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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT OF A HIGH-PRESSURE LINEAR MOTION VALVE

Speciality: 3313.02 - “Machines, equipment and processes”

Field of science: Technical sciences

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The dissertation was permformed at the "Industrial machines" department of Azerbaijan State Oil and Industry University.

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ADNSU-nun Elmi katibi,
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GENERAL CHARACTERISTICS OF THE WORK

The relevance of the work and degree of development. The advancement of the oil and gas industry, a key sector of the economy, necessitates that the technologies and technical equipment used to meet contemporary requirements and have a longer lifespan. Another essential component of complex assemblies used in the modern era is closing devices.

Closing devices consist of various components, one of which is the valve. Valves are the most widely used type of closing device and play a crucial role in numerous applications and their primary function is to regulate fluid and gas flow by either preventing movement or redirecting it from one path to another.

The most critical and dynamic component of a valve is its sealing assembly. The loss of sealing integrity between its sealing elements, often caused by the uneven distribution of relative pressure within the sealing assembly, is a key factor contributing to the failure.

The presence of abrasive and mechanical particles in the fluid passing through the valve accelerates the wear process, leading to a reduction in equipment efficiency, workability and premature failure before the end of its designated service life specified in the technical documentation.

Depending on operating conditions, selecting valve materials suitable for the working environment, optimizing the design to ensure tight sealing between gate -seal pairs, minimizing fretting and hydroabrasive wear, and enhancing valve performance to meet modern standards remain critical challenges and also, the continuous improvement of valve components, the development of innovative sealing assemblies are ongoing priorities in the industry.

The extent of wear in the valve construction increases due to the impact of high-pressure fluid. Additionally, as wear progresses, the affected surface area exposed to pressure expands, further accelerating deterioration. Therefore, enhancing the durability and longevity of valves operating under high pressure remains a critical challenge.

Research goals and objectives. Enhancing the resistance of high-pressure valve components to hydroabrasive wear and optimizing the valve design to support this durability.

Research methods. In the execution of the dissertation, the following software and research methods were utilized: “SolidWorks”, “finite element analysis”, “Python”, “Matplotlib”, “NumPy”, and “Matlab”. Additionally, physical and mechanical research methods were applied, including friction testing conducted using the “Jinan Fangyuan Testing Machine” based on ISO, GOST, and ASTM standards.

The main provisions of the defense: To achieve the stated objective, the following tasks were defined and addressed in the dissertation:

- Development of an advanced valve design featuring an improved sealing unit with enhanced resistance to hydroabrasive wear, ensuring high performance under operational conditions;
- Selection of suitable materials for the sealing unit elements of the improved valve, based on newly proposed friction resistance criteria;
- Study of a special analysis method based on fuzzy theory to determine the resistance of valve details to hydroabrasive wear;
- Development of an “if-then” fuzzy model that determines the dependence of the cross-sectional parameters of the improved packing element, which is one of the elements of the sealing unit, on deformation;
- Experimental evaluation of mechanical wear in the sealing unit components of the improved valve, including determination of the friction coefficient for various materials and analysis of wear characteristics in different environmental conditions;
- Development of a novel testing methodology for evaluating the performance of the improved valve construction;
- Stress testing of body and of sealing assembly components in the enhanced valve construction.

The scientific novelty of the research is as follows:

- A hydroabrasive wear-resistant valve construction was developed;
- The friction resistance criteria for materials withstanding to hydroabrasive wear was determined;
- The materials for the components of the sealing assembly were

selected based on friction resistance criteria;

- A specialized analysis method based on fuzzy theory was developed to determine the hydroabrasive wear resistance of valve components;
- A testing methodology was developed to ensure the operational performance of gate valve construction.

Practical significance of the work and application of results.

An improved sealing assembly for a linear motion gate valve was developed, and a patent has been obtained for the proposed valve construction (No. F 2023 0029). The valves produced based on this patent can be applied in the oil and gas industry.

The experiments were conducted at "NEFTQAZMAŞ" JSC and in the laboratory of the "Industrial Machines" Department at the Azerbaijan State Oil and Industry University. The operational performance of the valve was verified and confirmed using engineering simulation softwares.

The introduction of the proposed new valve into the industry will be more economically efficient. The proposed valve, which features a modified spindle-nut assembly, offers a cost advantage over existing similar valve constructions.

Approbation of work. The main findings of the dissertation have been published in national and international conferences, as well as in domestic journals and foreign journals indexed in WoS (Web of Science) and SCOPUS databases, including: Science, technology, and higher education materials of the IX international research and practice conference; Canada, 23-24 december, 2015; Doktorantların və gənc tədqiqatçıların XIX Respublika Elmi Konfransı; Azərbaycan Texniki Universiteti, Bakı, 7-8 aprel, 2015; International Scientific Conference of Young Researchers Devoted to the 94-th Anniversary of Azerbaijani National Leader Haydar Aliyev; Baku Engineering University, Baku, 5-6 may, 2017; Ümummilli lider Heydər Əliyevin anadan olmasının 98-ci ildönümünə həsr olunmuş gənc tədqiqatçı və doktorantların onlayn Elmi Konfransı; Azərbaycan Dövlət Neft və Sənaye Universiteti, Bakı, 21 may, 2021; Proceedings of VI International scientific conference of young researchers Dedicated to the 99th anniversary of the National leader of Azerbaijan, Heydar

Aliyev; Baku Engineering University, Baku, Azerbaijan, 29-30 aprel, 2022; Azərbaycan xalqının ümummilli lideri Heydər Əliyevin anadan olmasının 99-cu ildönümünə həsr olunmuş tələbə və gənc tədqiqatçıların “Gənclər və elmi innovasiyalar” mövzusunda Respublika elmi-texniki konfransı; Azərbaycan Texniki Universiteti, Bakı, 4-5 may, 2022;

Name of the organization where the dissertation work is performed. Azerbaijan State University of Oil and Industry in the “Industrial machines” department.

Applicant's personal contribution to the research conducted.

In the dissertation, the applicant justified the relevance of the research based on a review of literature sources, selected appropriate research methods, and applied them to solve scientific problems. The applicant also carried out the planned experiments at all stages of the research and systematized the obtained results. Additionally, the applicant analyzed the experimental findings, participated in discussions of the research at scientific conferences, and prepared scientific articles based on the obtained results.

Publications. A total of 17 scientific publications have been published based on the dissertation, including 10 articles (6 of which are indexed in WoS: SCI/SCIE or Scopus databases), 1 patent, and 6 conference and congress proceedings where research findings were presented and discussed.

The structure and scope of the dissertation. The dissertation consists of an introduction, three chapters (Chapter I: 87580 characters, Chapter II: 10944 characters, Chapter III: 85531 characters), conclusions, 176 scientific references, and 175 computer pages. It includes 7 tables, 52 figures,. The total length of the dissertation, excluding tables, figures, and the reference list, is 192859 characters.

MAIN CONTENTS OF THE WORK

The introduction provides a detailed presentation of the relevance of the dissertation, its research objectives and tasks, the key findings submitted for defense, as well as the scientific innovations and both theoretical and practical significance of the study. Additionally, it includes information on the validation of the research results, the institution where the dissertation was conducted, the structure, volume and scope of the dissertation, and the scientific articles published within the framework of the study.

The first chapter consists of three subsections. In the first subsection, modern valve designs are analyzed, and the performance and reliability indicators of various valve constructions produced under different brands are compared. Additionally, a comparative analysis of valves manufactured by different companies has been conducted. In the second subsection, the sealing assemblies of valve constructions are examined, and an analysis of the wear occurring in the sealing assembly was carried out. The third subsection is dedicated to the investigation of technical and technological processes occurring in the sealing assemblies of gate valves. The results of the critical review indicate that the extent of wear in the valve structure increases due to the impact of high-pressure fluid. Additionally, as wear progresses, the surface area exposed to pressure also expands. Therefore, enhancing the durability and longevity of gate valves under high pressure remains a relevant issue.

The second chapter examines the selection of the research object and methods. This chapter consists of four subsections. The first subsection is dedicated to the selection of the research object, while the second subsection focuses on research methods and the identification of equipment and devices required for their implementation, whereas the third subsection defines the key characteristics of the testing environments, and the fourth subsection is devoted to the mathematical methods used in processing the research results.

To address the defined objectives, the sealing assembly of an improved valve construction was selected as the research object

(Figure 1). The primary distinction of the selected gate valve design from its analogs lies in the structural modifications made to its sealing assembly. A patent numbered as F16K 11.052 (2006.01) was granted by the Intellectual Property Agency of the Republic of Azerbaijan for the sealing assembly of the selected research object.

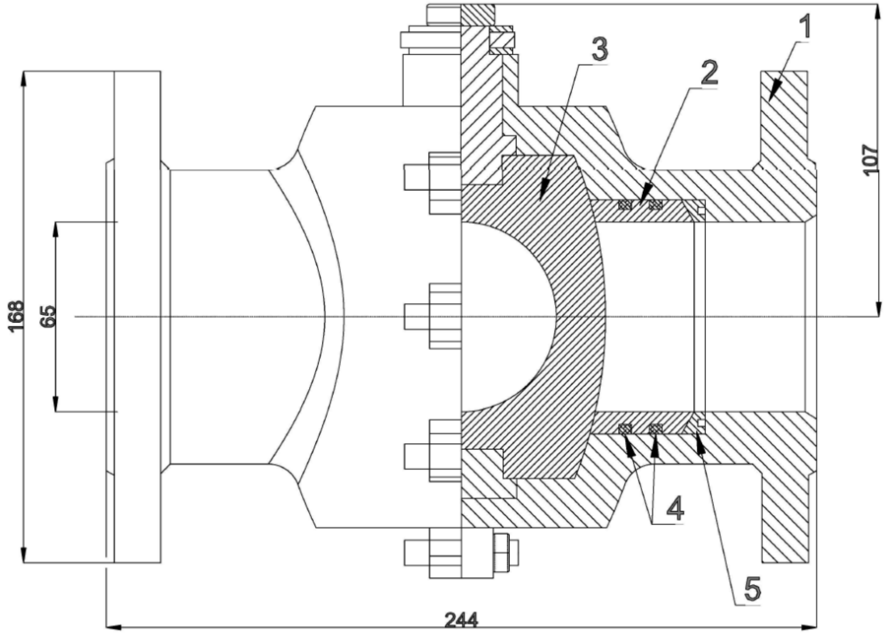


Figure 1. The general view of the improved valve
1–body; 2 – seal; 3 –gate; 4 – packing; 5 – spring

The opening and closing of the improved valve design are achieved by rotating its gate by 90 degrees. The flow of the product passing through the inlet port is blocked by the rotation of the gate, which is then exposed to the pressure of the passing fluid. The semi-ellipsoidal shape of the gate element ensures an optimal distribution of pressure over its surface. As a result, sealing elements of the valve's sealing assembly experience reduced loading, enhancing their durability. Due to the load distribution along the sealing surfaces, the gate is pressed against the seal-gate pair, creating a complete sealing at the outlet port of the valve, thereby fully stopping the fluid flow. The hermetic elements positioned behind the seal ensure a hermetic sealing between seal and valve body. A disc-shaped spring provides initial sealing between the gate and the seal during assembly and counteracts the fluid pressure in operational conditions.

The optimal distribution of operating pressure on the sealing assembly of the improved valve, along with the simplified control mechanism and the high sealing performance at the outlet, was significantly enhanced the reliability of this design.

The dissertation work focuses on the study of wear phenomena in the sealing assembly of the gate valve and the investigation of tightning effectiveness. As the research object, a linear motion gate valve currently used in the oil and gas industry—with an operating pressure of P = 70 MPa and a nominal bore diameter of d_k = 65 mm—was selected. A new design was proposed, and the research was conducted on this improved valve construction.

In the second paragraph of the second chapter, the research methods, the application of equipment and devices for their implementation, the characteristics of the test environments, and the mathematical methods used for processing research results were discussed.

To achieve the objectives of the dissertation, tests were conducted using the “MKS-10 MMW-1” vertical-universal friction and wear testing machine, manufactured by “Jinan Fangyuan Testing Machine CO. Ltd”.

Considering that friction and wear phenomena primarily occur in the gate-seal pairs, sample materials Steel 20X and Steel 40X were selected for testing their friction and wear behavior. When the gate material was Steel 20X, the seal material was selected as either Steel 20X or Steel 40X. Similarly, when the gate material was Steel 40X, the seal material was chosen as either Steel 20X or Steel 40X. As is well known, these materials exhibit different behaviors depending on their structural composition. The wear characteristics of identical material components in different shapes vary, as the acting force is influenced by the contact angle. For the experiments, steel rod samples with cylindrical, triangular, and circular tips, as well as circular steel samples, were prepared. The key parameters considered in the experiments were temperature, pressure, and time.

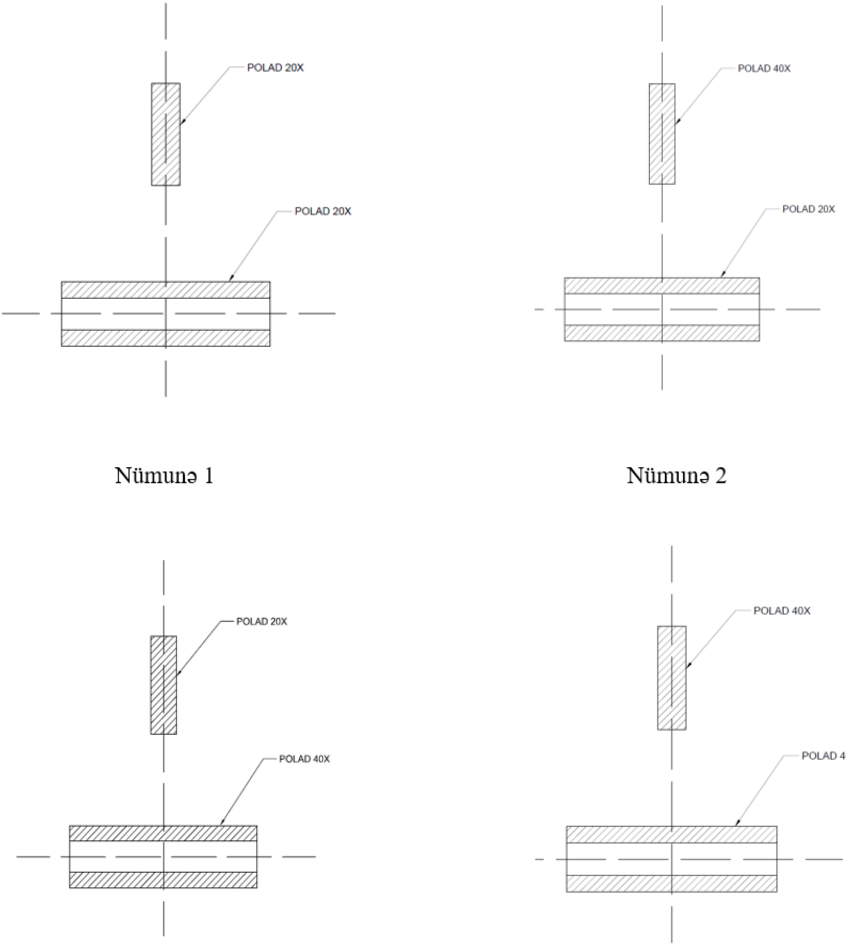
The friction and wear phenomena occurring during metal-to-metal contact (Steel 20X - Steel 20X, Steel 40X - Steel 20X, Steel 20X - Steel 40X, and Steel 40X - Steel 40X) were analyzed for all three cases, and the corresponding graphs were generated. The schematic diagram of the samples is provided in Figure 2.

In the dissertation, the methods used for processing the research results were based on both experimental observations and modern computer-based mathematical simulations. The use of “Solidworks”, “FEA”, “Python”, “Matplotlib”, “NumPy” and “Matlab” enabled a more effective and reliable analysis of the obtained results. Additionally, these tools facilitated the visualization of dynamic behaviors on the improved valve construction.

In the third chapter, the material selection for the sealing assembly components of the improved valve is discussed. Additionally, the determination of equivalent stress and deformation in the sealing elements of the improved valve is examined.

The static and dynamic forces acting on the sealing elements of the improved valve, as well as the hydroabrasive wear analysis of the gate-seal pair, are also investigated. Furthermore, a theoretical analysis of hydroabrasive wear in the sealing components of the improved valve is conducted at the third chapter. Additionally, the dynamic force assessment of the disc-shaped spring in the gate valve construction, along with the displacements caused by dynamic forces, is analyzed. The stress endurance of the valve body is also evaluated. Moreover, the fatigue life of the improved linear motion valve under cyclic pressure loading conditions has been determined.

Selection of materials for the sealing assembly components of the improved valve construction. Research conducted at "NEFTQAZMAŞ" JSC revealed that when the hardness of the pressure-exerting component is significantly higher than that of the component subjected to pressure, the working surfaces—particularly the secondary working surface—tend to undergo perforation. To conduct a detailed analysis, sample specimens made from Steel 20X



Nümunə 1 Nümunə 2

Nümunə 3 Nümunə 4

Figure 2. Schematic diagram for sample preparation under test conditions

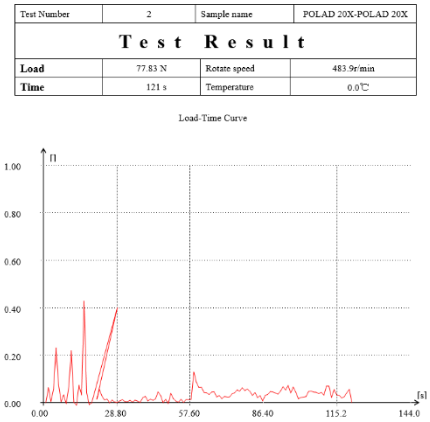
Sample 1 – Movement of Steel 20X on Steel 20X
Sample 2 – Movement of Steel 40X on Steel 20X
Sample 3 – Movement of Steel 20X on Steel 40X
Sample 4 – Movement of Steel 40X on Steel 40X

and Steel 40X were prepared and tested using the “MKS-10 MMW-1” vertical-universal friction and wear testing machine, manufactured by “Jinan Fangyuan Testing Machine CO. Ltd”.

The gate and sealing materials were selected in two different configurations—one where they were made of different materials and another where they were made of the same material—to facilitate a comparative study. Specifically, when the gate material was Steel 20X, the seal material was tested using both Steel 20X and Steel 40X.

In the dissertation, cylindrical steel rod samples and circular steel samples were prepared for the experiments. During testing, pressure and time were considered as the primary parameters. Following a predefined test schedule, a load was applied to the equipment at variable time intervals, causing the rod samples to move over the stationary circular sample placed in a fixed seat. The friction and wear phenomena occurring over metal-to-metal contact (Steel 40X - Steel 20X, Steel 20X - Steel 20X, Steel 20X - Steel 40X, Steel 40X - Steel 40X) were analyzed, and the corresponding graphs were generated (Graph 1, Graph 2, Graph 3, Graph 4). Subsequently, the results obtained in the graphs were compared based on the hardness of the steel materials. The test conditions included contact pressures ranging from 0.00 MPa to 1 MPa, a rotational speed between 200 and 600 rpm, room temperature conditions, a test duration of 200 to 250 seconds, and applied loads of up to 150 N. Each sample was tested at a rotational speed of 200 - 600 rpm, and data were recorded only after the friction coefficient stabilized at each cycle.

The analysis of the graphs obtained from experiments indicates that as hardness of the steel rod sample increases, wear caused by friction also intensifies. It was observed that the rotating steel sample had a lower hardness compared to the stationary sample fixed to the seat. Additionally, the gate material was selected to have a higher hardness than the seal and disc-shaped spring materials, while ensuring that the differences in hardness were not excessively large. Accordingly, a friction resistance criterion was established for the improved valve design. Furthermore, the selection of structural materials for the hermetic elements of the sealing assembly in our proposed improved valve was carried out in accordance with the following principle.



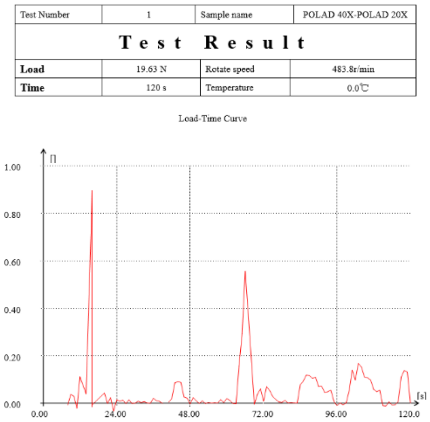
Test Number	2	Sample name	POLAD 20X-POLAD 20X

Test Result

Load	77.83 N	Rotate speed	483.9r/min
Time	121 s	Temperature	0.0℃

Load-Time Curve

Graph 1. Movement of Steel 20X on Steel 20X



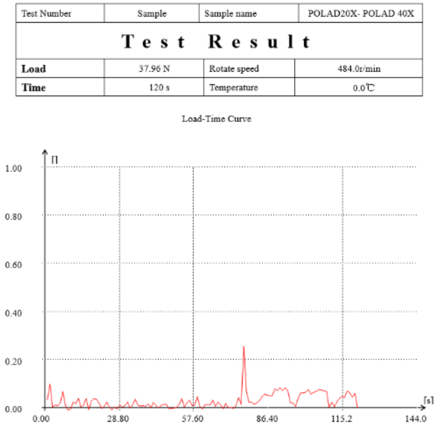
Test Number	1	Sample name	POLAD 40X-POLAD 20X

Test Result

Load	19.63 N	Rotate speed	483.8r/min
Time	120 s	Temperature	0.0℃

Load-Time Curve

Graph 2. Movement of Steel 40X on Steel 20X



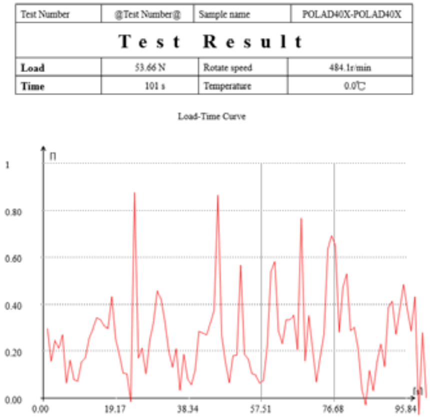
Test Number	Sample	Sample name	POLAD20X- POLAD 40X

Test Result

Load	37.96 N	Rotate speed	484.0r/min
Time	120 s	Temperature	0.0℃

Load-Time Curve

Graph 3. Movement of Steel 20X on Steel 40X



Test Number	@Test Number@	Sample name	POLAD40X-POLAD40X

Test Result

Load	53.66 N	Rotate speed	484.1r/min
Time	101 s	Temperature	0.0℃

Load-Time Curve

Graph 4. Movement of Steel 40X on Steel 40X

$$HB_{x1} < HB_{x2} > HB_{x3} \tag{1}$$

The formula (1) derived based on friction resistance for the hermetic elements of the proposed valve construction [63][1].

Determination of equivalent stress and deformation in the packing element of the improved valve construction.

The cross-sectional shape of the packing element can vary in different forms. In this study, the cross-sectional area of the packing ring was assumed to be trapezoidal. To determine the equivalent stress, the projections of the acting forces were taken along the X-axis (F_x) and Y-axis (F_y). The diameter of the packing element is denoted as D, while the passage diameter is represented as d.

If we denote the principal stress acting along the X-axis as σ_X, the principal stress along the Y-axis as σ_Y, and the shear stress as τ_{XY}, then the equivalent stress based on the computational scheme is determined as follows:

$$\sigma_{ekv} = \sqrt{\sigma_X^2 - \sigma_X \cdot \sigma_Y + \sigma_Y^2 + 3\tau_{XY}^2} \leq [\sigma] \tag{2}$$

here, σ_X, σ_Y – represent the principal stresses, while τ_{XY} denotes the shear stress.

In our calculations, $\tau_{XY} = 0$ has been assumed. Considering that the cross-sectional area changes by α due to the applied force and pressure, the principal stresses can be expressed as follows:

$$\sigma_X = \frac{F \cdot cos\,\alpha}{S} \tag{3}$$

$$\sigma_Y = \frac{F \cdot sin\,\alpha}{S} \tag{4}$$

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[1] Aslanov J.N., Mammadov K.S., Zeynalov N.A. Selection of structural materials for improved Liner motion gate valves based on friction correlation method// International Journal of Advanced Technology and Engineering Exploration, 2022, № 87, - pp.155-166

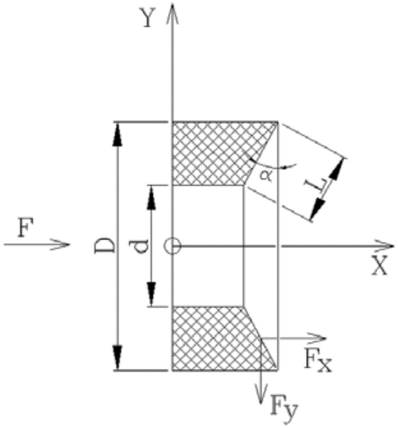


Figure 3. Computational Scheme

here, S represents the cross-sectional area of the packing element and is calculated as follows:

$$S = \pi \cdot L \cdot \left(\frac{D}{2} + \frac{d}{2}\right) \tag{5}$$

$$L = \frac{D - d}{2 \cdot cos\,\alpha} \tag{6}$$

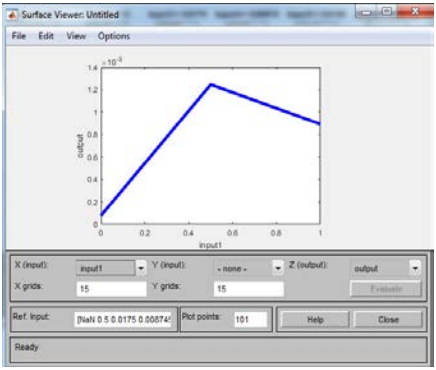
by substituting equations (5) and (6) into equations (3) and (4), we obtain:

$$\sigma_X = \frac{F \cdot cos\,\alpha}{\pi \cdot \left(\frac{D-d}{2 \cdot cos\,\alpha}\right) \cdot \left(\frac{D}{2} + \frac{d}{2}\right)} \tag{7}$$

$$\sigma_Y = \frac{F \cdot sin\,\alpha}{\pi \cdot \left(\frac{D-d}{2 \cdot cos\,\alpha}\right) \cdot \left(\frac{D}{2} + \frac{d}{2}\right)} \tag{8}$$

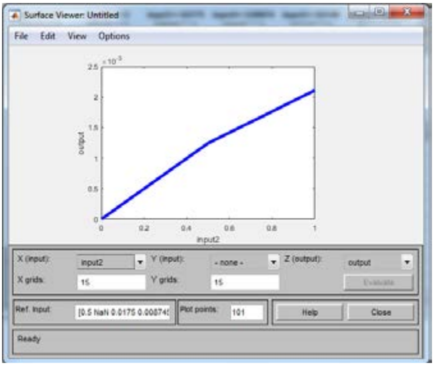
From the above equations, the dependence f (σ) = f (F,α) has been observed. Considering that the displacement occurs along the X-axis at a certain angle, calculations were performed accordingly. The given parameters were assumed as P = 70 MPa; D= 9 mm; d= 6 mm; $\mu = 0.34$; E= 0.1 MPa; $\alpha = 0^0 \div 90^0$.

Using the Matlab software, it is possible to visualize the interrelation of multivariable expressions on a generalized graph. In cases where the variation in obtained values is negligible, angle variations were disregarded, and constants were removed from the table, resulting in a simplified variable table. Based on this, by uploading the variable values into Matlab using the "artificial bee colony" method, the 3D representation of the variable values and their interrelation were determined (Graph 5, Graph 6, Graph 7, Graph 8).



X (input): input1
Y (input): - none -
Z (output): output
X grids: 15
Y grids: 15
Ref. Input: [NaN 0.5 0.0175 0.00874
Plot points: 101
Ready

Graph 5. Analysis of variables for "Input 1"



X (input): input2
Y (input): - none -
Z (output): output
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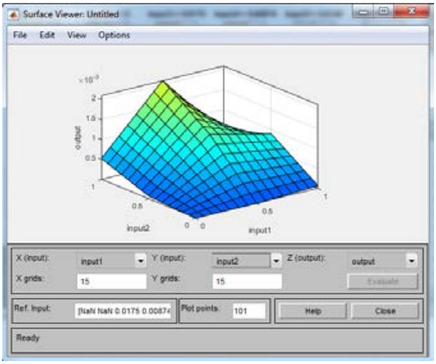
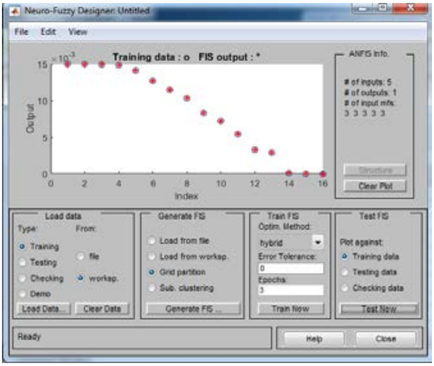
Y grids: 15
Ref. Input: [0.5 NaN 0.0175 0.00874
Plot points: 101
Ready

Graph 6. Analysis of variables for "Input 2"



X (input): input1
Y (input): input2
Z (output): output
X grids: 15
Y grids: 15
Ref. Input: [NaN NaN 0.0175 0.00874
Plot points: 101
Ready

Graph 6. Analysis of variables for “Input 2-input 1”



ANFIS Info.
\# of inputs: 5
\# of outputs: 1
\# of input mfs:
3 3 3 3 3

Load data
Type: ● Training ○ Testing ○ Checking ○ Demo
From: ○ file ● worksp.

Generate FIS
○ Load from file
○ Load from worksp.
● Grid partition
○ Sub. clustering

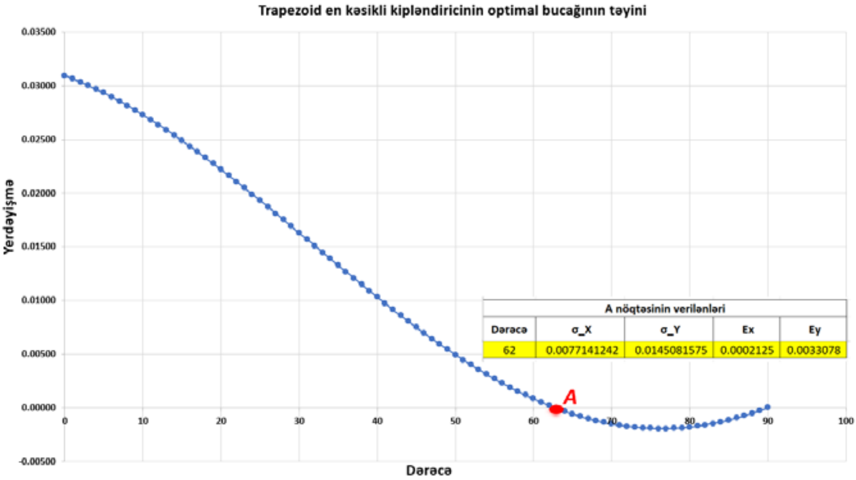
Train FIS
Optim. Method: hybrid
Error Tolerance: 0
Epochs: 3

Test FIS
Plot against:
● Training data
○ Testing data
○ Checking data

Ready

Graph 7. Transfer of Variables into a System

Based on the comparative analysis of the obtained variables, the optimal deformation angle of the trapezoidal-shaped packing element in the newly designed gate valve under pressure is determined to be 62 degrees (Graph 9).



A nöqtəsinin verilənləri				
Dərəcə	σ_X	σ_Y	Ex	Ey
62	0.0077141242	0.0145081575	0.0002125	0.0033078

Graph 9. Determination of the seating angle of the trapezoidal cross-section packing element

Investigation of wear in the gate-seal pair of the improved valve. A simulation of heat transfer within the internal components of the improved valve design was conducted. For the simulation, a SolidWorks model was created, with certain secondary effects omitted. The inner wall of the valve body was modeled as a thick wall to ensure that heat conduction does not interact with the movement of the hermetic sealing elements during simulation. The open, semi-open, and closed positions of the sealing elements in the sealing assembly were examined. The primary objective of this analysis was to determine heat transfer within the system. During the simulation process, the wear factor in the components must be considered, particularly when the fluid passes through the valve in a semi-open position at a 45-degree angle.

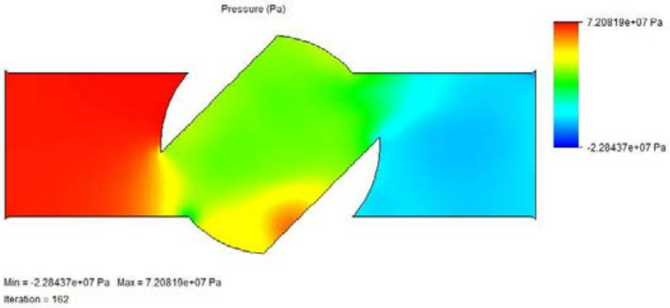
The atmospheric pressure is considered at the outlet of the valve, while the inlet is monitored under operating pressure. Heat transfer within the components is determined by the pressure levels they are exposed to. In order to analyze heat transfer and thermal conductivity, the results of the simulation conducted on the components of the valve were used. These results were based on pressure distribution and mapped onto a graph representing the simulation outcome.

For the mesh, boundary conditions were set to the default standard parameters defined by the software. The internal structure of the valve components and their response to pressure were examined in a 2D plane. Static pressure and temperature were selected as the initial thermodynamic parameters for the construction. The velocity vector was considered as an independent factor influencing fluid flow.

Although the flow within the construction is predominantly laminar, turbulence can be observed when the flow occurs at a 45-degree angle. Therefore, the turbulence characteristics of the equipment have been defined as follows: the turbulence intensity is set at 2.00%, and the turbulence length is taken as 0.002 m. Despite the application of static pressure at the inlet, it combines with atmospheric pressure at the outlet. As a result, these conditions are considered as boundary conditions for the current study.

Theoretical analysis of hydroabrasive wear in the sealing components of the improved valve

To evaluate the technical reliability of the sealing elements in the improved linear motion gate valve, a flow distribution simulation was conducted for the closed, open, and semi-open positions of the valve construction. The gate, seal, disc-shaped spring, packings, and several other valve components were designed using CAD software and then transferred to SolidWorks for further analysis. The fluid pressure passing through the improved gate valve was considered at its maximum operating pressure and was maintained static during the simulation. The static pressure was set at 70 MPa, and the nominal diameter of the valve was assumed to be 65 mm. The seal cross-section was considered trapezoidal, and its material selection included various steel grades according to GOST 7809, specifically Steel 20X and Steel 40X. After implementing the proposed trapezoidal disc-shaped spring, the system was observed to withstand a pressure load 10% higher than the operating pressure (Graph 10).



Graph 10. Simulation of flow movement in the semi-open position of the improved valve and its impact on the hermetic elements

The results of the study conducted in the semi-open position revealed that, after a certain period, the flow of the fluid passing through the linear motion gate valve transitions from laminar flow to turbulent flow.

The simulation was also performed for the closed position of the valve. The findings confirmed the reliability and efficiency of the proposed improved valve design. The results indicated that different components exhibit varying tendencies for failure depending on the valve's position. While this effect is not significantly pronounced in the open position, it becomes clearly visible in the closed position. However, with the newly designed gate and disc-shaped spring, these issues were partially mitigated, resulting in a more even distribution of relative pressure.

The study concluded that the improved linear motion gate valve design, particularly with the new gate and disc-shaped spring, demonstrates higher reliability and efficiency in high-pressure and conditions.

Investigation of dynamic forces acting on the spring of the valve. The cross-sectional variation of the disc-shaped spring, which is a part of the sealing assembly in the improved valve construction, enhances its resistance to various loading conditions. The distribution of pressure over the surface of the disc-shaped spring under trapezoidal loading conditions was analyzed in several cases to assess its effect on structural performance.

A 3D model of the newly proposed disc-shaped spring design was created in SolidWorks and integrated into the system for simulation purposes. To conduct the simulation, the necessary parameters were entered into the system using a structured hexahedral meshing method for proper blocking. The pressure distribution on the disc-shaped spring was analyzed in two different cases. In the first case, the force applied to both surfaces of the spring was examined in the flow direction. In the second case, the effect of reverse-direction fluid flow on the spring structure was investigated. The overall results demonstrated that, depending on the operating environment, the implementation of the modified disc-shaped spring in the improved gate valve design is essential. Additionally, these findings serve as preliminary data for future expanded research in this area. The pressure applied to the disc-shaped spring was gradually increased, starting from 0 MPa. When the working pressure reached 70 MPa, the spring was statically maintained under this pressure. In the next phase, following the API standard, the sealing element of the valve was subjected to an additional 10% pressure increase, and its shape and dimensional stability under static loading were examined. The study confirmed that the disc-shaped spring in the improved gate valve design is capable of withstanding a pressure load 10% higher than the working pressure without structural failure.

In this study, an analysis of the inner radius of the disc-shaped spring in the valve and the stress distribution within the element was conducted. The primary objective of the research was to analyze fatigue behavior and identify critical stress elements. For the given operating pressure of 70 MPa, a pressure range of 20 MPa below and 20 MPa above this value was analyzed, as it was deemed experimentally more suitable. During the simulation process, particular focus was placed on the stress variations within the disc-shaped spring. The applied pressure-induced stress was primarily observed along the inner radius of the spring, which suggests a potential for fatigue-induced crack formation in the material. The high-amplitude stress points indicate a higher likelihood of crack propagation, leading to component failure over time. The results of the Finite Element Analysis (FEA) confirmed that the disc-shaped spring of the gate valve's sealing assembly undergoes critical variations in stress along its inner radius (Figure 4).

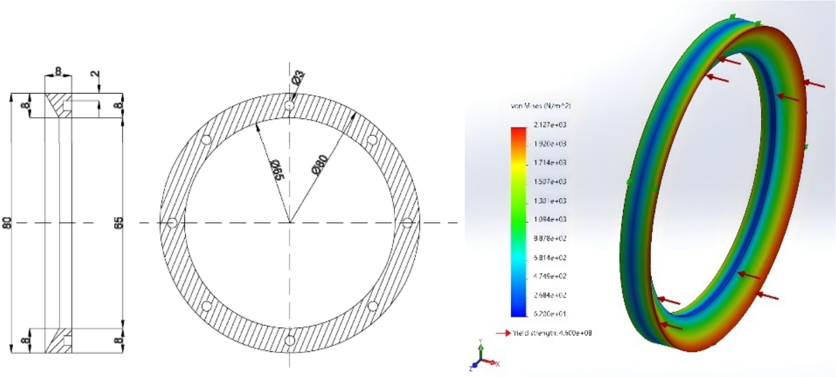


Figure 4. Simulation of forces acting on the improved disc-shaped spring

An increase in stress concentration along the inner radius was observed due to the applied pressure. The study revealed that the maximum stress the disc-shaped spring can withstand is 140 MPa. This stress is particularly concentrated in the inner section of the sealing assembly's disc-shaped spring, where fatigue-induced crack formation is most likely to occur.

The findings confirmed that stress accumulates predominantly in the inner radius of the spring. To address this, potential solutions include increasing the radius thickness, selecting higher-quality and more durable materials, and minimizing uneven stress distribution. However, considering that the tested disc-shaped spring withstood 140 MPa, while the required operating pressure is 70 MPa, the FEA results validate the functionality and reliability of the proposed valve construction.

The Finite Element Analysis (FEA) further demonstrated that the improved disc-shaped spring successfully withstands 140 MPa of stress while ensuring the required operating pressure of 70 MPa. These results confirm the reliability and performance of the proposed spring design in the improved valve construction.

Analysis of displacements in the improved valve's disc-shaped spring under dynamic forces. In this section of the dissertation, Finite Element Analysis (FEA) was utilized to analyze the displacement of the disc-shaped spring selected for the improved valve construction. This study examines the displacement and radial deformations of the disc-shaped spring under an operating pressure of 70 MPa. For this analysis, a high-strength, corrosion-resistant stainless steel sample was chosen. The spring was modeled as a cylindrical structure and was simulated as a cylinder within the program before being subjected to loading. The geometric parameters considered for the study were an inner radius of 65 mm, an outer radius of 80 mm, and a thickness of 8 mm. Although the operating pressure is 70 MPa, a pressure of 75 MPa was applied in the simulation to account for potential overload conditions.

To conduct the analysis, the "mesh" function was created in the software. In the meshing process, the spring was divided into 50 radial elements and 30 layers across its thickness to ensure accurate and precise results, which were then consolidated into a final averaged value. For displacement analysis, the following equation was used:

$$u_r = \frac{P \cdot r^2}{E \cdot t} \tag{9}$$

burada, u_r – radial displacement; P – internal pressure, MPa; r – distance from center, E – Yound's module, t – thickness.

Equation (9) represents the deformation of the disc-shaped spring element at each radial point.

Based on the results obtained from the study, the maximum displacement was observed along the outer edge of the disc-shaped spring in the gate valve, with a measured value of 0.0115 meters. The analysis indicated that as the radius increases, the radial force also increases, leading to greater material deformation. Conversely, along the inner radius, the displacement value was recorded at 0.011 meters, as this region experiences lower pressure impact and is subjected to less deforming force. Since radial displacement is influenced by Young's modulus and the selected material thickness, increasing the material thickness resulted in a reduction of displacement. Additionally, as the pressure range increased, a symmetrical rise in radial displacement was observed.

The study findings confirmed that the improved disc-shaped spring design effectively operates under an applied pressure of 75 MPa without undergoing significant deformations, demonstrating its structural reliability and efficiency.

Stress analysis of the main components of the improved valve construction. The current simulation of the improved gate valve analyzes the stress distribution occurring within the structure, particularly along the valve body and the cross-sectional area of the disc-shaped spring. Using the “Python” and “Matplotlib” programming languages, a simplified mathematical model was developed to simulate stress distribution, providing a computational approach to assess the structural performance of the improved valve design.

Based on the Finite Element Simulation (FEM) module of NumPy, the theoretical calculations of the parameters considered in the simulation were performed. The study focused on evaluating the radial and longitudinal stresses occurring in the body of the improved valve, as well as the circumferential stress distribution along its cross-section. The results of the 2D contour plot simulation of the valve body indicated that stress increases most significantly along the inner radius. As the radial stress approaches the center of the gate valve structure, it reaches its peak value, then gradually decreases as it moves toward the outer radius and surface.

The stress condition of the improved gate valve was analyzed through simulations of both the sealing element and the valve body. The findings confirmed that the improved valve design maintains structural integrity under high-pressure conditions of 75 MPa (5 MPa above the operating pressure), demonstrating its resistance to applied pressure variations.

The stress acting along the inner radius of the sealing elements reaches 325 MPa under varying pressure conditions. This stress level falls within the typical strength range of stainless steel. However, the compressive force moving inward also increases, reaching -75 MPa. Additionally, the longitudinal stress of 162.5 MPa contributes to additional pressure along the height of the gate valve, causing localized stress concentrations. The observed stress patterns help identify fatigue-prone areas and critical surfaces where wear is most likely to occur. The body of the gate valve primarily experiences stress along the inner radius.

The study determined that the 325 MPa stress is distributed along the inner surface of the valve body, which helps identify critical areas prone to failure. This, in turn, allows for a better assessment of the stress resistance of vulnerable components, particularly in the contact area between the valve body and the sealing elements.The initial stresses generated by the applied pressure on the sealing elements include radial, longitudinal, and cross-sectional stresses, with circumferential stress being a key factor. If the sealing element is considered as a cylindrical structure, the stress distribution along its cross-section can be expressed as follows:

$$\sigma_h = \frac{P \ \cdot r_i}{t} \tag{10}$$

here, σ_h - represents the stress occurring along the cross-section of the element over time; P – internal pressure; r_i – inner diameter; t – wall thickness. In this case, the resulting radial stress can be calculated as follows:

$$\sigma_r = -P \tag{11}$$

here, σ_r – represents the radial stress, which acts in opposition to the inner surface of the sealing element and is considered constant. Additionally, the resulting longitudinal stress is expressed as follows:

$$\sigma_t = \frac{P \ \cdot r_i}{2t} \tag{12}$$

here, σ_t – represents the longitudinal stress which acts along the axis of the valve.

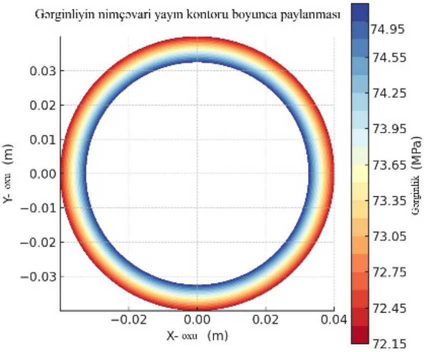
By applying the above equation to the improved valve construction under a working pressure of 75 MPa, and incorporating the proposed design parameters, the resulting values are obtained as shown in Table 1.

Table 1

Evaluation of considered parameters for the sealing element in the simulation

σ_h, MPa	P, MPa	t, m	r_i, m	σ_r, MPa	σ_t, MPa
325	75	0.015	0.065	-75	162.5

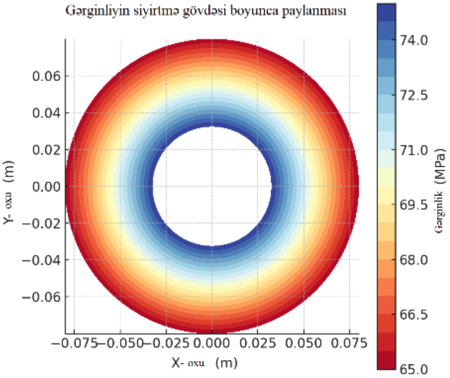
Using the "Matplotlib" software, the given parameters were processed, and the loading and stress resistance of the valve were analyzed at 0.30 MPa intervals (Graph 11).



Graph 11. Simulation of stress distribution on spring

On the X-axis, the positive and negative values represent the lateral movement of the disc-shaped spring from its center towards the left and right, expanding outward depending on the applied load. On the Y-axis, the positive and negative values indicate the vertical movement of the spring from its center upwards or downwards, also expanding outward. As seen from the graph, the highest stress concentration occurs around the inner radius of the disc-shaped spring, primarily near the sealing surfaces. The gradual increase in stress is visually represented in the model by a color gradient, transitioning from the outer edges toward the center. A similar simulation was applied directly to the improved valve construction, incorporating all its components to evaluate its overall stress resistance. For this purpose, the 2D structure of the valve was first processed in “AutoCAD”, then transferred to “Matplotlib” via a custom “Python” script, where the direct impact of pressure on the model was analyzed (Graph 12).

The 2D contour plot simulation of the valve body revealed that stress increases significantly along the inner radius. As radial stress approaches the center, it reaches its peak value, then gradually decreases outward toward the outer radius and surface. The circumferential stress is highest at the points where the internally distributed pressure directly impacts the material.



Graph 12. Simulation of stress distribution on the body of the improved valve construction

The stress condition of the improved valve was analyzed through the simulation of both the sealing element and the valve body, confirming its resistance to applied pressure variations under high-pressure conditions.

The stress acting along the inner radius of the sealing elements reaches 325 MPa due to varying pressure. This stress level falls within the typical strength range of stainless steel. However, as the compression force moves inward, its value increases, reaching -75 MPa. Additionally, the longitudinal stress of 162.5 MPa contributes to additional pressure along the valve height, causing localized stress concentrations. These stress distributions help identify fatigue-prone areas and critical surfaces susceptible to wear. The valve body primarily experiences stress along the inner radius, where 325 MPa of stress is distributed along the inner surface. This, in turn, allows for a better assessment of the stress resistance of vulnerable components, particularly in the contact area between the valve body and the sealing element.

The radial stress acting on the external surface of the improved gate valve body decreases to -49.5 MPa. This reduction also indicates that the compressive force diminishes as it moves outward. While the longitudinal stress of 162.5 MPa suggests a relatively uniform force distribution along the valve body, the highest stress concentration remains along the inner radius. The study confirmed that maximum stress accumulation in the improved gate valve body and disc-shaped spring occurs primarily along the inner radius. The 325 MPa maximum stress along the circumferential direction remains within the material’s strength limits, validating the structural reliability of the improved design under 75 MPa high-pressure conditions. The stress distribution analysis also helped identify potential fatigue and wear points in both the valve body and the sealing elements, contributing to further structural optimizations.

Determination of the failure-free operating life of the improved linear motion gate valve under cyclic pressure loading. The calculation investigates the fatigue limit of a gate valve body made of stainless steel, operating under cyclic pressure variations between 50 MPa and 90 MPa, with an average pressure of 75 MPa. The analysis employs Miner’s rule to predict the expected failure time, helping determine the performance degradation period of the valve. In many stainless steel grades, the fatigue limit is approximately 50% of the ultimate tensile strength of the material. For typical stainless steels such as AISI 304 or AISI 316, the permissible stress limit ranges between 240 MPa and 260 MPa. Below this threshold, stainless steel can endure cyclic stress without fatigue failure. However, as the stress amplitude increases, the number of cycles the material can withstand before failure decreases significantly. This relationship is represented by the S-N curve (Stress-Life Curve), which describes the correlation between stress magnitude and the number of cycles until failure.

For a valve operating within a pressure range of 50 MPa to 90 MPa, the stress values were calculated using equation (10), yielding 389.99 MPa and 216.67 MPa, respectively. The stress amplitude ($\Delta\sigma$), defined as the difference between the maximum and minimum stresses induced by pressure fluctuations within the structure, is calculated as follows:

$$\Delta\sigma = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{13}$$

here, $\Delta\sigma$ – represents the stress amplitude; σ_{max} - maximum stress; σ_{min} - minimum stress.

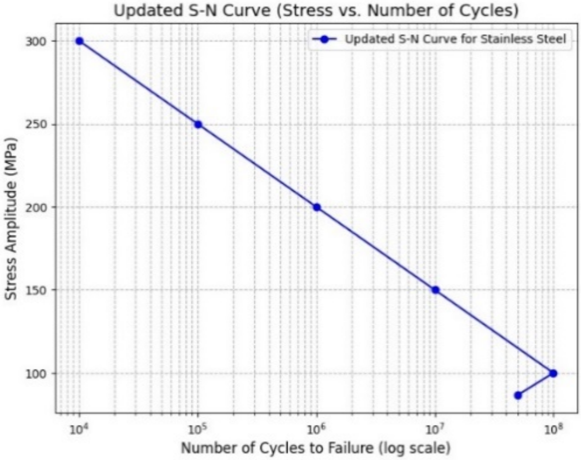
By considering the determined stress amplitude, the Miner's rule can be used to evaluate the performance and fatigue life of the gate valve under cyclic loading conditions. According to Miner's rule, the fatigue damage accumulation is expressed as follows:

$$D = \sum \frac{n_i}{N_i} \tag{14}$$

Here, D represents the accumulated fatigue effect under cyclic loading, where D = 1 indicates failure. n_i is the number of cycles applied at a specific stress level, and N_i - is the total number of cycles the material can withstand at that stress level before failure.

For the improved gate valve design operating under variable pressure, the number of daily cycles is a crucial factor in estimating its service life. Assuming that the valve undergoes 10,000 cycles per day, its fatigue life can be estimated using the S-N curve for stainless steel. After processing the collected data, an S-N curve was plotted for the selected material of the gate valve construction (Graph 13). Based on an 86.66 MPa stress amplitude, the gate valve is expected to operate up to approximately 50×10^6 cycles before failure.

At a stress amplitude of 300 MPa, stainless steel may fail after 10,000 cycles, whereas at 150 MPa, it can last up to approximately 50 million cycles. These findings are based on empirical fatigue tests conducted on common stainless steel grades such as AISI 304 and AISI 316 under cyclic loading conditions. For the improved gate valve operating under variable pressure, the daily number of cycles plays a critical role in evaluating the material's fatigue resistance. Assuming the valve undergoes 10,000 cycles per day, its service life can be estimated using the S-N curve for stainless steel.



Graph 13. Number of cycles until failure

Considering the previously calculated stress amplitude of 86.66 MPa, the gate valve is expected to operate up to approximately 50 × 10^6 cycles before failure. Using this data, the fatigue life of the material can be determined as follows:

$$D = \frac{50 \cdot 10^6}{10{,}000 \cdot 365} = 13.7 \text{ year} \tag{15}$$

The analysis results from equation (15) confirm that when the proposed gate valve design is manufactured using the selected materials, it can remain operational for up to 13.7 years. Additionally, if regular maintenance is performed on time, the reliability indicators of the valve can be maintained throughout its service life.

CONCLUSIONS

1. A new valve construction with an improved sealing assembly, capable of ensuring high operational efficiency under service conditions and resistant to hydroabrasive wear, was developed and patented.
2. The materials for the components of the improved sealing assembly were selected based on the newly proposed friction resistance criterion.
3. A special analytical method based on fuzzy theory was developed to determine the hydroabrasive wear resistance of the valve components.
4. An "if-then" fuzzy model was developed to determine the dependence of the cross-sectional parameters of the improved packing element on deformation.
5. Tests were conducted to evaluate mechanical wear in the components of the improved sealing assembly, determining the friction coefficient of various materials and assessing the wear characteristics based on environmental conditions.
6. A new testing methodology was developed for conducting performance tests on the improved valve construction.
7. The results of the Miner’s rule-based analysis confirmed that, when manufactured using the selected materials, the proposed valve construction can remain operational for up to 13.7 years. Furthermore, with regular and timely maintenance, the reliability indicators can be sustained throughout its service life.
8. A Finite Element Analysis (FEA) was performed to assess the stress resistance of the body and sealing components of the improved gate valve, confirming its ability to withstand pressures up to 70 MPa.

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Works No. [1, 12, 13, 15] – were performed independently by the author.

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