing.* Vol. 1306. Springer, Cham. DOI: 10.1007/978-3-030-64058-3_50.

2. Iskandarov E.K., Ismayilova F.B., Farzalizade Z.I. (2024). Oil Leaks Diagnosis in Pipelines Based on Artificial Neuron Technologies. *Lecture Notes in Networks and Systems.* Vol. 912. Springer, Cham. DOI: 10.1007/978-3-031-53488-1_38.

3. Temirbaeva N., Sadykov M., Osmonov Z., Osmonov Y., Karasartov U. (2024). Renewable energy sources in Kyrgyzstan and energy supply to rural consumers. *Machinery and Energetics.* No. 3. pp. 22–32. DOI: 10.31548/machinery/3.2024.22.

4. Hopkins P. (2003). The Structural Integrity of Oil and Gas Transmission Pipelines. Editors: M.H. Ferri Aliabadi, Winston O. Soboyejo. Comprehensive Structural Integrity. 2nd ed. Elsevier. pp. 498–534. DOI: 10.1016/B978-0-12-822944-6.00117-1. — https://www.sciencedirect.com/science/article/pii/B9780128229446001171

5. Pesinis K., Kong Fah Tee. (2017). Statistical model and structural reliability analysis for onshore gas transmission pipelines. *Engineering Failure Analysis.* No. 82. pp. 1–15. DOI: 10.1016/j.engfailanal.2017.08.008.

6. Amine M., Seghier B., Mourad B., Elahmoune B., Gaceb M. (2017). Probabilistic approach evaluates reliability of pipelines with corrosion defects. *OIL GAS J.* Vol. 115. pp. 64–68.

7. Kishawy H.A., Gabbar H.A. (2010). Review of pipeline integrity management practices. *International Journal of Pressure Vessels and Piping.* 87 (7). pp. 373–380.

8. Warman D.J., Johnston D., Mackenzie J.D., Rapp S., Travers B. (2006). Management of pipeline dents and mechanical damage in gas pipelines. *International Pipeline Conference*. Vol. 42622. pp. 551–560.

9. Ashworth B., Uzelac N., Willems H., Barbian O.A. (2000). Detection and Verification of SCC in a Gas Transmission Pipeline. *International Pipeline Conference.* Vol. 40252.

10. Chen P., Li R., Jia G., Lan H., Fu K., Liu X. (2023). A Decade Review of the Art of Inspection and Monitoring Technologies for Long-Distance Oil and Gas Pipelines in Permafrost Areas. *Energies*. 16 (4). Article 1751. DOI: 10.3390/en16041751.

11. Sachedina K., Mohany A. (2018). A review of pipeline monitoring and periodic inspection methods. *Pipeline Science and Technology.* 2 (3). pp. 187–203. DOI: 10.28999/2514-541X-2018-2-3-187-203.

12. Moles M., Dube N.L., Ginzel E. (2003). Pipeline girth weld inspections using ultrasonic phased arrays. *ASME Pressure Vessels and Piping Conference.* Vol. 16974. pp. 19–27.

13. Witek M. (2018). Validation of in-line inspection data quality and impact on steel pipeline diagnostic intervals. *Journal of Natural Gas Science and Engineering.* No. 56. pp. 121–133. DOI: 10.1016/j.jngse.2018.05.036.

14. Witek M., Batura A., Orynyak I., Borodii M. (2018). An integrated risk assessment of onshore gas transmission pipelines based on defect population. *Eng. Struct.* No. 173. pp. 150–165. DOI: 10.1016/j.engstruct.2018. 06.092.

15. ASME B31. Code for Pressure Piping. Process Piping. (2016). *The American Society of Mechanical Engineers*.

16. ASME B31.8. Gas Transmission and Distribution Piping Systems. (2022). *The American Society of Mechanical Engineers*. New York.

17. API 1111. (1993). Design, Construction, Operation, Maintenance of Offshore Hydrocarbon Pipelines. Washington, D.C.

18. API STD 537. (2020). Flare Details for Petroleum petrochemical and Natural Gas Industries. American Petroleum Institute.

19. OMAE 2008-57836. (2008). Stress Concentration Factors of Longitudinal and Transverse Plain Dents on Steel Pipelines.

20. AzDTN 2.9-2. (2009). State Construction Norms of the Republic of Azerbaijan. Design norms of main pipelines. Baku.

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Ісмаїлов Г.Г.[1], *докт. техн. наук, проф., ORCID: 0000-0002-5849-2488,*
Ісмаїлова Ф.Б.[1], *PhD техн. наук, ORCID: 0000-0002-5849-2488,*
Нагізаде А.[2], *ORCID: 0009-0003-6716-1626*

[1] ***Азербайджанський державний університет нафти та промисловості***
просп. Азадлиг, 16/21, Баку, AZ1010, Азербайджан, e-mail: fidan.ismayilova2014@mail.ru
[2] ***Інститут науково-дослідних проєктів нафти і газу***
просп. Г. Зардаби, 88А , Баку, AZ1010, Азербайджан, e-mail: nagizadeanar26@gmail.com

Розширена експлуатація ресурсів магістрального газопроводу природного газу за допомогою методів моделювання CFD

Анотація. Можливість подальшого використання трубопроводів, що перебувають в експлуатації, є одним із найважливіших питань нафтогазової промисловості. У зв'язку з цим необхідно періодично перевіряти (діагностувати) технічний стан трубопроводів. З огляду на суворі умови експлуатації трубопроводів можуть виникати втрати товщини їх стінок. У статті досліджено залишкові експлуатаційні ресурси різних елементів трубопроводу в результаті діагностичних робіт, виконано розрахунок товщини стінок магістрального газопроводу за допомогою ультразвукового товщиноміра OLYMPUS 27 MG. На основі фактичних даних, отриманих під час досліджень, було розраховано мінімально допустимі значення товщини стінок, які відповідають існуючому внутрішньому тиску в трубопроводі, та порівняно їх із фактичною мінімальною товщиною. Таким чином, на основі показань вимірювального приладу мінімальної товщини стінок та експлуатаційних навантажень було досліджено можливість безпечної експлуатації газопроводу. Під час розрахунків застосовувалися як аналітичні методи, так і сучасне програмне забезпечення. Фізична модель, створена завдяки програмному забезпеченню для структурного проєктування, може бути трансформована в аналітичну модель для структурного аналізу. За допомогою програмного забезпечення було створено тривимірну просторово-геометричну модель трубопроводу та розраховано міцність та стабільність трубопроводу під впливом різних сил. У результаті технічної діагностики трубопроводу було визначено можливість подальшої експлуатації елемента трубопроводу. *Бібл. 20, рис. 3, табл. 5.*

Ключові слова: магістральний газопровід, міцність, розрахунковий опір, межа плинності, коефіцієнт надійності, допустиме напруження.

Список літератури

1. Ismayilov G.G., Iskandarov E.K., Ismayilova F.B., Hacizade S.G. Analysis of the Gas Pipelines Operation Based on Neural Networks. *Advances in Intelligent Systems and Computing.* 2021. Vol. 1306. Springer, Cham. DOI: 10.1007/978-3-030-64058-3_50.

2. Iskandarov E.K., Ismayilova F.B., Farzalizade Z.I. Oil Leaks Diagnosis in Pipelines Based on Artificial Neuron Technologies. *Lecture Notes in Networks and Systems.* 2024. Vol. 912. Springer, Cham. DOI: 10.1007/978-3-031-53488-1_38.

3. Temirbaeva N., Sadykov M., Osmonov Z., Osmonov Y., Karasartov U. Renewable energy sources in Kyrgyzstan and energy supply to rural consumers. *Machinery and Energetics.* 2024. № 3. P. 22–32. DOI: 10.31548/machinery/3.2024.22.

4. Hopkins P. The Structural Integrity of Oil and Gas Transmission Pipelines. Editors: M.H. Ferri Aliabadi, Winston O. Soboyejo. Comprehensive Structural Integrity. 2nd ed. Elsevier, 2003. P. 498–534. DOI: 10.1016/B978-0-12-822944-6.00117-1. — https://www.sciencedirect.com/science/article/pii/B9780128229446001171

5. Pesinis K., Kong Fah Tee. Statistical model and structural reliability analysis for onshore gas transmission pipelines. *Engineering Failure Analysis*. 2017. № 82. P. 1–15. DOI: 10.1016/j.engfailanal.2017.08.008.

6. Amine M., Seghier B., Mourad B., Elahmoune B., Gaceb M. Probabilistic approach evaluates reliability of pipelines with corrosion defects. *OIL GAS J*. 2017.

Vol. 115. P. 64–68.

7. Kishawy H.A., Gabbar H.A. Review of pipeline integrity management practices. *International Journal of Pressure Vessels and Piping.* 2010. Vol. 87, № 7. P. 373–380.

8. Warman D.J., Johnston D., Mackenzie J.D., Rapp S., Travers B. Management of pipeline dents and mechanical damage in gas pipelines. *International Pipeline Conference*. 2006. Vol. 42622. P. 551–560.

9. Ashworth B., Uzelac N., Willems H., Barbian O.A. Detection and Verification of SCC in a Gas Transmission Pipeline. *International Pipeline Conference.* 2000. Vol. 40252.

10. Chen P., Li R., Jia G., Lan H., Fu K., Liu X. A Decade Review of the Art of Inspection and Monitoring Technologies for Long-Distance Oil and Gas Pipelines in Permafrost Areas. *Energies*. 2023. Vol. 16, № 4. Article 1751. DOI: 10.3390/en16041751.

11. Sachedina K., Mohany A. A review of pipeline monitoring and periodic inspection methods. *Pipeline Science and Technology.* 2018. Vol. 2, № 3. P. 187–203. DOI: 10.28999/2514-541X-2018-2-3-187-203.

12. Moles M., Dube N.L., Ginzel E. Pipeline girth weld inspections using ultrasonic phased arrays. *ASME Pressure Vessels and Piping Conference.* 2003. Vol. 16974. P. 19–27.

13. Witek M. Validation of in-line inspection data quality and impact on steel pipeline diagnostic intervals. *Journal of Natural Gas Science and Engineering.* 2018. No. 56. P. 121–133. DOI: 10.1016/j.jngse.2018.05.036.

14. Witek M., Batura A., Orynyak I., Borodii M. An integrated risk assessment of onshore gas transmission pipelines based on defect population. *Eng. Struct.* 2018. No. 173. P. 150–165. DOI: 10.1016/j.engstruct.2018.06.092.

15. ASME B31. Code for Pressure Piping. Process Piping. *The American Society of Mechanical Engineers*. 2016.

16. ASME B31.8. Gas Transmission and Distribution Piping Systems. *The American Society of Mechanical Engineers*. New York, 2022.

17. API 1111. Design, Construction, Operation, Maintenance of Offshore Hydrocarbon Pipelines. Washington, D.C., 1993.

18. API STD 537. Flare Details for Petroleum petrochemical and Natural Gas Industries. *American Petroleum Institute*. 2020.

19. OMAE 2008-57836. Stress Concentration Factors of Longitudinal and Transverse Plain Dents on Steel Pipelines. 2008.

20. AzDTN 2.9-2. State Construction Norms of the Republic of Azerbaijan. Design norms of main pipelines. Baku, 2009.

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