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Development of a Flow-Measuring Hydropneumatic Bench for Testing Pipeline Valves

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Abstract

Pipe fittings are an important element of any pipeline network, ensuring stable and safe operation by regulating the flow of the working medium. To control the performance of pipeline valves, it is necessary to conduct various tests, the main ones of which are hydraulic and pneumatic. It is important to expand testing capabilities and reduce time costs. The purpose of this work is to combine hydraulic and pneumatic tests into one test complex, which will reduce the time of the test complex due to the absence of the need for reinstallation and reconfiguration. The subject of the study is the determination of the design, technical, and operational characteristics of such a stand, as well as the simulation of operating conditions to confirm its operability. During the development, methods of solid and surface modeling, the finite element method, and analytical calculation methods were used. The results of the stand design are presented, and the features of the process of its development are described, including the analysis of the stress-strain state and the analysis of reliability and durability indicators. The obtained values of the distribution of equivalent stresses, deformations, and displacements of the structure elements do not exceed the maximum allowable values and do not lead to destruction. The analysis shows that the developed stand has improved capabilities compared to those previously used.

Keywords: Pipeline Valves; Pipeline System; Hydraulic Testing; Pneumatic Testing; Flow-Measuring Hydropneumatic Bench.

1. Introduction

Pipeline valves are devices designed to control flows of working medium in pipeline networks that are integral elements of technological systems in chemical, energy, thermal, transport, power, and other industries and plants with an extremely wide range of technical characteristics [1–3]. Valves are an integral part of any pipeline system that can transport water—cold and hot—saturated and superheated; chemical materials in the form of products, semi-products, or waste; metal melts; gaseous media; pulpy mixtures; and others [4–6]. Working media can be under overpressure up to hundreds of atmospheres and at temperatures ranging from absolute zero to hundreds of degrees [7–9]. To ensure the process conditions of units, plants, and systems, pipeline valves must maintain overpressure, deep vacuum, or a specified law of their alternation. Additionally, modern production facilities impose increased requirements for resistance to corrosion and wear resistance on pipeline valves. Currently, special coatings are applied to improve the reliability and durability of pipeline valves [10].

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Pipeline valves often determine the safety, parametric reliability, durability, and efficiency of operating technological systems, units, and plants, serving in the most severe operating conditions [11, 12]. The production of pipeline valves, as a rule, includes many operations, and the finished product quality ultimately depends on the quality of each of them [13]. An inseparable stage in the process of development and implementation of new technical solutions is experimental testing. Testing pipeline valves is one of the most responsible stages of production because it determines the main technical characteristics and quality of the product manufacturing. Reliable and safe operation of the valves will only be possible if the main technical characteristics of the valves meet the relevant requirements and the performance of the systems and units in which the valves will operate [14, 15].

According to the technical requirements, pipeline valves are subject to mandatory hydraulic and pneumatic tests [16] for the strength and tightness of body parts and gasket joints, as well as the tightness of the closure. In the first case, tests detect cracks and leaks in the metal of bodies and covers and the strength of body and cover joints [17]. In the second case, tests checked the tightness of the locks (no leakage between the body sealing rings and valve disc or the body and wedge along the seal perimeter) and the tightness of the gland seal. Tests on the tightness of the closure determine its ability to prevent gas or liquid exchange between the media separated by the closure [18, 19].

Hydraulic and pneumatic tests of pipeline valves are performed on special technological equipment—separate benches for hydraulic and pneumatic tests, respectively [20, 21]. The test bench is a complex of technical systems, equipment, measuring tools, accessories, mechanization and automation, and collective means of protection that ensure safe testing of the valves [22, 23]. The test bench also contains auxiliary equipment for particular tests. Combining hydraulic and pneumatic tests into one test complex on the flow-measuring hydropneumatic bench will significantly expand the bench's scope and make it possible to reduce the time required to conduct the entire complex of tests due to the lack of the need to reset and readjust test objects and equipment between different benches. The operating principle of such a bench is the generation of test pressure in the hydraulic or pneumatic system of the test circuits using pumps and compressors [24, 25]. Pressure indicators (pressure gauges) monitor the pressure level, and flow meters monitor the flow rate of the test medium. The test object is suitable if medium penetration through the material structure is absent and the indicating devices (sensitive pressure gauges) did not record a change in pressure during the regulated time.

Thus, the purpose of the study was to develop a flow-measuring hydropneumatic bench designed for in-plant hydraulic and pneumatic tests of pipeline valves using a test medium (water and air) under pressure (during hydraulic tests – 0.1 MPa; during pneumatic tests – 1 MPa) and the corresponding flow rate of the test medium (during hydraulic tests – flow rate of not more than 5 m/s; during pneumatic tests – not more than 60 m/s) to determine the leak tightness, strength of structural materials, and flow capacity of swing check valve structures. Thus, the main distinguishing advantage of this study is an attempt to create a test bench that combines the possibilities of hydraulic and pneumatic testing of valves in various loads. This stand should provide a significant reduction in time and labor, as it will allow you to perform tests without reinstallation and adjustment, as was previously the case with the sequential use of hydraulic and pneumatic stands.

2. Literature Review

When developing a pipeline system to create a structure fully compliant with the given specifications, highly qualified specialists from different disciplines interact with each other. Decisions made at an early stage in the design process influence investment, construction and operating costs, maintenance schedules, and, importantly, the environmental and safety aspects of the entire system. Some previous works identify a set of actions required at this stage. It includes geotechnical studies, modeling of hydro-gas-dynamic, thermal, chemical, and other processes that occur during the operation of pipeline systems, studies of environmental conditions along the pipeline route, studies of the behavior of structural materials under loading conditions corresponding to operational conditions, studies of the characteristics of working media and their interactions with structural materials of the system, etc. [26, 27].

Although pipelines are considered one of the safest and most economical modes of transportation, a breach in the integrity of the pipeline network can lead to catastrophic consequences [28]. Shang & Shenb found that, according to statistics from the Pipeline and Hazardous Materials Safety Administration (PHMSA), more than 12,500 pipeline incidents were recorded from 2001 to 2020 [26]. Alexandrov et al. confirm the relevance of the issue of increasing reliability, durability, as well as a correct assessment of the performance of both the system as a whole and individual structural element, including those used during maintenance and repair work [29, 30].

Zheng et al. confirm the important role of pipeline valves in ensuring the stable and safe operation of pipeline networks for various purposes [31]. Due to the valves of the armature, the starting, distribution, control and regulation of working media, their mixing and shutting off the flow occurs. When designing pipelines, the piping design code, ASME B31.3 Process Piping, is used as one of the industry standards according to which all pipelines must be hydrostatically tested for tightness [32]. In cases where hydro-testing is impossible, they are replaced by pneumatic ones. Arti et al. cite as an example cryogenic pipeline in natural gas liquefaction plants, where very low temperatures mean that even a small amount of water that can remain after hydrostatic testing is not allowed [33]. Also, pipelines for various purposes are subjected to hydro- and pneumatic tests.

However, at present, some works [34, 35] highlight the problem of completing production facilities with testing equipment, because a significant part of the equipment fleet is no longer capable of fully fulfilling the tasks. Therefore, the active development of new projects of testing equipment for, among other things, pneumatic testing production facilities is underway [36–38].

3. Description of Bench Structure

The developed bench structure includes high-precision measuring tools and the necessary auxiliary equipment to perform all main (mandatory) hydraulic and pneumatic tests, which significantly optimizing the quality control process during production. Table 1 shows the main technical characteristics (parameters) of the bench.

Table 1. Main technical characteristics of the bench

No.	Parameter name	Unit	Value
1	Working pressure during hydraulic tests	MPa	0.1
2	Working pressure during pneumatic tests	MPa	1.0
3	Maximum velocity of the test medium in water	m/s	5
4	Maximum speed of the test medium in air	m/s	60

To adjust the test medium pressure, regulating devices (control valves) are installed on the bench pipelines, ensuring the required pressure value in the system. Pressure indicators (manometers) perform continuous monitoring of the test medium pressure during testing. Flow meters are installed on the straight section of the pipeline in the test loops to determine the flow characteristics of the tested pipeline valves.

The structure of the developed bench (Figure 1) is a complex system of technological pipelines for transporting gases and liquids, consisting of pressure pipes of different diameters, pipeline parts, and fittings tightly connected to each other. The main elements of the bench design are:

- Base
- Water tanks
- Water supply pump
- Water disposal pump
- Receiver
- Compressor

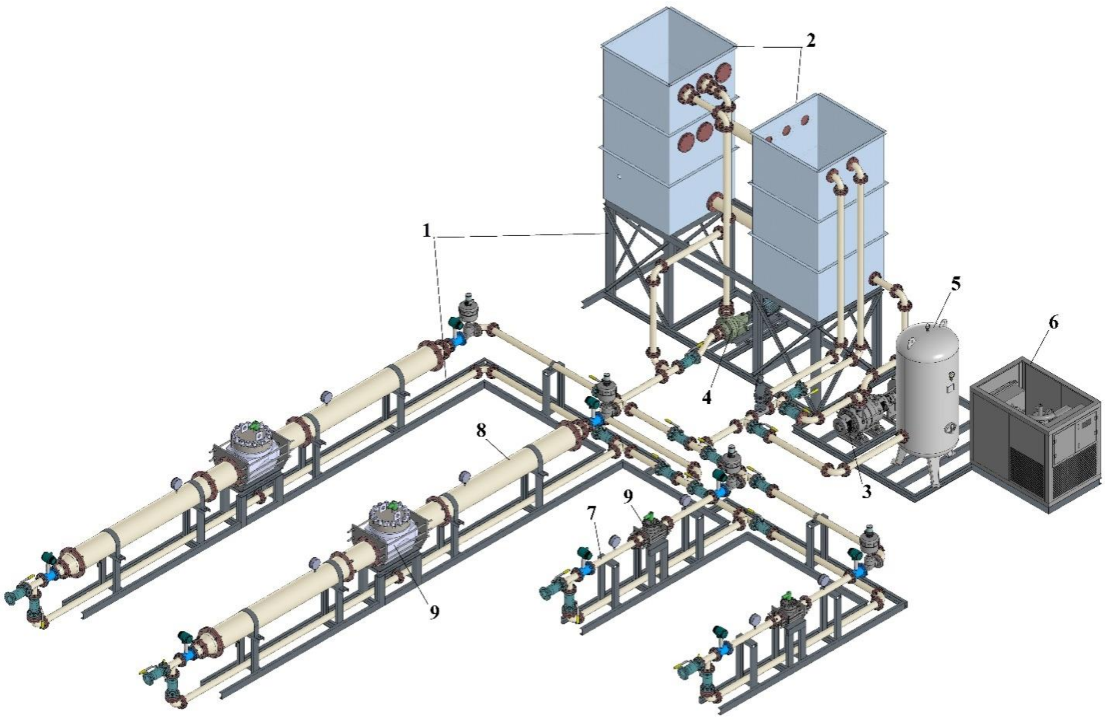


Figure 1. Structure of flow-measuring hydropneumatic test bench for testing of pipeline valves: 1 – base; 2 – water tanks; 3 – water supply pump; 4 – water disposal pump; 5 – receiver; 6 – compressor; 7 – test loop 1; 8 – test loop 2; 9 – tested product

The bench base, according to the mounted structural elements, can be conditionally divided into several sections (Figure 2): a ramp (1) for the water tanks and water disposal pump, a platform (2) for the elements of the pneumatic and hydraulic testing systems, and a frame, which in turn includes section 1 (3) for the test loop 1 and section 2 (4) for the test loop 2.The base structure can withstand loads caused by the weight of all units, assemblies, and test equipment filled with the test medium.

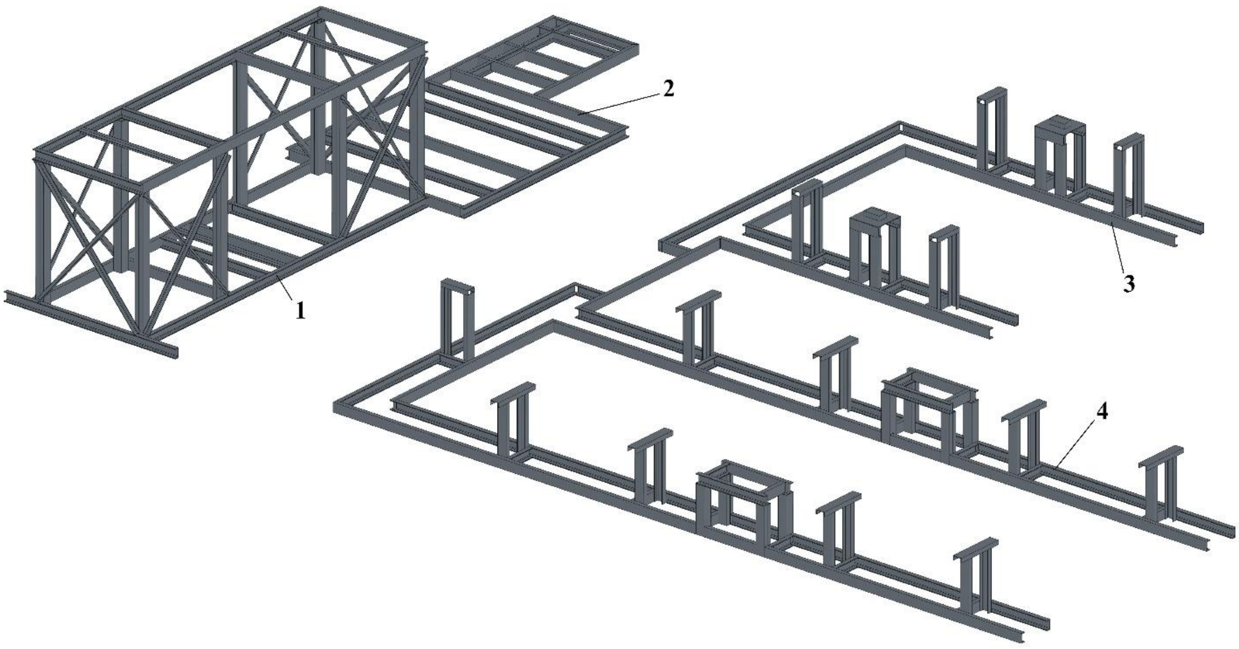


Figure 2. The bench base structure: 1 – the ramp for water tanks and pump; 2 – the platform for elements of systems for pneumatic and hydraulic tests; 3 – section 1 for test loop 1; 4 – section 2 for test loop 2

The water tanks (Figure 3) are two tanks – a spout and a receiving, installed on the ramp, connected by pipes, and filled with the test medium (water). The water tanks provide the test medium for the loops with the tested pipeline valves. Structurally, the tanks are welded sealed shells with an overall size of 1250×1256×2500 mm, made of carbon steel with stiffening ribs and a protective coating.

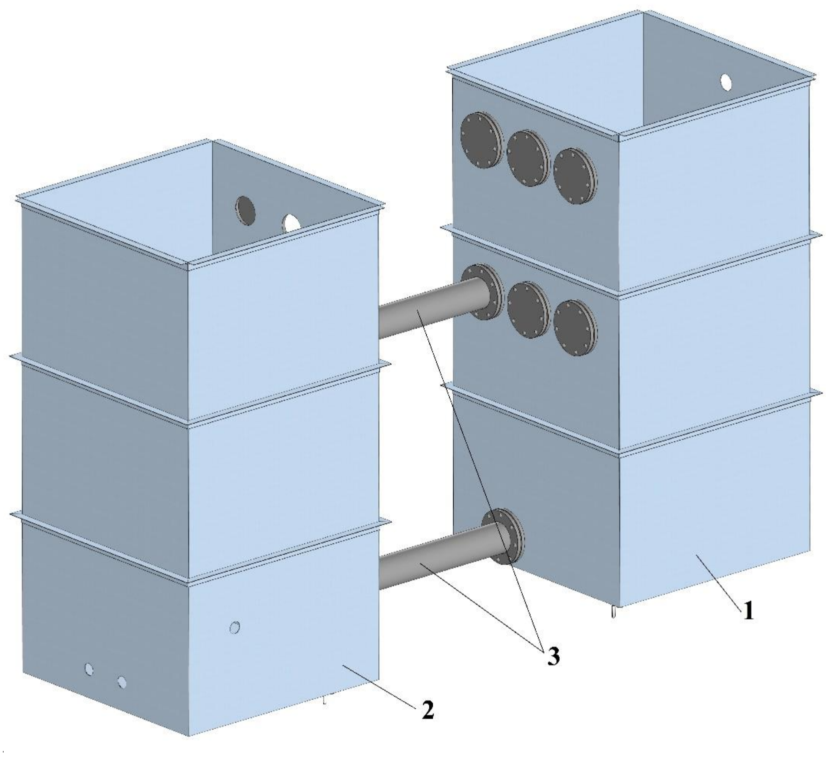
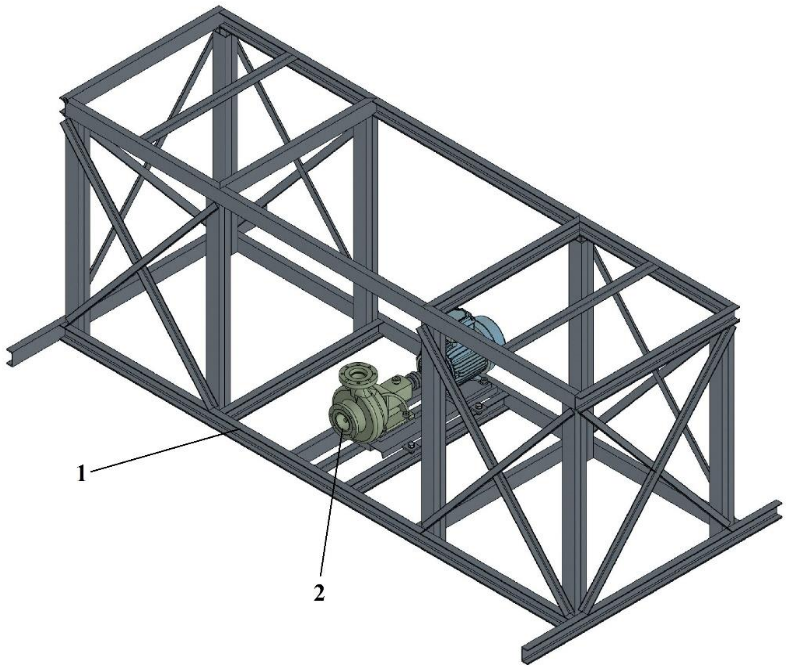
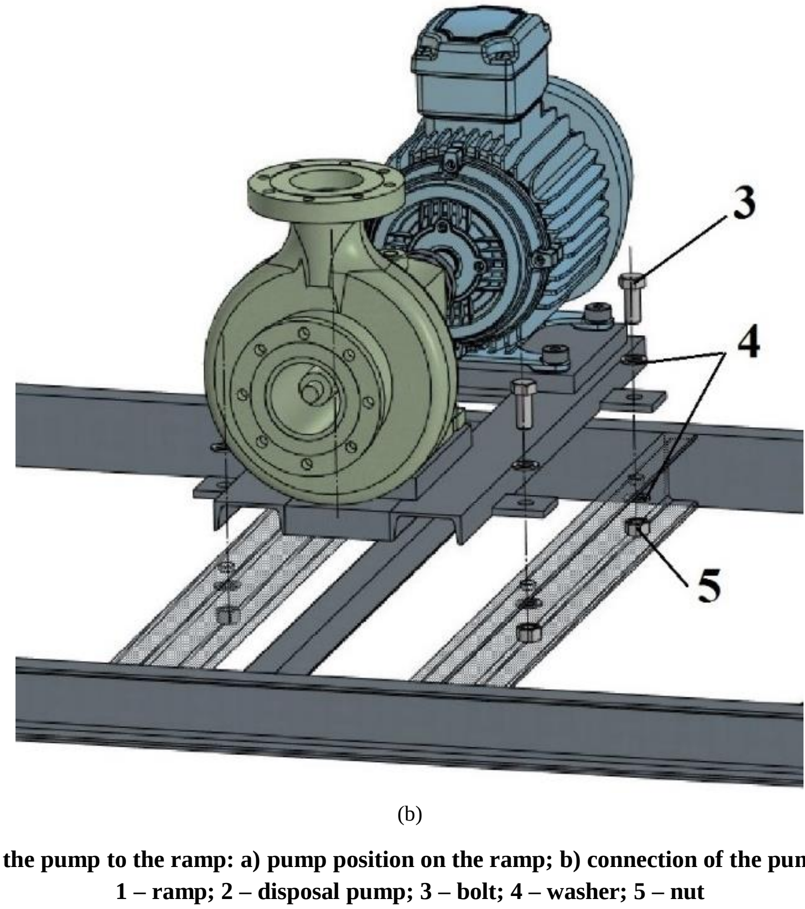


Figure 3. Structure of water tanks: 1 – spout tank; 2 – receiving tank; 3 – connecting pipes

A centrifugal pump for pumping the test medium from the test bench pipelines (Figure 4) is installed on the cross beams of the ramp lower frame with bolts.



(a)



(b)

Figure 4. Connecting the pump to the ramp: a) pump position on the ramp; b) connection of the pump to the frame beams; 1 – ramp; 2 – disposal pump; 3 – bolt; 4 – washer; 5 – nut

Test loops for pipeline valves of different diameters (Figure 5) are a system of pipes, fittings, connectors, filters, and control devices, forming a hydraulic and pneumatic system for testing. The test loops were on the appropriate sections of the base frame.The dimensions of the straight pipe sections of the loops before and after the tested pipeline valves ensure that the test medium flows close to the laminar.The first loop is designed for testing pipeline valves with a nominal diameter (DN) of 80–150 mm, and the second one – with a DN of 150–300 mm.

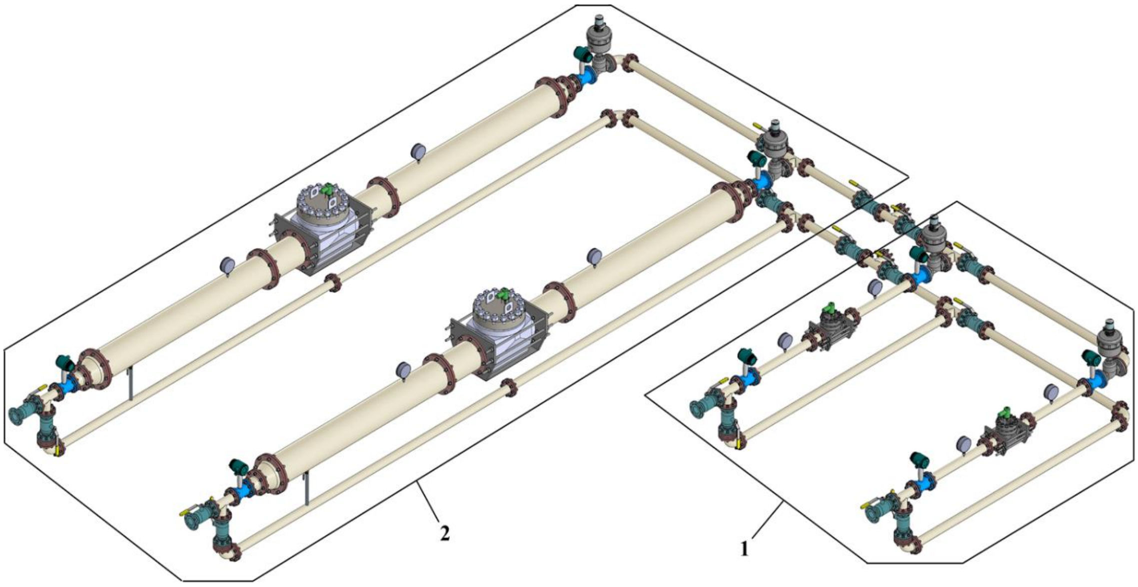


Figure 5. Test loops: 1 – loop for pipeline valves with DN of 80–150 mm; 2 – loop for pipeline valves with DN of 150–300 mm

The platform for the elements of the pneumatic and hydraulic test systems serves to install a water pump, receiver, and compressor (Figure 6).

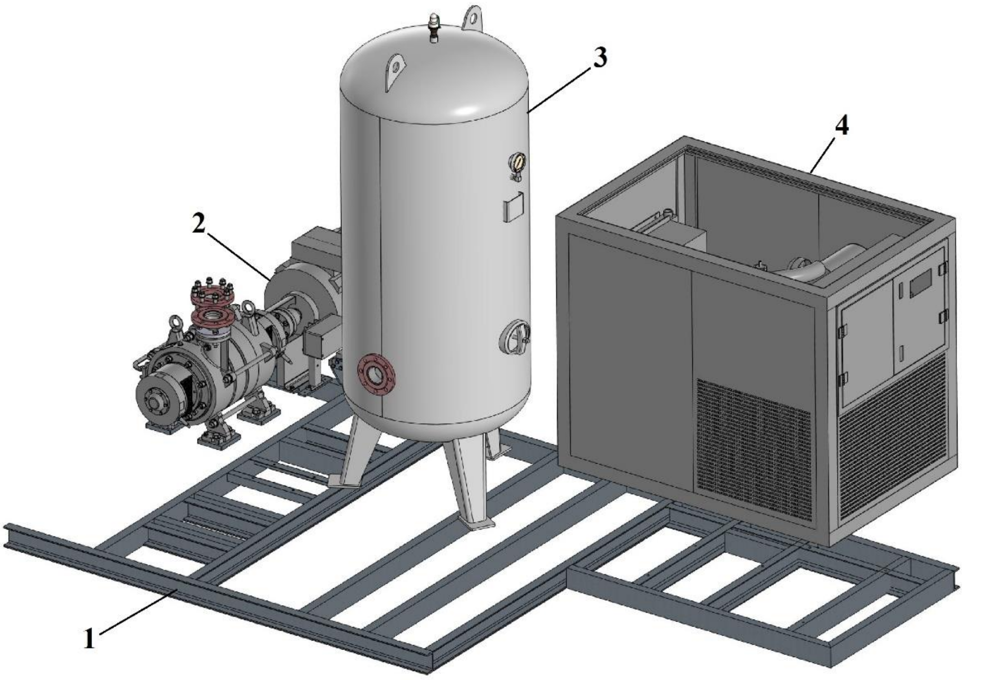


Figure 6. Auxiliary equipment of the bench: 1 – platform; 2 – water supply pump; 3 – receiver; 4 – compressor

Auxiliary equipment of the system for pneumatic and hydraulic tests included

- A compressor and pumps provide the required pressure and flow rate necessary to ensure the flow velocity of the test medium for testing pipeline valves;
- A receiver to accumulate the test medium;
- Shut-off valves to regulate the test medium flow;
- Adapters to organize the hydraulic and pneumatic system;
- A flow meter was installed on a straight section of the pipeline to determine the flow characteristics of the tested pipeline valves;
- Manometer to monitor pressure.

All elements of this system are mounted on the corresponding base sections. Flow meters and manometer make it possible to monitor the relevant parameters of the test medium during the tests and to adjust them by regulating the valves in the test medium supply section and changing the compressor and pump settings. Safety valves provide emergency pressure relief when exceeding the specified pressure parameters in the system.

4. Research Methodology

Strength analysis of the bench structure determines the most loaded areas and structural elements under critical loading conditions. When analysing the stress-strain state of the bench components, finite-element modeling software complexes are used under the loads corresponding to the operating conditions.

The use of the finite element method is due to the need to simplify the methods for assessing durability and reliability, since this process itself is complex, time-consuming and at the same time necessary. Thus, in this work, approximate analytical dependencies were used to numerically estimate these parameters.

The computational model building excludes from consideration insignificant unloaded low-dimensional structural elements (roundings, chamfers, hinges, and others) that do not significantly affect the final calculation result. A finite element mesh uses built-in modules to evaluate element sizes and shapes to optimize the required computational resources. Special attention was paid to stress concentrators and connection points to provide sufficient analysis accuracy.

For thin-walled elements and surfaces, the finite element mesh was built by splitting the faces into a finite number of equal segments, forming a two-dimensional finite element mesh. Solid structural elements were divided into three-dimensional finite elements with a predominance of Hex dominant. Splitting with these customizable methods provides greater accuracy and reduces the risk of unwanted stress raisers. After a verification calculation with an automatically adjusted finite element mesh, the most loaded areas were determined, in which a mesh was built with a smaller finite element size to improve accuracy and reduce the risk of erroneous stress concentrators. Loads were applied to the loaded surfaces of the structure in accordance with the operating conditions.

5. Simulation Results

The research results are the data on the maximum deformations, stresses, and displacements of the bench structure elements, shown in Figures 7 to 18. Figure 7 shows the distribution of equivalent stresses, where it can be seen that the maximum values, which do not exceed the allowable ones, are achieved at the lower tops of the tanks, and the values in the upper and middle parts are minimal, which means that it indicates a sufficient degree of structural strength.

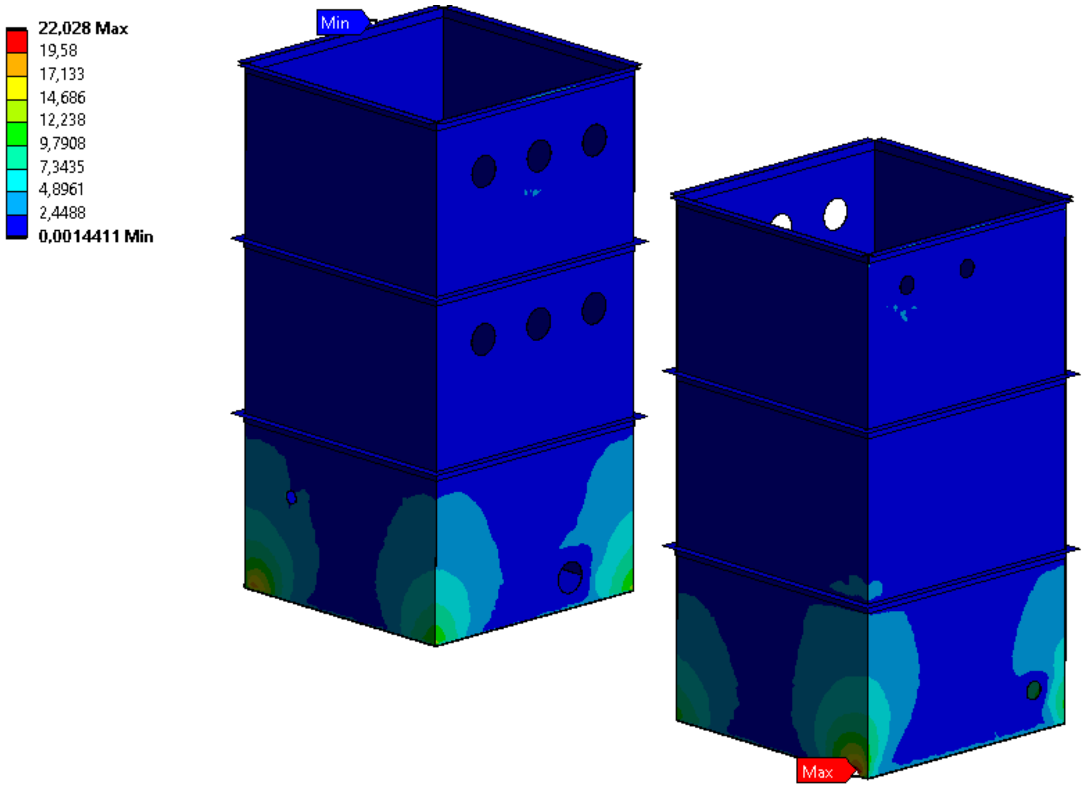


Figure 7. Distribution of equivalent stresses in the model volume of water tanks, MPa

Figure 8 shows the distribution of equivalent deformations, which shows that the maximum values, which do not exceed the allowable ones, are achieved at the lower tops of the tanks, and the values in the upper and middle parts are minimal, indicating a sufficient degree of structural strength.

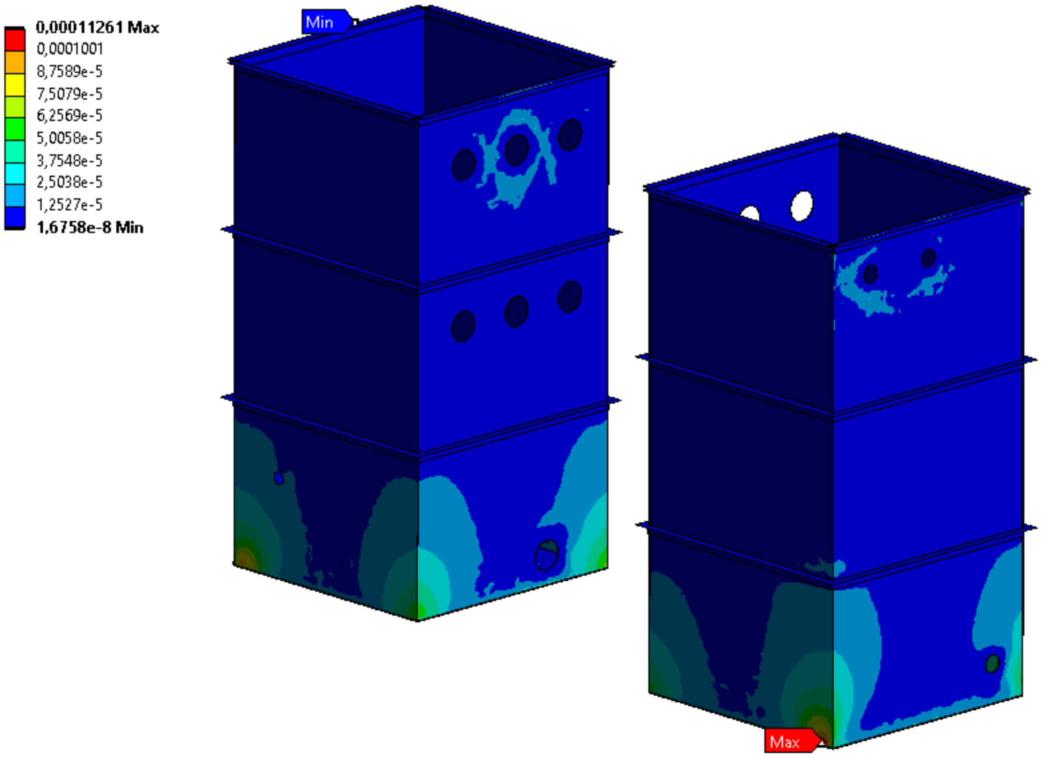


Figure 8. Distribution of equivalent deformations in the model volume of water tanks, mm/mm

Figure 9 shows the distribution of maximum displacements, where it can be seen that the minimum values are achieved in the extreme lower nodes of the tanks, and the maximum ones are distributed along the ribs of the rear wall of the structure.

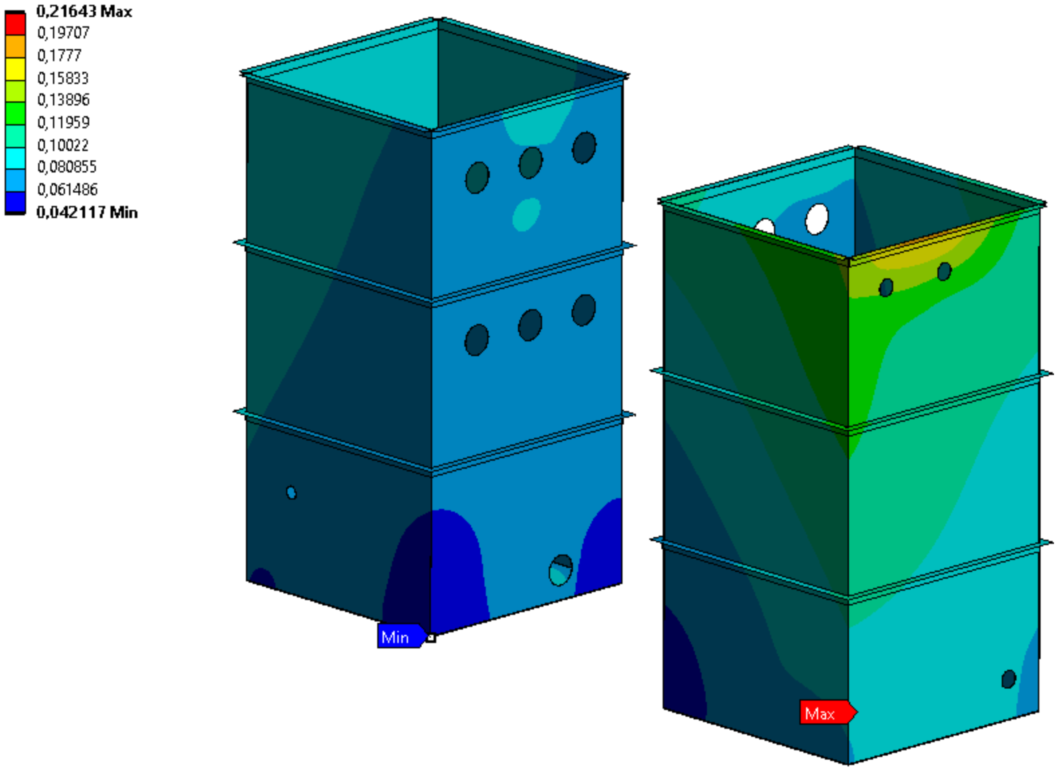


Figure 9. Distribution of maximum displacements in the model volume of water tanks, mm

Figure 10 shows the distribution of equivalent stresses, which shows that the maximum values, which do not exceed the allowable ones, are achieved on the lower central beams of the overpass, and the values on the remaining beams are minimal, which means that the structure is sufficiently strong.

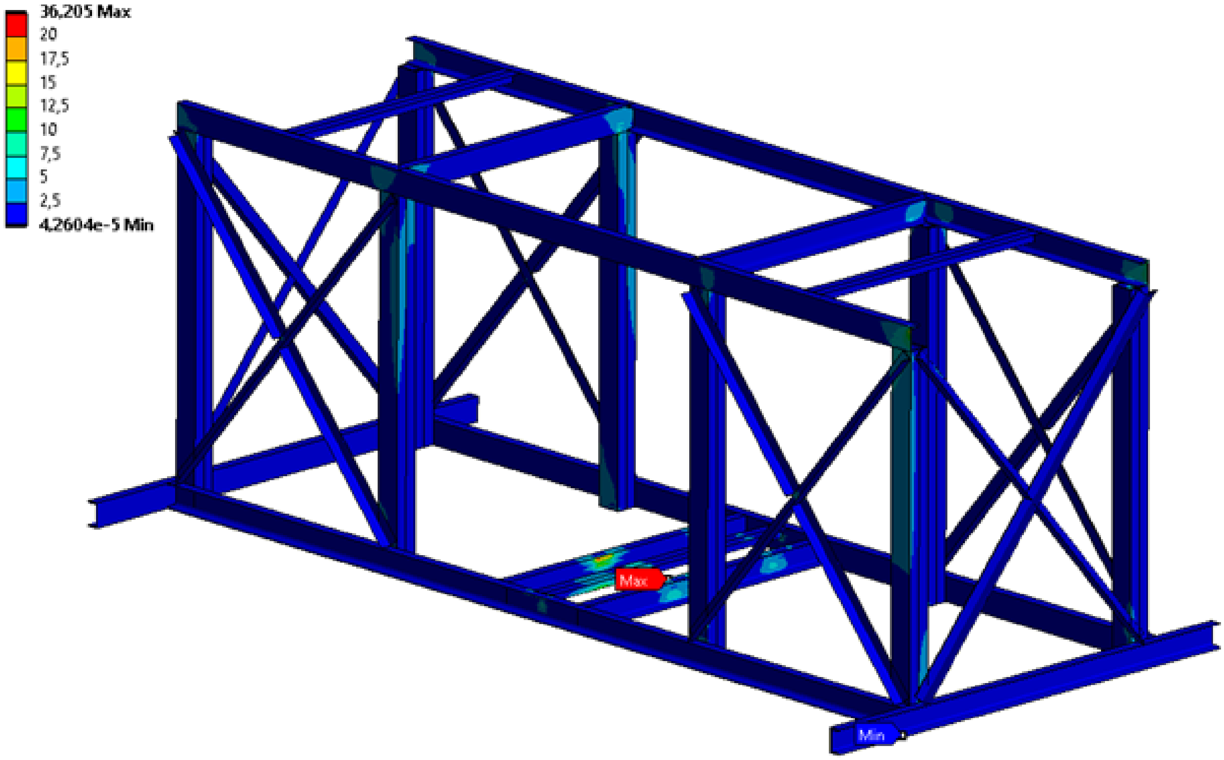


Figure 10. Distribution of equivalent stresses in the model volume of the ramp for water tanks, MPa

Figure 11 shows the distribution of equivalent deformations, which shows that the maximum values, which do not exceed the allowable ones, are achieved in the upper extreme nodes of the overpass, as well as in the vertical beams of the structure. The values in the rest of the beams are the minimum.

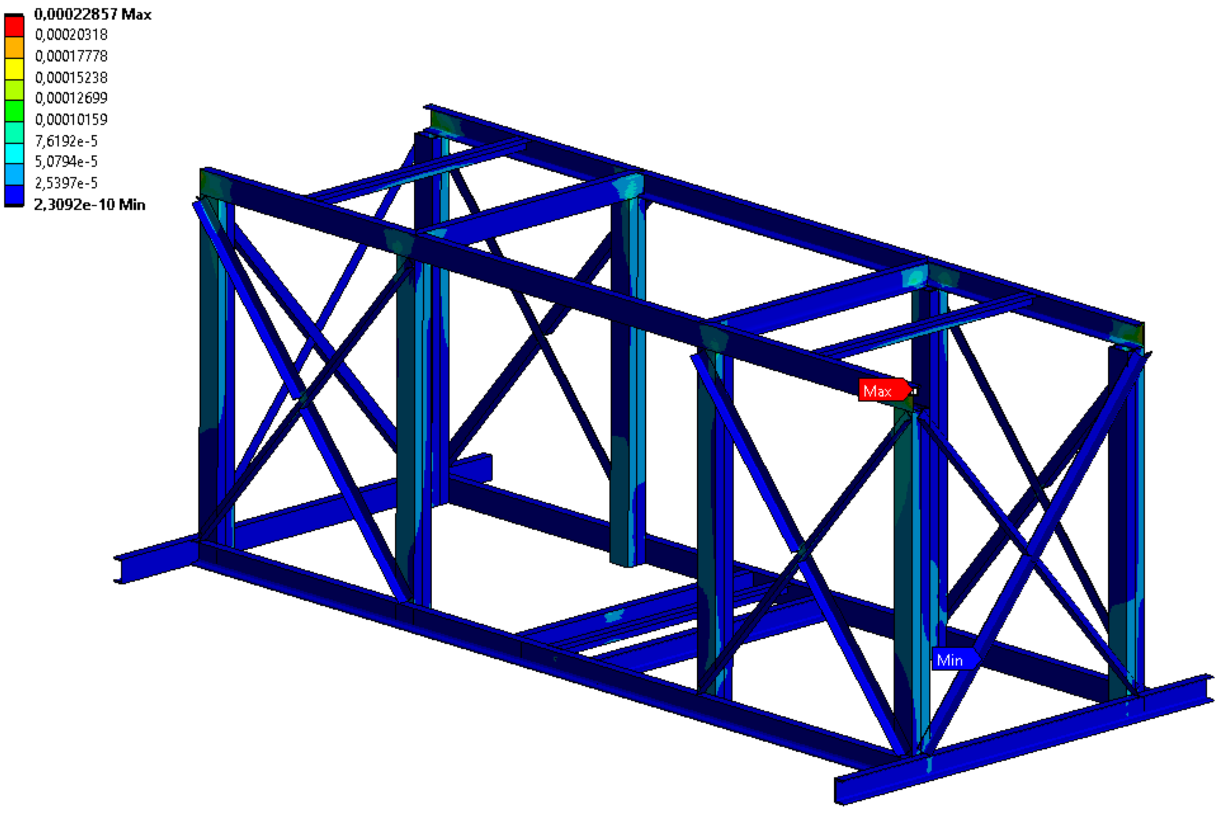


Figure 11. Distribution of equivalent deformations in the model volume of the ramp for water tanks, mm/mm

Figure 12 shows the distribution of maximum displacements, where it can be seen that the maxima are achieved in the upper, horizontal, reinforcing beams, and zero values are achieved in the beams located at the base of the structure.

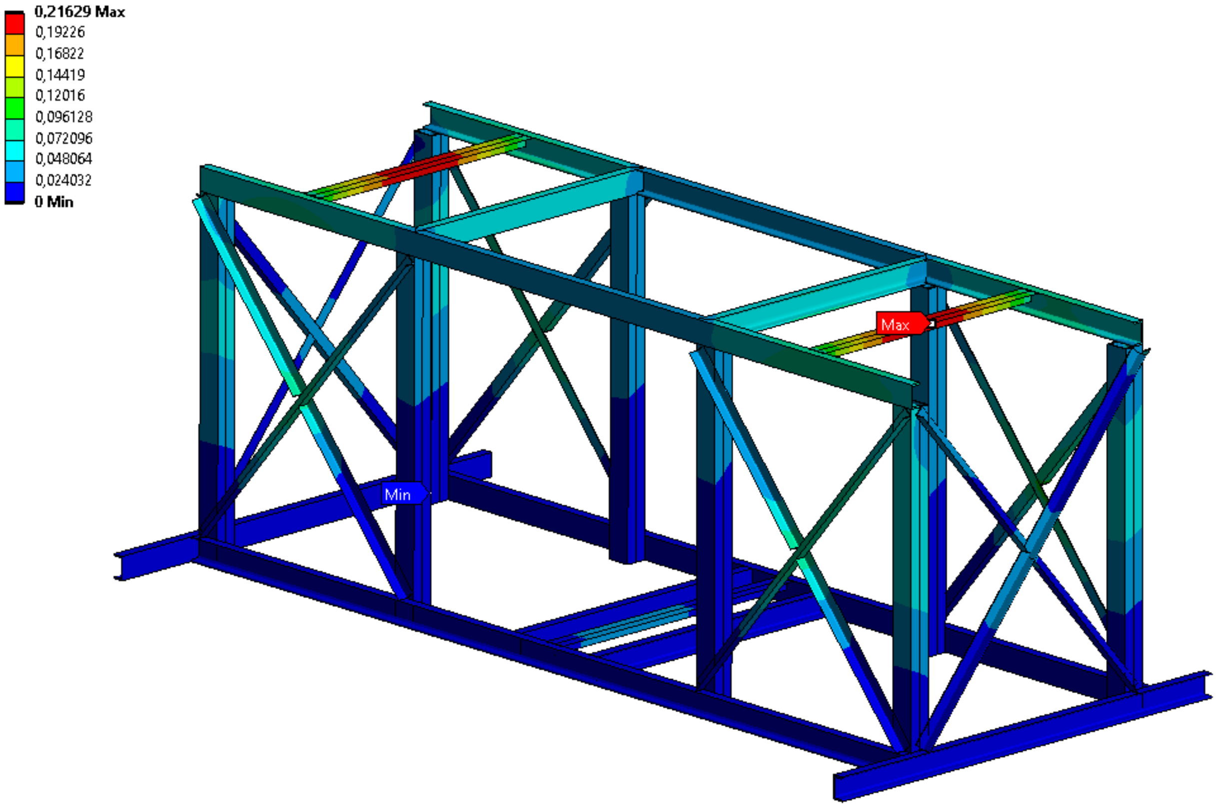


Figure 12. Distribution of maximum displacements in the model volume of the ramp for water tanks, mm

Figure 13 shows the distribution of equivalent stresses, where it can be seen that the minimum values are achieved in the rotary check valves and beams on which the circuit stands.

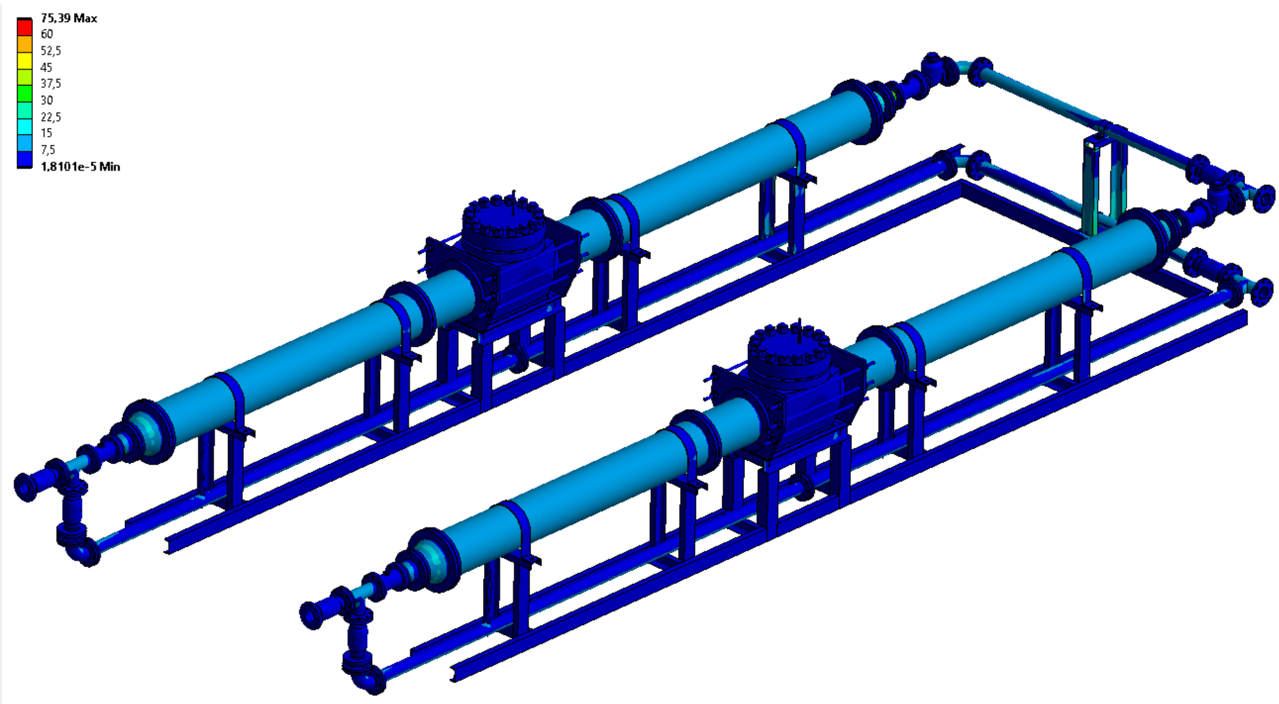


Figure 13. Distribution of equivalent stresses in the model volume of the subsystem, test loop 1, MPa

Figure 14 shows the distribution of equivalent deformations, where it can be seen that the minimum values are achieved in the rotary check valves and beams on which the circuit stands.

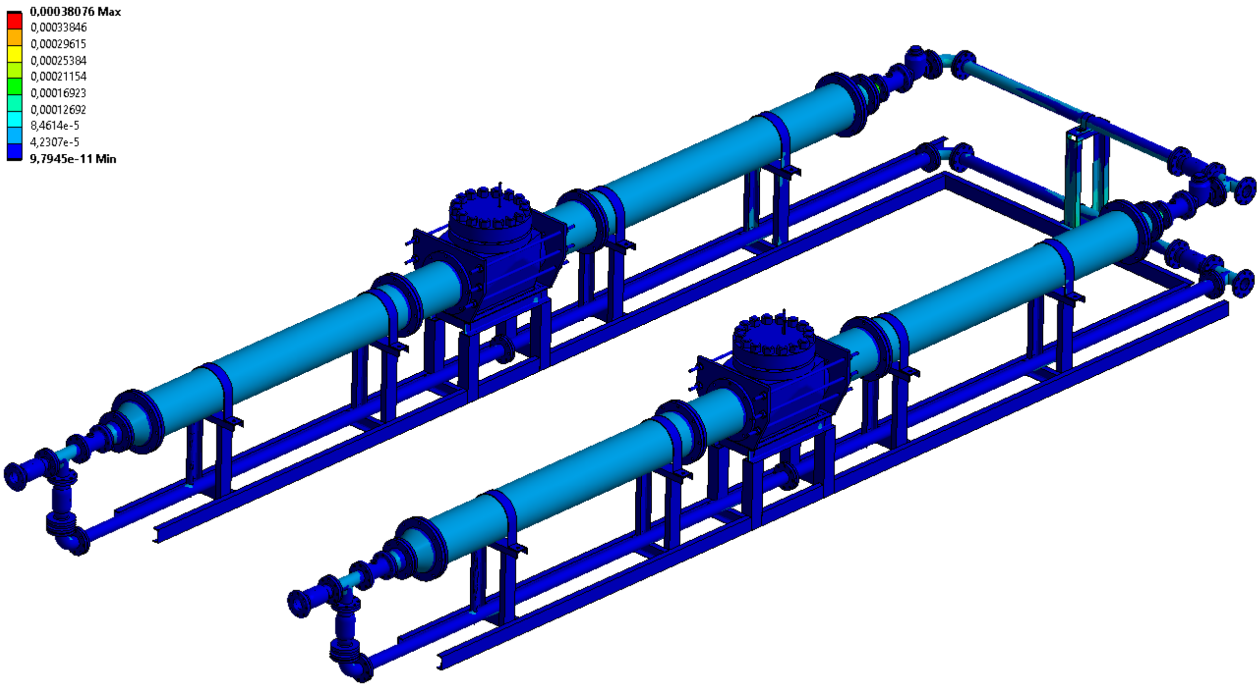


Figure 14. Distribution of equivalent deformations in the model volume of the subsystem, test loop 1, mm/mm

Figure 15 shows the distribution of maximum displacements, where it can be seen that the maximum values are achieved in the rear upper pipe of the circuit, and the minimum values are in the rotary check valves and pipes extending from them.

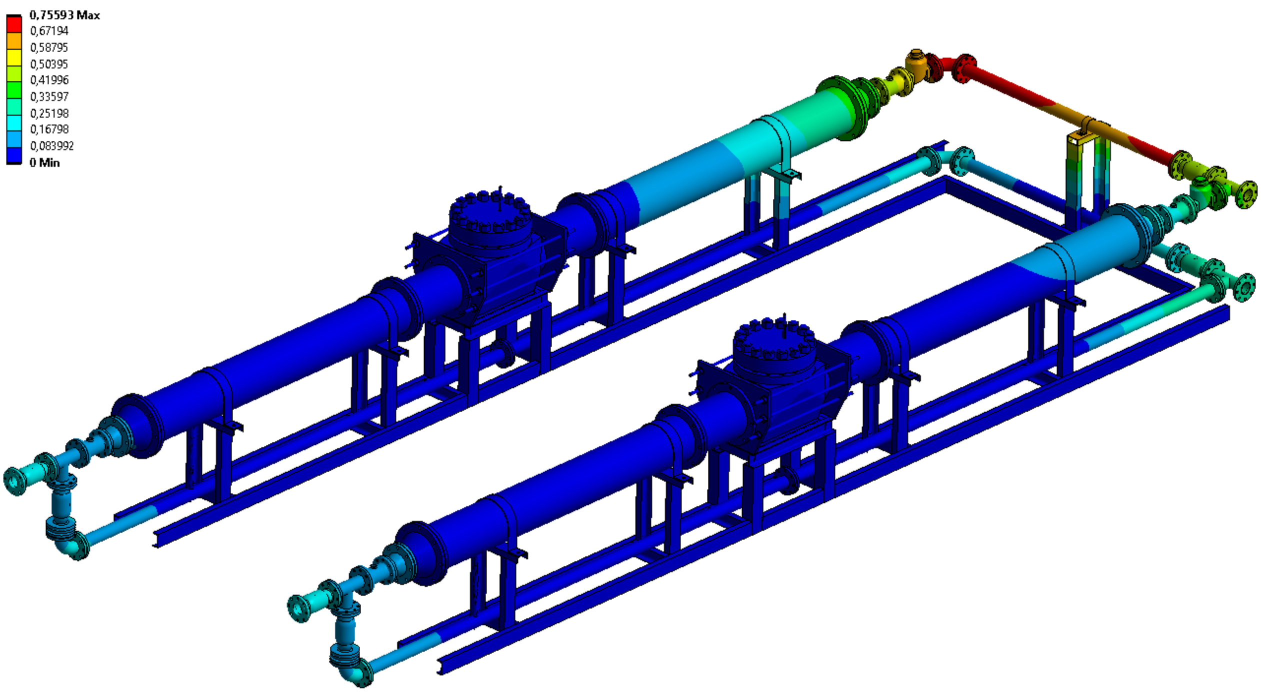


Figure 15. Distribution of maximum displacements in the model volume of the subsystem, test loop 1, mm

Figure 16 shows the distribution of equivalent voltages, where it can be seen that the maximum values are achieved in rotary check valves.

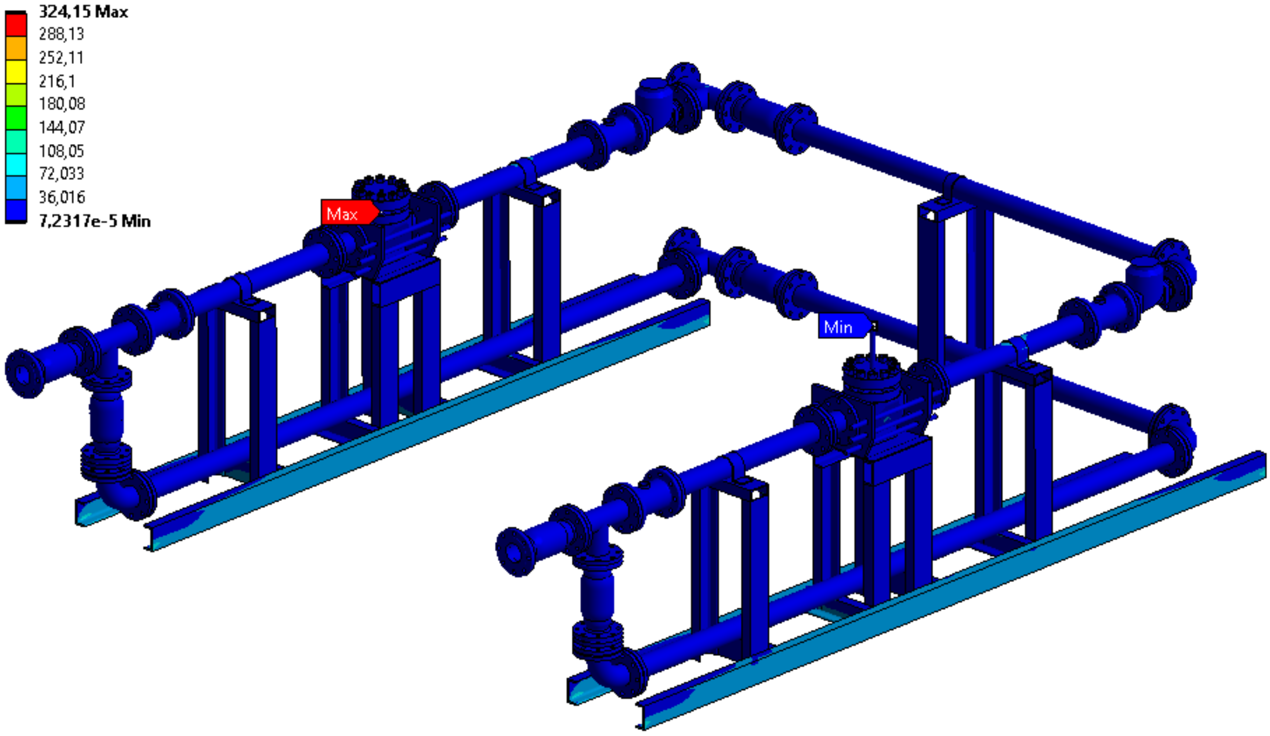


Figure 16. Distribution of equivalent stresses in the model volume of the subsystem, test loop 2, MPa

Figure 17 shows the distribution of equivalent deformations, where it can be seen that the maximum values are achieved in butterfly valves.

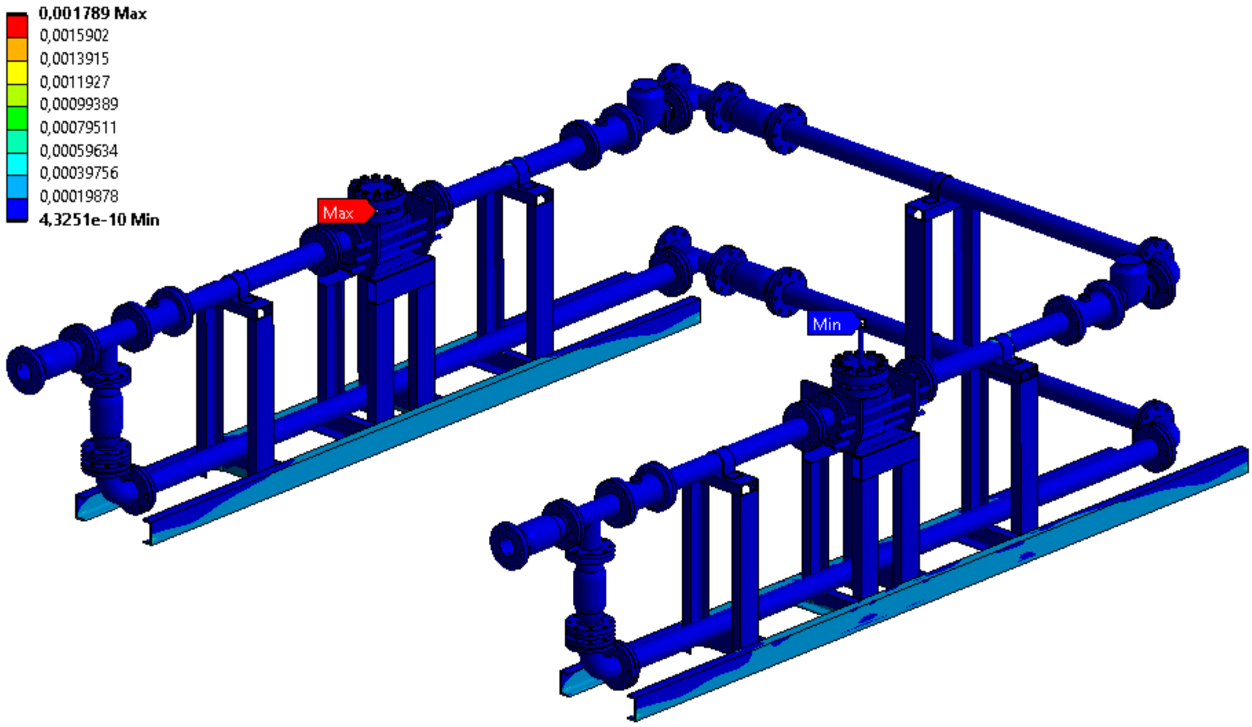


Figure 17. Distribution of equivalent deformations in the model volume of the subsystem, test loop 2, mm/mm

Figure 18 shows the distribution of maximum displacements, where it can be seen that the minimum values are achieved in rotary check valves, and the maximum values are achieved in the upper corner nodes of the contour.

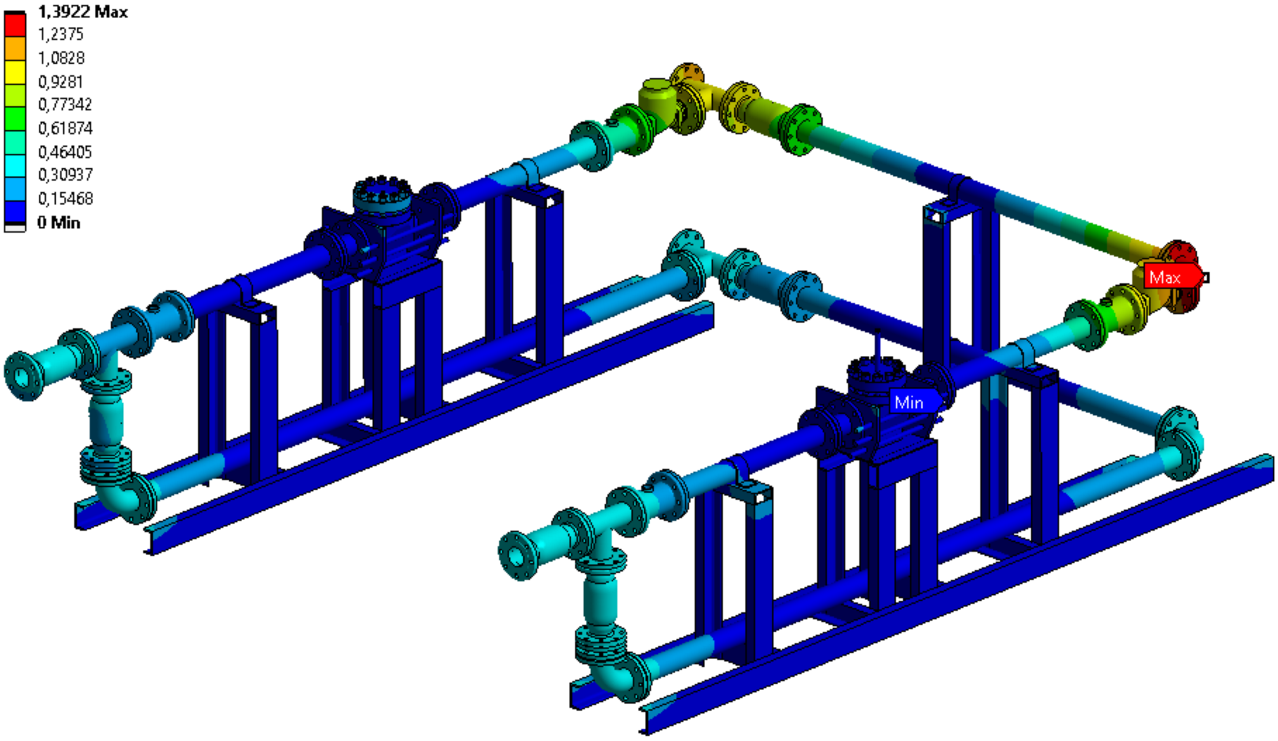


Figure 18. Distribution of maximum displacements in the model volume of the subsystem, test loop 2, mm

Table 2 summarizes the simulation results of the stress-strain state of the bench structure elements.

Table 2. Results of the strength analysis of the bench structure

Structural elements	Maximum equivalent stresses σ_{max}, MPa	Maximum deformations Δ_{max}, %	Maximum displacements δ_{max}, mm
Tanks	22.028	0.011	0.216
Frame	36.21	0.018	0.216
Plugs	2.97	0.0016	0.097
Flange and stacks	22.79	0.045	1.363
Tank flanges and pipes	3.96	0.025	0.093
Pump	19.09	0.01	0.091
Subsystem elements, test loop 1			
Pipes, sockets, and flanges	43.61	0.023	0.756
Sensors and taps	40.93	0.022	0.690
Pumps	66	0.004	0.050
Frame	30	0.038	0.655
Subsystem elements, test loop 2			
Pipes, sockets, and flanges	45	0.054	1.39
Sensors and taps	35	0.036	1.32
Pumps	40	0.179	0.204
Frame	60	0.074	0.411

Further, to assess the reliability of the developed installation, the analyses of failure rate indicators and the probability of failure-free operation of the installation were performed based on the structural method of reliability calculation. The installation belongs to the class of repairable, restorable items with an assigned resource and service life and regulated restoration discipline.

In practice, most often, the failure rate of the individual component elements of the products is a constant (nominal) value $\lambda_i = const$.The failure rate of each *i*-th element λ_i' under load is determined using the Equation:

$$\lambda_i' = k_1 \cdot \lambda_{0i}, \tag{1}$$

where λ_{0i} is the average intensity of failures of an element during operation, determined (given, indicated) regardless of whether the element is under load or unloaded; k_1 is the correction factor that considers the failure rate increase of loaded elements.

The failure rate of the *i*-th unloaded elements $\lambda_i^{"}$ determined using the Equation:

$$\lambda_i^{"} = k_2 \cdot \lambda_i' = k_2 \cdot k_1 \cdot \lambda_{0i}, \tag{2}$$

where k_2 – the correction factor that considers the failure rate reduction of unloaded elements (taken as 1×10^{-3}).

In the first approximation, the failure rate can be estimated as follows:

$$\lambda_c = \sum \lambda_i \tag{3}$$

here, all elements of the same type are equally reliable, i.e., the failure rate λ_i is the same for all identical elements.

Analytical dependence connects the quantitative reliability characteristics. Therefore, by knowing an indicator, it is possible to determine the others. For example, the average time to the first failure $T_{av.}$ (h) can be determined using the approximate Equation:

$$T_{\text{cp.}} = 1/\lambda \tag{4}$$

Failure-free operation probability is the probability that a product will not fail at any given time under the given operating conditions. Its statistical estimation for repairable products is as the Equation:

$$P(t) = 1 - \frac{n(t)}{N_0}, \tag{5}$$

where $n(t)$is the number of products that had at least one failure during the time from 0 to *t*; N_0 is the number of observed products.

The probability of failure-free operation of one element, knowing λ_i' and λ_i''', can be calculated using the Equation:

$$P_i(t) = e^{-\left(\lambda_i' t_i' + \lambda_i^{"} t_i^{"}\right)}, \tag{6}$$

where t_i' – time of the element under load, h; $t_i^{"}$ – time of the unloaded element, h.

If the probability of failure-free operation of the *i*-th element ($P(t^*)$) for a fixed time or operating time t^* is known, then;

$$P_i(t) = e^{\frac{t}{t^*} ln\left(P_i(t^*)\right)} \tag{7}$$

If the system includes several elements, and the failure of one of them leads to the failure of the entire system, this connection of elements is called a series connection. Accordingly, when the elements are connected in parallel, system failure occurs when all the elements have failed, without exception. If the probability of failure-free operation of the *i*-th element $P_i(t)$ for a fixed period or operating time *t* is known, then the following formula is used to calculate the series connection:

$$P_c = \prod_{i=1}^{n} P_i(t) \tag{8}$$

Accordingly, to calculate the parallel connection, this expression has the following form:

$$P_c = 1 - \prod_{i=1}^{n} \left(1 - P_i(t)\right) \tag{9}$$

The connection of the elements of the developed bench is parallel, and an appropriate formula is applied to calculate the probability of failure-free operation.

According to the calculation results, the average time of non-failure bench operation $T_{\text{cp.}}$ is 14,950 h, and the probability of failure-free operation during one month of continuous operation ($t^* = 720$ h) is 0.955.Obtained values of reliability indicators have an indicative character, but, at this stage of work, these indicators make it possible to give an initial assessment of the considered bench systems and to establish the compliance of the bench and its units' reliability with technical requirements.

Table 3 compares the characteristics of the developed and existing benches for hydraulic and pneumatic tests.

Table 3. Comparison of the characteristics of developed and existing benches

Parameter name	Unit	Bench under development	The previously used outdated bench of 1989
Working pressure during hydraulic tests	MPa	0.1	0.1
Working pressure during pneumatic tests	MPa	1.0	0.7
Maximum velocity of the test medium (water)	m/s	5	2.3
Maximum velocity of the test medium (air)	m/s	60	45
Number of test loops, not fewer	pcs.	2	1
Control		Digital	Analog
Designated lifetime	years	10	7
Failure-free operation time	h	14,950	8,790

The comparative table shows that the characteristics of the developed bench are 1.5 times higher than the known. Thus, the main distinguishing advantage of the developed test bench is the combination of the possibility of hydraulic and pneumatic tests in various loads. This stand, compared with analogs, should provide a significant reduction in time and labor costs, as it will allow testing in a wider range of possibilities without reinstallation and adjustment, as was previously the case with the consistent use of obsolete equipment.

6. Conclusion

In this work, a bench was developed for hydraulic and pneumatic in-plant testing of check valves to determine their main technical characteristics by measuring the following parameters of the test medium: flow and pressure. The main advantage of the developed stand is the combination of the possibility of hydraulic and pneumatic testing of valves in various loads. This stand should provide a significant reduction in time and labor, as it will allow you to perform tests without reinstallation and adjustment, as was previously the case with the sequential use of hydraulic and pneumatic stands. The results of the stand design are presented, and the features of the process of its development are described, including the analysis of the stress-strain state and the analysis of reliability and durability indicators. The obtained values of the distribution of equivalent stresses, deformations, and displacements of the bench structural elements do not exceed the maximum allowable values for the specified materials and operating conditions and do not lead to distortions in the structure and destruction of connections.

The developed standard for testing pipeline fittings has the following restrictions on the use of a test medium (water and air) under pressure: during hydraulic tests, 0.1 MPa; during pneumatic tests, 1 MPa; consumption of the test medium during hydraulic tests is no more than 5 m/s; flow rate of the test medium during pneumatic tests is no more than 60 m/s. A direction for further research and development may be to expand the range of performance characteristics of similar stands as well as the R&D of stands required for testing in aggressive environments (abrasive media, acids, alkalis, etc.). Such studies will provide an expansion of testing capabilities and an increase in the technical characteristics of shut-off valves for critical production facilities for petrochemical and energy purposes.

7. Declarations

7.1. Author Contributions

Conceptualization, N.D.; methodology, I.L.; validation, V.L.; formal analysis, V.L.; investigation, M.N.; data curation, N.D.; writing—original draft preparation, V.L.; writing—review and editing, N.D.; visualization, M.N.; supervision, N.D. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

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7.4. Conflicts of Interest

The authors declare no conflict of interest.

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