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Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 12, December, 2023

Operation Simulation for a Check Valve Used in High-Performance Systems

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Received 16 August 2023; Revised 18 November 2023; Accepted 21 November 2023; Published 01 December 2023

Abstract

This research aims to increase the reliability and safety of pipeline systems by creating an improved model range of Butterfly Check Valves (BCV). Pipes through which working fluids are transported, parts related to shut-off and control valves, control measuring instruments, fasteners, anticorrosion elements, and other structural components are the main elements that make up pipelines. Fittings can be of different types; BCV refers to protective ones. These devices protect pipelines by disconnecting the working line in the event of a sudden change in the transported fluid parameters (pressure, flow direction), resulting in the failure of the entire system. Based on an analysis of the key requirements for valves, namely reliability, tightness of a closed system, ensuring safe operation, and analysis of existing BCVs, the design of the presented valve was created. Improved overall dimensions and tightness, both in the open and closed states, as opposed to the existing analogs, are distinctive features of the developed design of butterfly check valves. To confirm the results, the authors, using the finite element method, calculated the stress–strain state of the structure under normal conditions and with regard to the maximum temperatures of the working fluid. The reliability indicators of the developed elements were also calculated to confirm their operability. As a result, it was concluded that after the developed valves have passed acceptance tests, the research findings will make it possible to increase the reliability and safety of the valve itself and the entire pipeline system by introducing these structures into enterprises.

Keywords: Butterfly Check Valve; Pipeline Fittings; Pipeline Systems; Finite Element Method; Calculation of Reliability Indicators.

1. Introduction

Nowadays, the scope of the application of pipeline systems is enormous. Pipelines are used in gas and oil production, chemical and nuclear industries, transport, metallurgy, and housing and communal services [1]. Pipelines transport cold and hot water, saturated and superheated steam, chemical media, including aggressive ones, liquid metals and molten salts, gases of various states of aggregation, pulp-like mixtures, etc. [2-4]. Working environments can be under high pressure up to hundreds of atmospheres and at temperatures from close to absolute zero to thousands of degrees [5, 6]. Fittings include a number of mechanisms mounted in collectors that regulate certain work flows [7]. Depending on the functional purpose, fittings are divided into different types: check valves, control, shut-off, safety, diverter, shutdown valves, etc. [8–10]. To ensure the technological operating mode of pipeline systems, the valves must maintain excess pressure, deep vacuum, or alternation of these parameters [11, 12]. Stable and safe operation of pipelines and pipeline fittings is crucial for the efficient operation of the entire system [13].

Safety fittings are designed to protect equipment from an emergency excess of any parameter of the working fluid (pressure, temperature, etc.) by disconnecting the pipeline section. This type includes check valves [14]. Butterfly check

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http://dx.doi.org/10.28991/CEJ-2023-09-12-017

valves are a type of fitting that allows a working fluid (liquid or gas) to flow in only one direction through a pipeline and prevents reverse flow. The check valve closes automatically when the direction of the working fluid motion changes to the opposite. It provides protection against emergency changes in fluid parameters by disconnecting the corresponding section of the pipeline (complete shutdown of the line) [15].

During valve operation, partial or complete failure is possible, which occurs when one or an entire group of elements breaks down. If the pipeline fittings completely fail, the risk of emergency situations is very high. Emergency circumstances in industries where butterfly check valves are used will not only cause harm to personnel and the plant but also adversely affect the environment [16, 17]. Due regard for the operating conditions of the device and ensuring the reliability of the structure are two of the most significant tasks when designing safety fittings [18, 19]. These indicators, in turn, represent the structural ability to maintain tightness and operability throughout its entire service life [20]. To assess these parameters during production and operation, various methods of product quality control are used, mainly non-destructive methods and simulation modeling [21–23].

When creating pipeline fittings, numerical and mathematical modeling methods are indispensable [24–26]. They make it possible to obtain information about the behavior of the valve and its individual parts and to determine the optimal parameters to satisfy the conditions of strength and tightness at the early stages of design [27, 28]. Mathematical modeling enables us to obtain information about the system behavior under various types of loading when working with fluids in different states [29, 30].

To date, various valves have been developed; however, their main disadvantage is low tightness, which negatively affects the efficiency of regulating the operating parameters of the valve [31]. Thus, this research aims to develop a durable and reliable design for a butterfly check valve, confirmed by calculations that guarantee trouble-free operation of systems at hazardous production facilities.

2. Literature Review

As it has already been mentioned, a sufficient number of different designs of butterfly check valves have been developed, the typical design of which will be discussed in more detail below.

Dirk & Kopp developed a check valve, the main elements of which are a body, whose axes of the inlet and outlet pipes are located at right angles, seats, and a turntable [32]. The process of mounting the seat and plate, which is carried out by welding, is a significant disadvantage of this design. This method complicates the repair of the valve because, during repair, it is necessary to mechanically cut out the seat and install a new one in the same place. The NBS Co. Ltd. valve consists of a body and a seat with a disk mounted on a movable connection with an axis, dividing the flow part into inlet and outlet cavities [33]. However, this design is low-tech, difficult to manufacture, and non-repairable. The main property of the valve—tightness during the reverse flow of the fluid—is also lost.

Dalluge & Davis presented a check valve, the distinctive feature of which is an additional cavity in the body, made to accommodate a valve with a rotary flap [34]. The body is attached to the cover using a flange connection, sealed with a gasket. This design solution has large weight and dimension characteristics and low tightness of the internal cavity relative to the external environment due to the presence of a connector with a gasket connection. In the butterfly check valve, developed by Nowell et al., the seat is connected to the body by a threaded bushing with a gasket to improve tightness. Sealing of the valve when blocking the flow is ensured using a plate mounted on an axis located upstream of its outer surface [35]. The body consists of two parts connected to each other using a threaded connection sealed with a gasket.

The low reliability of the valve, which occurs due to the presence of detachable connection points between the component parts of the body and between one of them and the seat, is a significant disadvantage of this solution. This problem can be solved by using sealing gaskets, but this approach is undesirable for pipelines with harmful and potentially hazardous media. The butterfly check valve, developed by Norrman (2006), like those discussed above, consists of a body, a rotary disk, and a seat [36]. It differs in the connection between the locking disc and the piston hydraulic brake rod using a lever-joint system. The hydraulic brake, whose body is fixed to the valve body, is designed to ensure smooth movement of the locking disk to close the valve and dampen the impact of the disk on the seat. An important area of research is also the introduction of new materials and technologies for production [37].

The bulkiness resulting from the lever-hinge system is a disadvantage of the design. The valve presented by Zimmerman et al. consists of a body, a seat, a shaft, a locking disk, and a hydraulic damper [38]. The latter element is designed to regulate the opening and closing speeds. The hydraulic damper contains a hydraulic cylinder with a flange, a cover, and working cavities of variable volume. Working cavities of variable volume are formed in the hydraulic damper body by dividing partitions and rotating blades; they are filled with damper liquid, united in pairs, and communicate with each other through a throttle device, which is used to regulate the valve opening and closing speed.

However, the valve does not have high tightness of the working cavities of the hydraulic damper, which reduces the efficiency and accuracy of regulating the specified operating parameters of the valve.

3. Material and Methods

Figure 1 shows a flowchart diagram compiled by the authors that clearly demonstrates the sequence of the study stages.

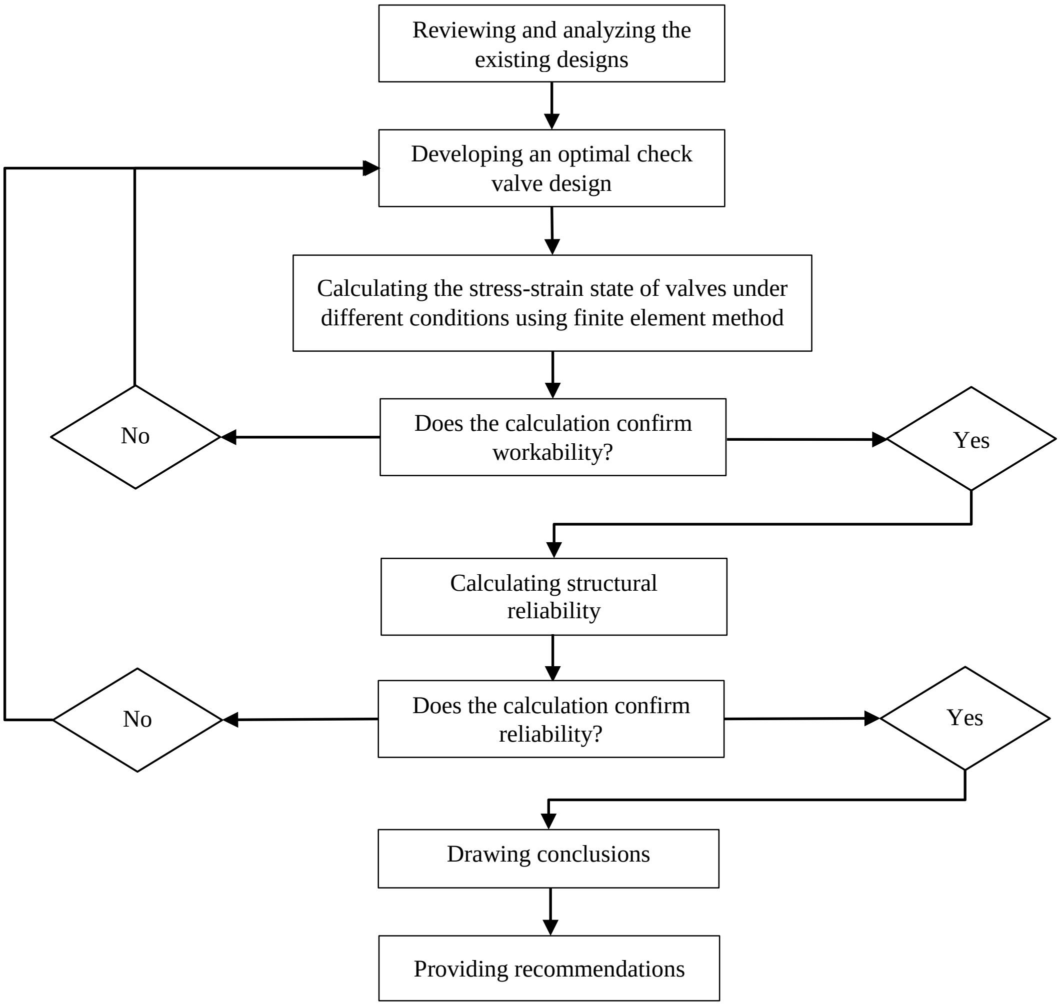


Figure 1. Flowchart of the conducted research.

4. Description of the Check Valve Design

A butterfly check valve was designed that can be mounted on systems with diameters of 80, 250, and 300 mm. A butterfly check valve with a nominal diameter of 300 mm is considered as an example. The design of the butterfly check valve developed by the authors (Figure 2) consists of the following main parts: sealing cap (1), metal body (2), and shutter valve (3).

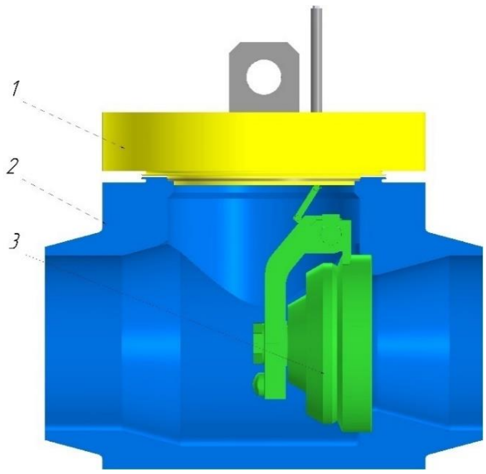


Figure 2. Design of the butterfly check valve with a nominal diameter of DN300: 1 – sealing cap, 2 – body, 3 – shutter valve

The body of the developed valve model range is a cast and milled part made of corrosion-resistant steel (Figure 3), which has two openings (inlet and outlet) with nominal diameters of 80, 250, and 300 mm, depending on the model, compatible with the drift diameters of pipeline systems.

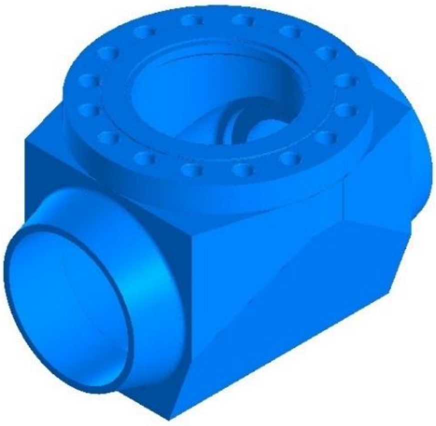


Figure 3. Metal body

The main elements of the BCV are installed in the body. The design of the body is monolithic to ensure the proper level of strength and provides for its installation on horizontal, inclined, and vertical sections of the pipeline by means of a welded connection. The sealing cap of the valve is a machined, milled metal part (Figure 4), designed to ensure valve tightness and protect the structural elements from foreign bodies and external mechanical influences during transportation and storage.

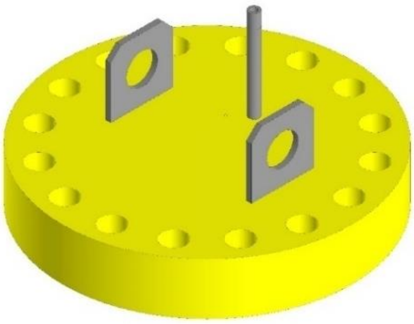


Figure 4. Sealing cap

To ensure tight fixation, the sealing cap has a technological groove in which the sealing ring is installed on the body. There is a technological protrusion on the lower surface of the cap that facilitates assembly by centering it in the technological hole of the housing. Technological transportation lugs are located on the top of the cap. The check valve design consists of three main elements: the seat, the disc and the lever. The seat is a machined metal structure (Figure 5) designed to ensure a tight fit of the disc and prevent reverse flow of the working fluid when the shut-off element is automatically activated.

Figure 5. Seat

The disk is a machined metal part (Figure 6) and has a technological recess for installing a fixing element and a control lever on the contraction.

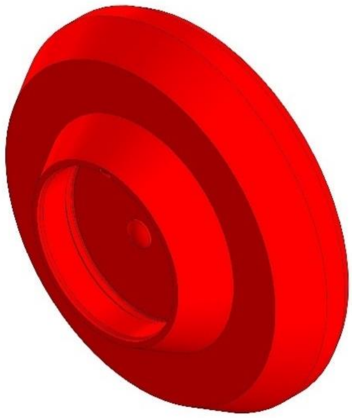


Figure 6. Disk

Because of the disk design features and the tight fit of its working surface to the seat, the disk provides complete sealed shutoff of the transported fluid flows and protection of equipment against emergency changes in environmental parameters by automatically triggering and shutting off the service line. The lever is an L-shaped milled metal part with holes for mounting the disk (Figure 7). The lever is designed to activate automatic flow shutoff. A lug in the upper part of the lever is designed to install a remote indicator of the shut-off device position.

Figure 7. Lever

To assemble the structural elements of the valve, a technological hole is provided in the body through which the sealing cap, seat, disk, and lever are assembled and installed in the working position (Figure 8).

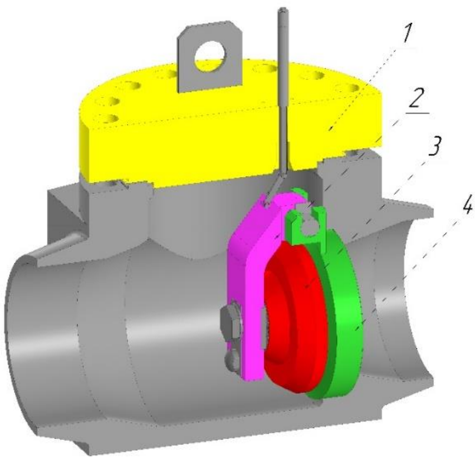


Figure 8. Position of the disc, lever, and seat in the valve body: 1 – sealing cap, 2 – lever, 3 – disk, 4 – seat

The BCV body is designed to ensure unimpeded motion of the working fluid in the operating direction and free movement of the shut-off element during operation.

The sealing cap is installed on the top hole of the body using 12 bolts. A flanged rubber gasket is used to seal the valve cavity. The design of the cap also involves the installation of a remote indicator of the shut-off element position;

a technological hole is provided for this purpose (Figure 9). Such a cap simplifies the replacement of the main structural parts without removing the valve from the pipeline.

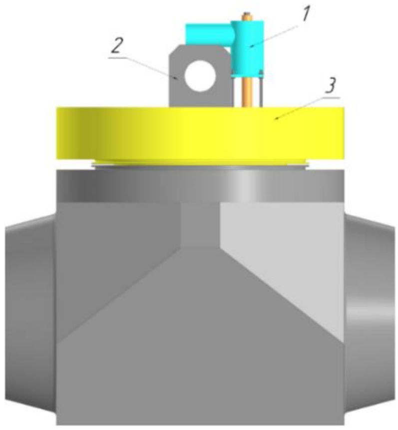


Figure 9. Position of the valve cap and remote indicator of the shut-off element position: 1 – remote indicator of the shut-off element position, 2 – lugs, 3 – cap

A metal pipe is welded to the upper surface of the cap. The shut-off element target which can move freely is located inside the pipe. To determine the state in which the valve is (open or closed), additional equipment is used: a remote indicator of the shut-off element position (Figure 10).

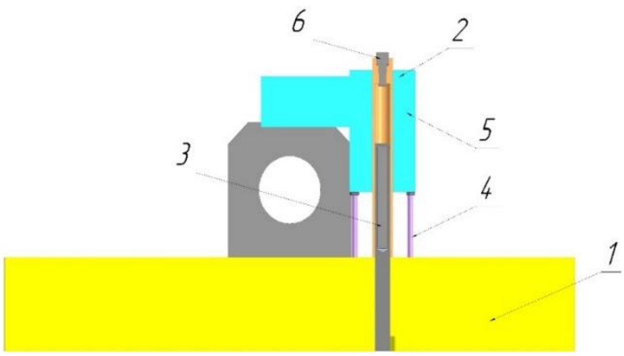


Figure 10. Design of the remote indicator of the shut-off element position: 1 – cap, 2 – bushing, 3 – target, 4 – studs for the remote indicator of the shut-off roller position, 5 – remote indicator of the shut-off element position, 6 – plug

The upper part of the lever has a special hole for installing a pusher. When the valve is open, the push rod raises the target of the remote indicator of the shut-off element position, which allows its position to be determined. In the closed position of the valve, the pusher lowers the target of the remote indicator and displays the position of the shut-off element. The pusher is attached to the lever and target using axes, which are fixed in the holes with cotter pins.

5. Procedure for the Design Analysis

When developing butterfly check valves, methods of computational experiment and mathematical modeling are indispensable. During the analysis, calculations are made for the strength, rigidity, and stability of the valve under various operating conditions. These calculations make it possible to determine the permissible limits of stress and strain for safe valve operation. The stress–strain state of the valve structure is examined in the course of analysis. This allows to determine the durability and reliability of the valve operation under pre-set loads and operating conditions.

To assess the load on a check valve, it will be necessary to calculate its ultimate strength. For this purpose, the stress–strain states of each valve element are studied using finite element methods. The ultimate strength is calculated with regard to the highest constant loads inherent in the normal operation of the product in question. The finite element method is based on the division of the study area into a finite number of sections – finite elements. Finite elements can have different shapes and sizes. As a result of this division, a mesh is created. At the boundaries of the finite elements, nodes are created in which the values of the desired function are determined. Adjacent elements have common nodes. Additional nodes can also be created inside elements and on their boundaries. The set of all finite elements (FE) and nodes is the basis of the finite element model of a strained body.

The assessment is based on a specialized software package that splits the mechanism into a number of individual components. This assessment is characterized by high speed and significant energy efficiency, resulting in the possibility of identifying the most congested sections and assessing sectors that require detailed study. Optimization of three-dimensional geometric models of a structure is a process aimed at improving efficiency and optimizing structure performance by changing its shape, size, or materials. Various methods and approaches can be used to optimize 3D geometric models of a structure. Optimizing three-dimensional geometric models of a structure can improve its performance, efficiency, strength, and other characteristics and reduce the costs of production and use of the structure.

Each multidimensional problem, the solution of which serves as the basis for strain theories, can be expressed as follows:

$$\begin{cases} \sigma_{ij,j} = 0 \ in \ V; \\ \sigma_{ij} = F_{ij}(\varepsilon_{kl}) \ in \ V \cup \sum; \\ \varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right) \ in \ V; \\ u_i = u_i^e \ on \ \Sigma_{u1}; \ u_i = 0 \ on \ \Sigma_{u2}; \\ \sigma_{ij} n_j = 0 \ on \ \Sigma_{\sigma}, \end{cases} \tag{1}$$

In this case, σ_{ij}, ε_{kl} are the Cartesian strain and stress affinors; u_i are components of the displacement gradient; $F_{ij}(\varepsilon_{kl})$ are nonlinear dependencies of affinors that describe the simulation of ductility; $u_{i,j}$ are private compilations; u_i^e established displacements for increment Σ_{u1} of body planes. We will consider surface fragments Σ_{u2}as reliably fixed. Thus, a flat plate in the form of a thin parallelepiped is characterized by the fact that most displacements will be specified by the value Ox_1, and hence:

$$\begin{aligned} u_1^e &= U(t) = \dot{U}_0 t \\ u_2^e &= u_3^e = 0 \end{aligned} \tag{2}$$

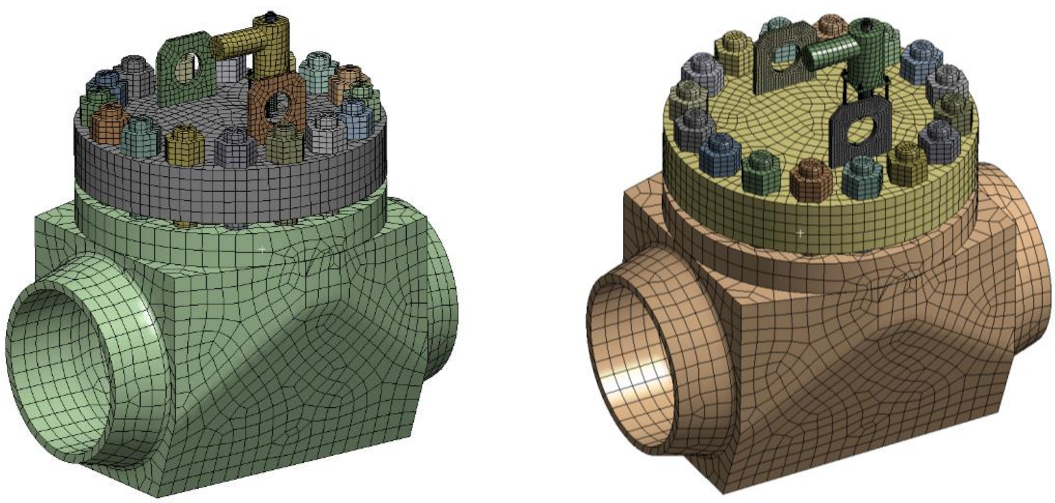
When calculating the ultimate strength of a valve simulation, we developed a static loading design scheme that represents the superficially applied pressure on the internal cavity of the valve. Calculations were carried out at load P=20 MPa. While calculating the stress–strain state, the valve model was simplified by excluding minor unloaded and small elements (roundings, chamfers, etc.) that do not affect the final result of the calculation.

The following assumptions were made during the stress–strain state modeling: the materials are continuous and homogeneous; the chemical composition and aggregate state of material matter are unchanged during the calculation process; strains cause no heating processes; there are no extraneous external effects on the base; loads are constant, applied in one direction, and their values do not depend on time.

To analyze the stress–strain state of the structural elements of the valve, the 08X18H10T material was chosen. When statically calculating the stress–strain state, we consider the outer surfaces of the valve inlet and outlet to be motionless, since they are rigidly fixed to the pipeline sections connected thereto, and we limit their motion along the axes of the Cartesian XYZ coordinate system. Rotation around all coordinate axes is also limited.

At the same time, a quantitative solution was achieved by automated fragmentation of the simulation – a final element mesh. A static final element calculation was then performed, which resulted in the establishment of stresses in the simulations and the identification of the maximum loaded components of the designed valve. The results obtained were necessary for optimizing the finite element mesh in these areas.

Based on the calculations performed with the automatically generated finite element mesh (FEM), this FEM was optimized within the valve design in the closed and opened state (Figure 11).



a) b)

Figure 11. Optimized finite element mesh in the DN300 butterfly check valve in the (a) closed state and in the (b) opened state

6. Results

6.1. Calculation of the Stress–Strain State

After obtaining the optimized finite element mesh, a static finite element calculation of the valve model in the closed and opened states is performed to obtain more accurate results. The calculation results are the maximum stresses and strains of the valve structural elements loaded in accordance with the design diagram. Figures 12-17 show graphical representations of the distribution of equivalent stresses, strains, and displacements in the volumes of the valve structural element models in closed and opened states.

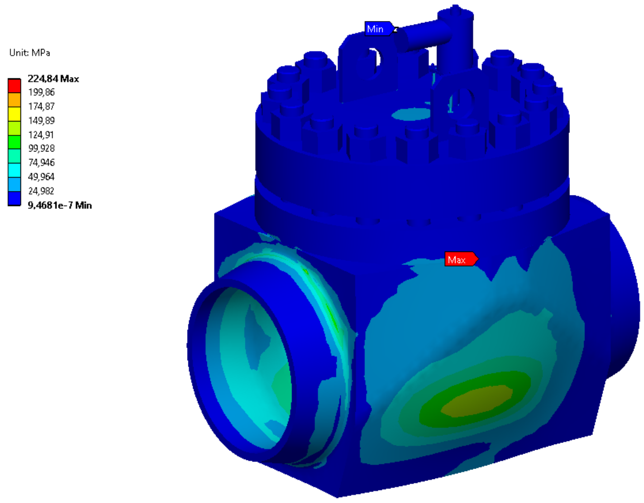


Figure 12. Distribution of equivalent stresses in the volume of the DN300 butterfly check valve in the closed state

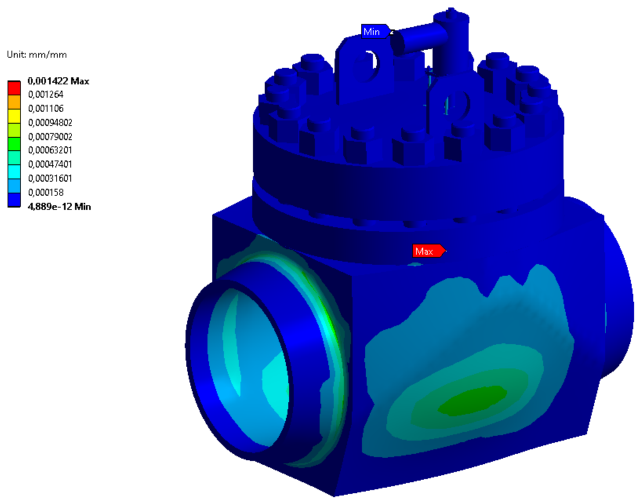


Figure 13. Distribution of equivalent strains in the volume of the DN300 butterfly check valve in the closed state

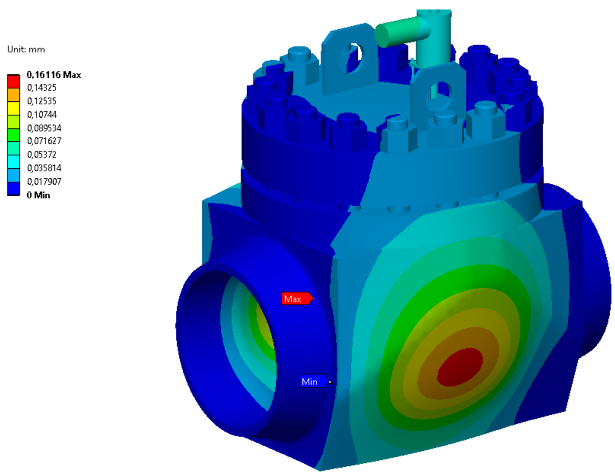


Figure 14. Distribution of displacements in the volume of the DN300 butterfly check valve in the closed state

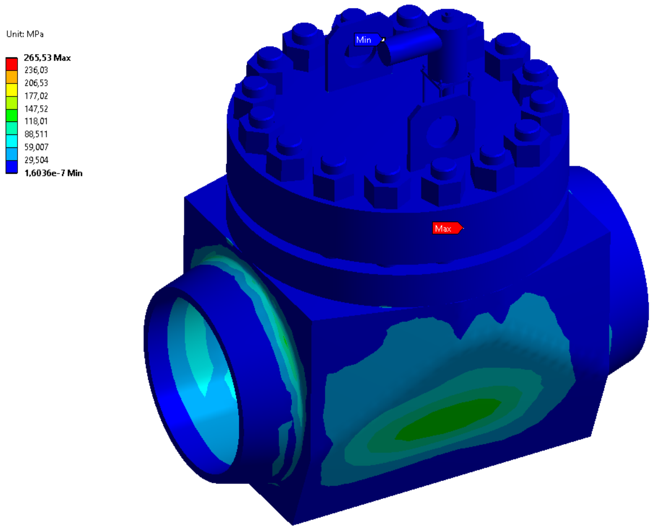


Figure 15. Distribution of equivalent stresses in the volume of the DN300 butterfly check valve in the opened state

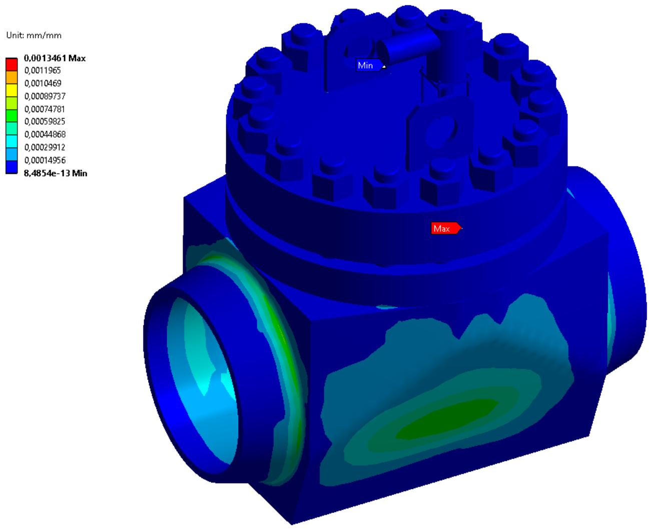


Figure 16. Distribution of equivalent strains in the volume of the DN300 butterfly check valve in the opened state

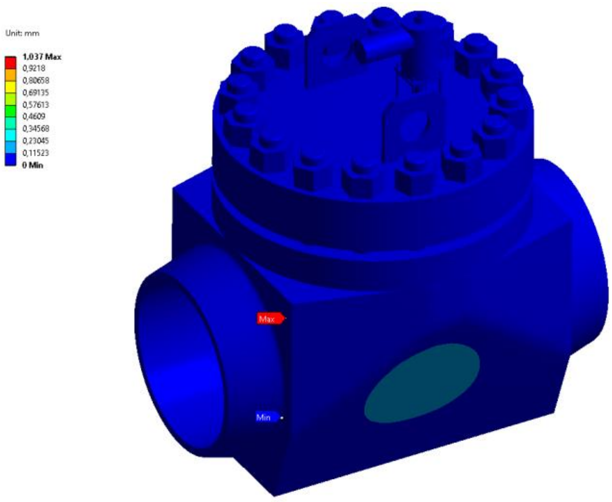


Figure 17. Distribution of displacements in the volume of the DN300 butterfly check valve in the opened state

Comparative Table 1 presents the results of calculating butterfly check valves in all versions in the closed and opened states in the stress–strain state, namely, the maximum equivalent stresses, strains, and displacements of structural elements under static loads.

Table 1. Calculation of the stress–strain state with the optimized FEM

Version / Parameter	DN 80 - closed	DN 80 - opened	DN 250 - closed	DN 250 - opened	DN 300 - closed	DN 300 - opened
Maximum equivalent stresses σ_{max}, MPa	160.26	290.96	250.68	264.29	224.84	265.53
Maximum strains Δ_{max}, %	0.090	0.200	0.126	0.133	0.142	0.135
Maximum displacements δ_{max}, мм	0.04	0.41	0.13	0.56	0.16	1.04

6.2. Calculation of the Stress–Strain State Regarding Maximum Operating Temperatures

A static finite element analysis was carried out to determine the stress concentrators in the volumes of the models and the most loaded structural elements of the valves (DN80, 250 and 300) in the closed and opened states. This calculation is necessary to identify the most loaded areas of structural elements at a maximum working fluid temperature of 350°C.

The results of the calculation are the maximum stresses and strains of the valve structural elements (DN80, 250 and 300), loaded in accordance with the design diagram. Figures 18-23 show graphical representations of the distribution of equivalent stresses, strains, and displacements in the volumes of models of valve structural elements in closed and opened states.

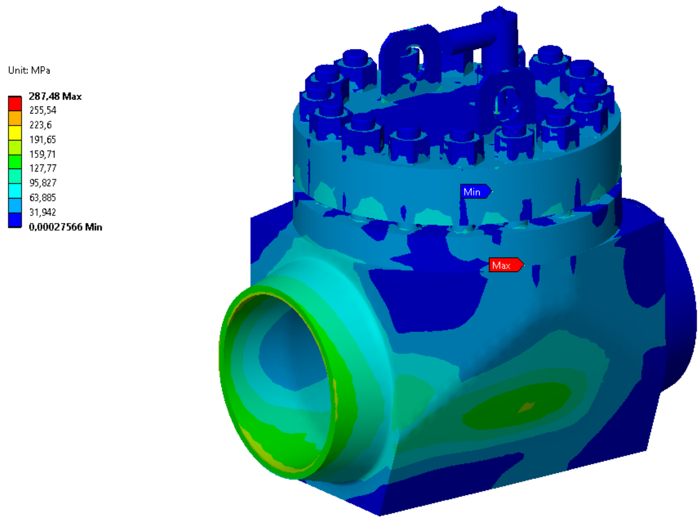


Figure 18. Distribution of equivalent stresses in the volume of the DN300 butterfly check valve in the closed state

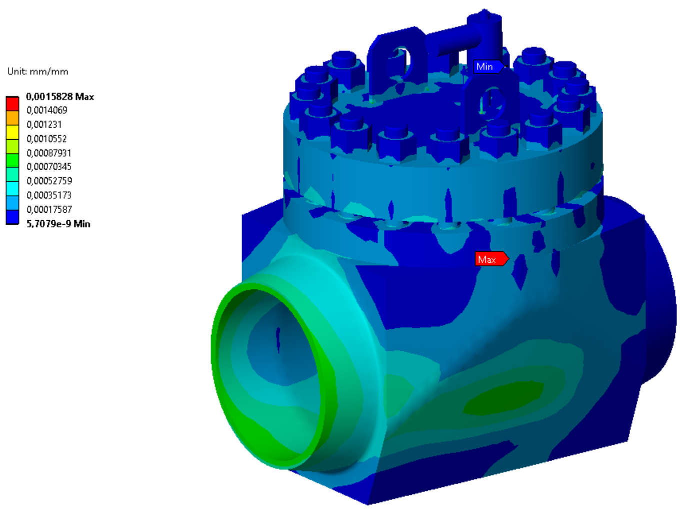


Figure 19. Distribution of equivalent strains in the volume of the DN300 butterfly check valve in the closed state

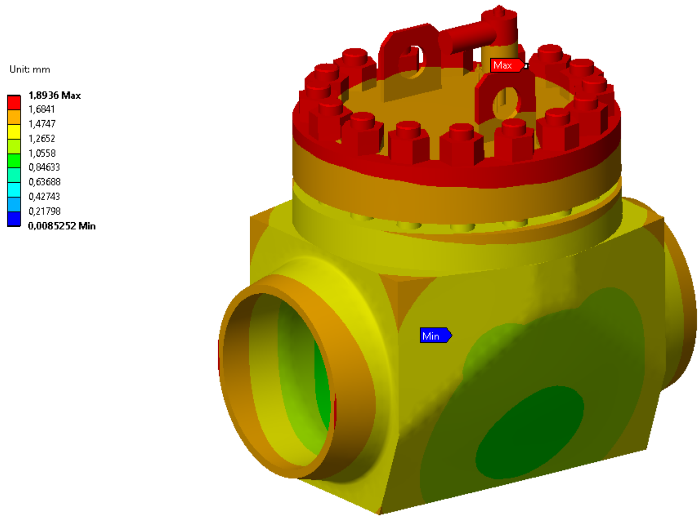


Figure 20. Distribution of displacements in the volume of the DN300 butterfly check valve in the closed state

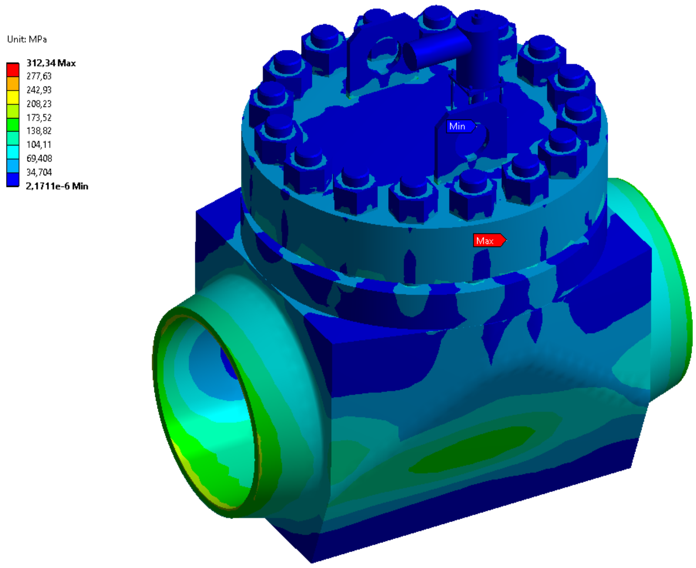


Figure 21. Distribution of equivalent strains in the volume of the DN300 butterfly check valve in the opened state

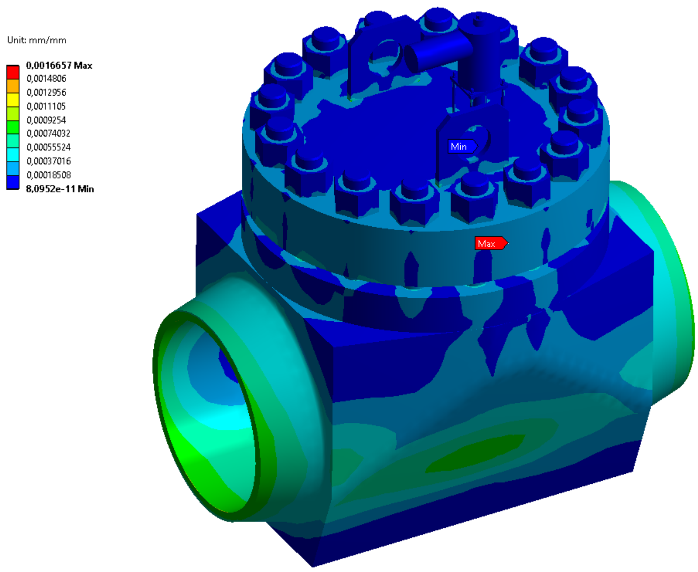


Figure 22. Distribution of equivalent strains in the volume of the DN300 butterfly check valve in the opened state

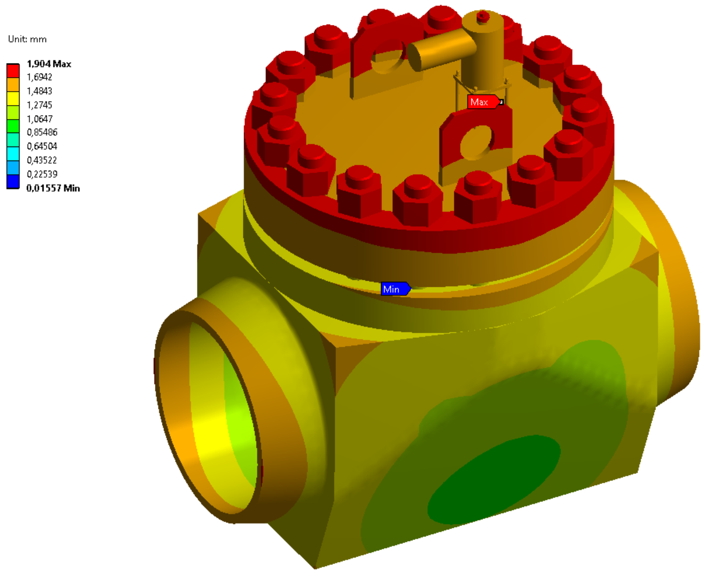


Figure 23. Distribution of displacements in the volume of the DN300 butterfly check valve in the opened state

Comparative Table 2 presents the calculation results for butterfly check valves in all versions (DN80, 250 and 300) in the closed and opened states in the stress–strain state, regarding maximum operating temperatures, namely, maximum equivalent stresses, strains, and displacements of structural elements under static loads.

Table 2. Calculation of the stress–strain state regarding maximum operating temperatures

Version / Parameter	DN 80 - closed	DN 80 - opened	DN 250 - closed	DN 250 - opened	DN 300 - closed	DN 300 - opened
Maximum equivalent stresses σ_{max}, MPa	312.44	260.08	286.71	249.04	287.48	312.34
Maximum strains Δ_{max}, %	0.24	0.181	0.144	0.141	0.158	0.167
Maximum displacements δ_{max}, MM	0.89	0.88	1.83	1.87	1.89	1.90

The values obtained as a result of calculating the stress–strain state, namely, the maximum equivalent stresses, strains, and displacements of structural elements under static loading, confirm the required level of strength necessary for the functioning of the developed design.

6.3. Calculation of Reliability Indicators

To assess the reliability of the valves being developed, an approximate calculation is conducted using the structural method for calculating the reliability of pipeline fittings. As a result of the calculation, some quantitative characteristics were obtained that describe the mechanism reliability (probability of failure-free operation, number of failures, etc.). In accordance with the technical requirements, the butterfly check valves being developed must meet the following reliability and durability requirements:

- The designated service life of the valve must be at least 50 years;
- The designated service life of internal (removable) parts must be at least 15 years;
- The designed durability of the valves is at least 1350 "opening–closing" cycles;
- Maintenance frequency should be at least 30,000 hours of continuous operation or at least once every 5 years;
- The period between major repairs (life between overhauls) is at least 12 years.

The failure rate of each *i*-th element of the butterfly check valve λ_i', under load is determined by the Equation 3:

$$\lambda_i' = k_1 \cdot \lambda_{0i,} \tag{3}$$

where λ_{0i} is the average statistical failure rate of an element over the period of operation, determined (given, indicated) regardless of whether the element is under load or without load; k_1 is a correction factor that considers the increase in the failure rate of loaded elements.

The failure rate of i-th components of λ_i'' that are not currently loaded can be calculated as

$$\lambda_i^{"} = k_2 \cdot \lambda_i^{'} = k_2 \cdot k_1 \cdot \lambda_{0i}, \tag{4}$$

here k_2 is a correction factor that considers the reduction in the failure rate of each unloaded component.

Therefore, trouble-free operation can be expressed by the ratio:

$$P_i(t) = e^{-(\lambda_i^{'} t_i^{'} + \lambda_i^{"} t_i^{"})}, \tag{5}$$

here t_i' is the duration of the component being under load; t_i'' is the duration of the component being in the unloaded state.

At the same time, knowing the percentage of failure-free operation of the i-th components of $P(t^*)$ over any period (t^*), we can calculate:

$$P_i(t) = e^{\frac{t}{t^*} ln(P_i(t^*))} \tag{6}$$

Thus, we have designed multi-dimensional simulations of check valve mechanisms that guarantee trouble-free operation of collectors with diameters of 80, 250, and 300 mm. The formula for calculating a series connection is as follows:

$$P_c = \prod_{j=1}^{n} P_{j.} \tag{7}$$

The formula for calculating a parallel connection is as follows:

$$P_C = 1 - \prod_{j=1}^{n} (1 - P_j). \tag{8}$$

The formula for assessing the probability of valve failure-free operation is as follows:

$$P = P_1 \cdot P_2 \cdot P_3 \cdot P_4 \cdot P_5 \cdot (1 - (1 - P_6)^{16}) \cdot (1 - (1 - P_7) \cdot (1 - P_8)). \tag{9}$$

Tables 3 and 4 provide data for calculating the reliability of the valve elements in accordance with the developed structural reliability block diagram.

Table 3. Initial data for the approximate calculation of reliability

Elements and assemblies	Known data on the probability of failure-free operation over a 10-year period	Probability of failure-free operation for a required period of 12 years
Body	0.9995	0.99940003
Cap	0.9995	0.99940003
Disk (flap)	0.9991	0.9989201
Cap-body threaded connections (for one stud)	0.97	0.96410888
Cap-body weld	0.999	0.99880012
Gasket	0.999	0.99880012

Table 3. Initial data for the approximate calculation of reliability

Characteristics	Metal-to-metal seal	Hinge
Average failure rate for the current component per unit of time, $\lambda_{0i} \times 10^{-6}$	0.02	0.53
Number of components in the mechanism, n	1	1
Correction factors considering the increase in the failure rate of each loaded component, k_1	2	5
Failure rate for components in the loaded state, $\lambda_i' \times 10^{-6}$	0.04	2.65
Duration of the component stay in the loaded state, t_i', h	52560	3.75
Correction factors considering the failure rate in the unloaded components, k_2	0.001	0.001
Failure rate for unloaded components, $\lambda_i^{"} \times 10^{-6}$	0.00004	0.00265
Duration of the component stay in the unloaded state, $t_i^{"}$, h	52560	105116.3
Percentage of failure-free operation for the considered time interval	0.99789771	0.99971155

As a result of the calculations, we obtained the probability of failure-free operation of the butterfly check valve, which is equal to 0.99535688; this result corresponds to the technical requirements for the butterfly check valve.

7. Conclusion

The main findings of the present study are that a butterfly check valve, guaranteeing trouble-free operation, was designed with diameters of 80, 250, and 300 mm. The design was analyzed, and the features of the developed elements were described. To confirm the reliability and operability of the developed butterfly check valve design, finite element analysis and analytical studies were conducted. This confirms the performance of the butterfly check valve design under operating conditions with ultra-high working fluid parameters. The results of strength calculations for valves (DN 300) in the closed and opened states are reflected to assess the strength characteristics and confirm their strength reliability. Comparison with other studies: comparison with other studies confirms that unlike the butterfly check valves discussed in the literature review, the developed design is not oversized and ensures tightness, both in the opened and closed states. Implications and explanation of findings: the reliability of butterfly check valves was calculated, on the basis of which it was concluded that the valves comply with the specified technical requirements. The results obtained are indicative in nature; however, these indicators make it possible to assess the valve systems under consideration and establish compliance of the valve reliability with technical requirements. Strengths and limitations: the strength of the developed model range is its operability at a working fluid temperature of up to 350 ℃, which confirms the result of calculating the stress–strain state under these conditions. The limitation is the nominal diameter of the valves, which ranges from 80 to 300 mm.

8. Declarations

8.1. Author Contributions

Conceptualization, J.S.; methodology, J.S.; validation, A.K.; formal analysis, S.A.; investigation, M.K.; resources, A.K.; data curation, J.S.; writing—original draft preparation, M.K.; writing—review and editing, A.K.; visualization, S.A.; supervision, J.S. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available in the article.

8.3. Funding

Some results of this research were obtained as part of the work under the Subsidy Agreement dated June 24, 2021 No. 075-11-2021-041 on the topic: “Development and commercialization of the butterfly check valves model range for pipeline systems of hazardous production facilities with ultra-high working parameters environment” with the Ministry of Science and Higher Education of the Russian Federation.

8.4. Conflicts of Interest

The authors declare no conflict of interest.

9. References

[1] Sotoodeh, K. (2021). A Practical Guide to Piping and Valves for the Oil and Gas Industry. Gulf Professional Publishing, Texas, United States. doi:10.1016/c2020-0-00637-7.

[2] Liu, E. Bin, Tang, H., Zhang, Y. H., Li, D. J., Kou, B., Liu, N., & Azimi, M. (2023). Experiment and numerical simulation of distribution law of water-based corrosion inhibitor in natural gas gathering and transportation pipeline. Petroleum Science, 20(3), 1857–1873. doi:10.1016/j.petsci.2023.01.015.

[3] Lyu, Y., Huang, Q., Liu, L., Zhang, D., Xue, H., Zhang, F., Zhang, H., Li, R., & Wang, Q. (2022). Experimental and molecular dynamics simulation investigations of adhesion in heavy oil/water/pipeline wall systems during cold transportation. Energy, 250, 123811. doi:10.1016/j.energy.2022.123811.

[4] Sotoodeh, K. (2021). Piping and Valve Corrosion Study: A Practical Guide to Piping and Valves for the Oil and Gas Industry. Elsevier: Amsterdam, The Netherlands, 585-627. doi:10.1016/b978-0-12-823796-0.00009-x.

[5] Zhou, F., Dong, X. liang, Jiang, W. chun, Wang, X., & Xie, Y. tong. (2023). Contact mechanical behavior and leakage prediction of metal lenticular gaskets in bolt flange joints of ultrahigh pressure pipelines. International Journal of Pressure Vessels and Piping, 206, 105038. doi:10.1016/j.ijpvp.2023.105038.

[6] Mina, D., Karampour, H., & Forcellini, D. (2023). Resilience of HP/HT pipelines to combined seismic and thermal loadings. Ocean Engineering, 275, 114098. doi:10.1016/j.oceaneng.2023.114098.

[7] Zhang, S., Luo, M., Qian, H., Liu, L., Yang, H., Zhang, Y., ... & Zhang, W. (2023). A review of valve health diagnosis and assessment: Insights for intelligence maintenance of natural gas pipeline valves in China. Engineering Failure Analysis, 107581. doi:10.1016/j.engfailanal.2023.107581.

[8] Parisher, R. A., & Rhea, R. A. (2022). Chapter 3 - Pipe Fittings. Pipe Drafting and Design (August 2021), 15-59. Gulf Professional Publishing, Texas, United States. doi:10.1016/b978-0-12-822047-4.00019-4.

[9] Sotoodeh, K. (2021). Butterfly valve applications and design. In A Practical Guide to Piping and Valves for the Oil and Gas Industry, 147–241, Gulf Professional Publishing, Texas, United States. doi:10.1016/b978-0-12-823796-0.00017-9.

[10] Sotoodeh, K. (2021). Subsea valve and actuator standards. In Subsea Valves and Actuators for the Oil and Gas Industry, 37–100, Gulf Professional Publishing, Texas, United States. doi:10.1016/b978-0-323-90605-0.00001-3.

[11] Parisher, R. A., & Rhea, R. A. (2022). Valves. Pipe Drafting and Design, 87-117. Gulf Professional Publishing, Texas, United States. doi:10.1016/b978-0-12-822047-4.00007-8.

[12] Stewart, M. (2016). Fluid flow and pressure drop. Surface Production Operations, 343–470. Gulf Professional Publishing, Texas, United States. doi:10.1016/b978-1-85617-808-2.00006-7.

[13] Zheng, X., Hu, F., Wang, Y., Zheng, L., Gao, X., Zhang, H., You, S., & Xu, B. (2021). Leak detection of long-distance district heating pipeline: A hydraulic transient model-based approach. Energy, 237, 121604. doi:10.1016/j.energy.2021.121604.

[14] Liu, B., Gao, R., Du, X., Wang, Y., Shang, Y., Zhang, Y., Zhao, K., & Li, A. (2022). Study on a check valve for air ducts with a nonmobile guide vane based on a random forest model. Building and Environment, 219, 109243. doi:10.1016/j.buildenv.2022.109243.

[15] Zhang, G., Wang, W. W., Wu, Z. Y., Chen, D. S., Kim, H. D., & Lin, Z. (2023). Effect of the opening degree on evolution of cryogenic cavitation through a butterfly valve. Energy, 283, 128543. doi:10.1016/j.energy.2023.128543.

[16] Lu, H., Xi, D., & Qin, G. (2023). Environmental risk of oil pipeline accidents. Science of the Total Environment, 874, 162386. doi:10.1016/j.scitotenv.2023.162386.

[17] Xi, D., Lu, H., Fu, Y., Dong, S., Jiang, X., & Matthews, J. (2023). Carbon dioxide pipelines: A statistical analysis of historical accidents. Journal of Loss Prevention in the Process Industries, 84, 105129. doi:10.1016/j.jlp.2023.105129.

[18] Liang, Q., Peng, C., & Li, X. (2023). A multi-state Semi-Markov model for nuclear power plants piping systems subject to fatigue damage and random shocks under dynamic environments. International Journal of Fatigue, 168, 107448. doi:10.1016/j.ijfatigue.2022.107448.

[19] Yan, Y., & Chai, M. (2020). Sealing failure and fretting fatigue behavior of fittings induced by pipeline vibration. International Journal of Fatigue, 136, 105602. doi:10.1016/j.ijfatigue.2020.105602.

[20] Li, H., Liu, J., Wu, J., Xu, Z., Zhang, X., Zhang, L., & Li, Z. (2021). Grouting sealing method of flow-control speed-down in karst pipelines and its engineering application. Tunnelling and Underground Space Technology, 108, 103695. doi:10.1016/j.tust.2020.103695.

[21] Alexandrov, I. A., Muranov, A. N., & Mikhailov, M. S. (2021). Development of an Algorithm for Automated Evaluation of the Operability of Structural Elements of Shut-off Valves. Proceedings of the 2021 IEEE International Conference, Quality Management, Transport and Information Security, Information Technologies, 257–261. doi:10.1109/ITQMIS53292.2021.9642718.

[22] Tatarkanov, A. A., Alexandrov, I. A., Mikhailov, M. S., & Muranov, A. N. (2021). Algorithmic Approach to the Assessment Automation of the Pipeline Shut-Off Valves Tightness. International Journal of Engineering Trends and Technology, 69(12), 147–162. doi:10.14445/22315381/IJETT-V69I12P218.

[23] Zuev, M., Tatarkanov, A. A., Ivanov, N. Z., Mikhailov, M. S., & Muranov, A. N. (2022). Multiphysics Process Simulation in the Working Area of the Plasma Unit of the Multicomponent Nanocomposite Coating Plant. International Journal of Engineering Trends and Technology, 70(5), 317–327. doi:10.14445/22315381/IJETT-V70I5P235.

[24] Kyriakopoulos, G. L., Aminpour, Y., Yamini, O. A., Movahedi, A., Mousavi, S. H., & Kavianpour, M. R. (2022). Hydraulic performance of Howell–Bunger and butterfly valves used for bottom outlet in large dams under flood hazards. Applied Sciences, 12(21), 10971. doi:10.3390/app122110971.

[25] Hong, B., Li, Y., Li, Y., Gong, J., Yu, Y., Huang, A., & Li, X. (2023). Numerical simulation of solid particle erosion in the gas-liquid flow of key pipe fittings in shale gas fields. Case Studies in Thermal Engineering, 42, 102742. doi:10.1016/j.csite.2023.102742.

[26] Deng, H., Liu, Y., Li, P., Ma, Y., & Zhang, S. (2018). Integrated probabilistic modeling method for transient opening height prediction of check valves in oil-gas multiphase pumps. Advances in Engineering Software, 118, 18–26. doi:10.1016/j.advengsoft.2018.01.003.

[27] Li, W., Zhang, H., & Qu, W. (2021). Stress response of a straight hydraulic pipe under random vibration. International Journal of Pressure Vessels and Piping, 194, 104502. doi:10.1016/j.ijpvp.2021.104502.

[28] Zhang, H., Qin, M., Liao, K., Wang, K., & He, G. (2021). Pipe-soil vibration characteristics of natural gas pipelines during the pigging process. Journal of Natural Gas Science and Engineering, 95, 104148. doi:10.1016/j.jngse.2021.104148.

[29] Kim, N. S., & Jeong, Y. H. (2021). An investigation of pressure build-up effects due to check valve's closing characteristics using dynamic mesh techniques of CFD. Annals of Nuclear Energy, 152, 107996. doi:10.1016/j.anucene.2020.107996.

[30] Mukataeva, Z., Dinmukhamedova, A., Kabieva, S., Baidalinova, B., Khamzina, S., Zekenova, L., & Aizman, R. (2023). Comparative characteristics of developing morphofunctional features of schoolchildren from different climatic and geographical regions. Journal of Pediatric Endocrinology and Metabolism, 36, 158-166. doi:10.1515/jpem-2022-0474.

[31] Jason, D. D., Fripp, M. L., & Dejesus, O. (2013). Method and apparatus for controlling fluid flow using movable flow diverter assembly. Patent US8616290B2. Available online: https://patents.google.com/patent/US8616290B2/en (accessed on June 2023).

[32] Dirk, S., & Kopp, R. (2007). Service friendly valve for firefighting systems. Patent US20090001309A1. Available online: https://patents.google.com/patent/US20090001309 (accessed on June 2023).

[33] NBS Co Ltd. (2017). A butterfly valve. Kazuhiro C/O Nbs Co. Ltd. Miyairi, Patent EP2751454B1. Available online: https://patents.google.com/patent/EP0459509B1/en (accessed on June 2023).

[34] Dalluge, P. R., & Davis, L. O. (2015). Floating ball valve seal with bellows and c-seal. Patent US8720854B2. Available online: https://patents.google.com/patent/US20110266482A1/en (accessed on June 2023).

[35] Nowell, M. S., Foster, K. J., May, M. E., & Ayres, B. S. (2017). Sealing high pressure flow devices. Patent US10288178B2. Available online: https://patents.google.com/patent/US10591070B2 (accessed on June 2023).

[36] Norrman, J. (2006). Shut-off device for a pipe. Patent US20080121298A1. Available online: https://patents.google.com/patent/US20080121298A1/en (accessed on June 2023).

[37] Semenov, A. B., Kutsbakh, A. A., Muranov, A. N., & Semenov, B. I. (2019). Metallurgy of thixotropic materials: The experience of organizing the processing of structural materials in engineering Thixo and MIM methods. IOP Conference Series: Materials Science and Engineering, 683, 012056. doi:10.1088/1757-899X/683/1/012056.

[38] Zimmerman, S. D., Lukashenko, Y. L., Brusnitsyn, N. A., Kudinov, L. A., & Lukanov, V. M. (2004). Rotary check valve Patent RU2217638C2. Available online: https://www.patentguru.com/RU2217638C2 (accessed on June 2023).