Development of methods and equipment for bellows assemblies testing under hydrostatic pressure

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Abstract. The paper presents a new bellows assemblies test method for stop and safety valves. To create the real conditions it is suggested testing under external hydrostatic pressure, which is available in the piping system. A designed test apparatus allows testing of the bellows under the effect of external hydrostatic pressure. The paper describes the design of the apparatus, its specifications and the test procedures.

1. Introduction
Pipeline valves with a bellows seal of a spindle (stem) is widely used in engineering, shipbuilding and energy, because it has a higher specification for its reliability. However, for a number of structural and technological solutions the bellows unit does not always provide the necessary durability. Major problems occur for the valves operating under a high temperature of coolant, in the modes of above 200 °C. The traditional methods of bellows fixing on the spindle are provided by its soldering, less seam welding or mechanical crimping. These technologies are well established, fully worked out and tested in practice.

The analysis of strength and stiffness of the welded metal bellows is performed on the basis of theoretical studies, numerical modeling and direct testing. In paper [1] it was found that the main type of the bellows fracture is the stress relaxation. Then the residual capacity is confirmed as a criterion of failure of the bellows. Jha and Diwakar in [2] conducted a detailed metallurgical and chemical analysis of causes of bellows destruction in the weld zone. They established the effect of thermal stresses from welding as a typical cause of stress corrosion cracking (SCC). Wan and Wang in [3] examined the geometrical parameters of bellows for developing of the empirical relationship between the seal and the axial stiffness. They have proposed a coefficient taking into account the change in the temperature of elasticity. In paper [4] the metal bellows is modeled with the finite element method (FEM), using commercial software ABAQUS to find the optimal design parameters. The use of the design parameters of the construction allowed obtaining the product with the acceptable quality. Article [5] presents the method of determining the formation of limit diagrams and limit stress in the bellows assemblies; the data correlate well with the calculations on FEM. Thus, from the literary analysis we can conclude that there is the necessity of the direct tests of bellows assemblies and calculations by means of FEM. Only in this combination we can obtain the adequate data for new compounds of the bellows designs.

Most of the known faults are associated with the violation of bellows tightness during its operation at the high temperatures. The destruction usually takes place in the region of its connection with the
spindle or the upper flange. It can be a soldered connection or the break in the weld zone. Moreover, the widespread cause of destruction of the bellows assembly is the excess of high hydraulic pressure.

One of the major defects that are manifested in the traditional welding of the bellows assembly is skewness or offset of the bellows end with respect to the spindle or the top flange. Even a slight shift from the central axis of the bellows leads to formation of the eccentric forces of compression and reduction of the critical pressure. The effective area of the bellows, and, hence, the properties of the fatigue resistance remain constant only under the axial tension and compression, the presence of the force skew leads to the constant bending moment of loading of the bellows, which negatively affects its durability. Moreover, deep penetration of the tungsten electrode leads to significant warming of both the bellows and the spindle construction that adds to the internal thermal stresses, which reduce the need of the additional heat treatment. Current technology requires the subsequent machining of the weld that reduces the individual compounds strength.

2. Description of the problem

Most of the standards (ISO 15348: 2002 Pipework – Metal bellows expansion joints - General) intended for the bellows testing provide only a limited set of test methods. Typically, they include the tests for the uniaxial ‘tensile’ – ‘compression’ and internal pressure. In practice, the pipeline stop and safety valves with the bellows seal stem operate under high hydraulic pressure, which exerts the load effecting the bellows. When designing strength and stiffness of bellows assemblies, as a rule, the external hydraulic load is taken as dependent on the area of the pressure action, i.e. the outer area of the bellows. If the assembly is in the stretched condition, the contribution of the external pressure is considered to be minimal. Most of the methods for calculation of the long-term low-cycle bellows strength with the influence of the high temperature and the residence time under the load are based on the use of the strain-kinetic criteria. It is necessary to solve the problem of the stress-strain state of the bellows with long-term cyclic loading, as well as to obtain the data on mechanical properties of materials under these conditions. However, the analysis of these methods does not allow us to identify the conditions of the effect of the external hydraulic pressure on the strength of the bellows assembly.

3. Description of experimental equipment

A special stand was used in a classical test of bellows assemblies. It allows for the desired mode of cyclic deformation of the bellows under axial tension and compression with a given scale displacement, where in the frequency of loading composes 10–50 cycles per minute. Additionally, the bellows assembly received the excess internal pressure of 0.1 MPa. Then, the moment of destruction was recorded automatically during the pressure drop due to the leakage of the air through the cracks. Slight pressure has almost no effect on the strain state of the structure and its durability.

Thus, the experimental methods for assessing of the durability of the bellows assemblies under the external hydrostatic pressure have not been identified. The need of performance of such tests has been confirmed by us in the development of the new models of the ship stop valves. The main objective of this work is creation of instruments and methods for the bellows testing in the mode of loading uniaxial tension-compression under the external hydrostatic pressure. While doing this work, we used the existing scientific potential and experience in the development of the test benches (stands) – [6, 7].

In works [8, 9] we offered technologies allowing executing a high-quality connection of the bellows with a spindle or a basic flange due to the use of the precision laser welding and high-energy plasma processing of the surface. These technologies allow achieving a stable quality of the connection and herewith they donot cause residual (superficial) stresses.

The designed test apparatus is shown in Figure 1. Its main purpose is to test the bellows assemblies having the diameter of not more than 100 mm. The experimental test apparatus is simple to use and it does not require a special training. The basis of the experimental setup is a high-pressure chamber (position 1, Figure 1), which locks the top cover (position 5, Figure 1), that establishes an upper support flange bellows assembly. The drive spindle (position 3, Figure 1) passes through the upper cover and has mobility in the guide sleeve (position 6, Figure 1). With an adjustable mechanical drive
(position 8, Figure 1) through the eccentric shaft it is loaded by an axial force, wherein the axial deformation is controlled by the geometry of the cam-follower (position 7, Figure 1). The hydrostatic pressure on the bellows assembly is fed through the passages in the high pressure chamber; the measurement pressure method is realized by an electronic manometer. The liquid used for hydraulic loading is the industrial oil. We have done a series of tests on the bellows assemblies in order to develop the new models of the ship stop valves. The bellows material is stainless steel 316L (ISO 2604-1 F59), whereas the wall thickness of the bellows for various tests was from 0.5 to 1.0 mm. All tests were successful; the destruction of the bellows was fixed with the sufficient accuracy by the number of cycles and the amount of deformation (sweep). In all experiments the deformation of the bellows was only positive (tensile). It corresponds to a majority of the designs of the stop valves, for which the normal position is open, the bellows are not loaded by the axial force and there is only the external hydrostatic pressure.

![Figure 1](image)

*Figure 1. The apparatus of bellows testing for external pressure:*

*a* – Tested bellows assembly (diameter 65 mm, bellows length 120 mm)

*b* – 1 – the high-pressure chamber; 2 – the bellows; 3 – the spindle; 4 – the stud fastening; 5 – the camera shutter pressure; 6 – the guide bushing; 7 – the cam-follower; 8 – the drive.

4. The results of the experimental studies

In total 15 different tests of bellows were carried out, which is sufficient to assess the quality of the proposed test method and to develop the experimental apparatus. The value of the linear deformation of the bellows is ranged from 5 to 35 mm, which is consistent with real working conditions of the
bellows assembly. The external hydrostatic pressure was adjusted from 1.6 MPa to 5 MPa that also corresponds to the type series of pressures for pipes and valves for various purposes. The number of load cycles per minute was between 10 and 50 cycles, this option is recommended by a variety of standards. A higher loading rate affects critically the research process as it leads to self-heating of the bellows sample. To prevent self-heating of the bellows there should be a possibility to pump hydraulic fluid for cooling.

5. Conclusion
The tested scheme has several advantages compared with the classical ones. Firstly, it is possible to adjust the axial deformation of the bellows by changing the cam. Secondly, due to adjustment of the frequency drive it is possible to create different modes of the fatigue testing from low cyclic to cyclic ones. Thirdly, through the gauge method of the pressure measuring it is possible to control the destruction of the bellows assembly precisely. In case of the bellows destruction there is a sharp decrease in hydrostatic pressure, which is measured by an electronic manometer.

A notable result, which is associated with the change in the stress-strain state of the metal bellows using different options of its force loading, has been obtained. At normal (atmospheric) pressure, in most cases a crack is developed in the direction of the inner radii of the bellows, whereas the additional impact of external hydrostatic pressure developed cracks directed at the outer radius of the bellows. This is due to a change in the stress-strain state. Under the influence of hydrostatic pressure, the exterior elements of the bellows are compressed in the axial direction, and the tensile force on the spindle cannot establish equilibrium. Thus, it is possible to make practical recommendations aimed at increasing of the service life of the bellows assembly.

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