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Technical note

DURABILITY TESTS OF BALL VALVE PROTOTYPE WITH FLOWMETER OPERATION

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The results of the investigation of the prototypical ball valve are presented in this article. The innovation of the tested valve is a ball with a built-in measuring orifice. The valve has been subjected to durability tests. Leakage under three temperatures: ambient, *-30*°C and *+100*°C was analyzed. Sealing elements of the valve were tested for roughness and deviation of shape before and after the cycles of operation. Ball valve operation means cycles of open/close. It was planned to perform 1000 cycles at each temperature condition accordingly. Tests of the valve were performed under gas pressure equal to *10* MPa. The research was carried out under the Operational Program "Intelligent Development" (POIR 01.01.01-00-0013 / 15 "Development of devices for measurement of media flow on industrial trunk-lines".

Key words: friction, leakage, ball valve, prototype.

1. Introduction

Ball valves are commonly used in the transport of a variety of media, including water, gas, diesel oil. Their sizes start from a few millimeters to as much as *1400 mm* in diameter [1]. These valves are not only used in industry specialized in the field, but are also found in the life of ordinary people, for example, as a ball-tap. The problem arises only when the valve has to work under high pressure and high/low temperature conditions, and with an increasing diameter, the difficulty of designing such a valve increases. Additionally, depending on the valve destination, it must meet very strict requirements, for example, to maintain tightness in case of fire - the solution most commonly used in the transport of flammable fluids [2]. The simple ball valves do not have such a complicated construction, they are normally sealed with a simple PTFE seal [3], and the flow control is carried out with a handle by the control pin. This solution fully meets the tightness requirements. Valves working at high pressure, about *100* atm. and more [4], have more advanced sealing systems and their regulation requires more force and hence there are known solutions with different transmissions, electric, electrohydraulic and hydraulic-pneumatic drives. Ball valves are not control valves. They have only two working states, completely closed and completely opened. Adjustment of flow is therefore not possible. Depending on operating conditions the valves can be designed for overground and underground installation [5]. In the latter case, the control element and additional elements, including venting, must be above the surface of the earth to enable operatives to control the flow freely. Valve companies most often commit themselves to provide drive systems.

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2. Valve prototype

The functionality of the prototypical valve consists in allowing the flow rate to be measured by the orifice through the pipeline. This solution, patented by ZPDA Ostrów Wielkopolski (No: 404055) allows a replacement of the orifice without the need to dismantle the device from the pipeline and it is different from other patents (US 20090032762 A1, US 4130128 A [6, 7]). The prototype is designed as a seat supported ball valve [8].

In order to ensure accurate flow measurement, it is important to ensure tightness between the ball with orifice inside the ball channel and the housing. Good seal solution will prevent the impermissible flow between the outer surface of the ball and the housing, which could cause a poor reading of the flow rate measurement. It was decided to use a double seal (seal set) consisting of a rubber ring and a PTFE ring. Such an arrangement must ensure tightness at every position of the ball. The secondary function of the prototype is the possibility of closing the flow through the measuring device by rotating the ball inside the valve housing - the prototype acts as a valve.

With the rotation of the ball, friction resistance is generated, which can affect the choice of actuator systems.

The schematic of the tested valve is presented in Fig.1.

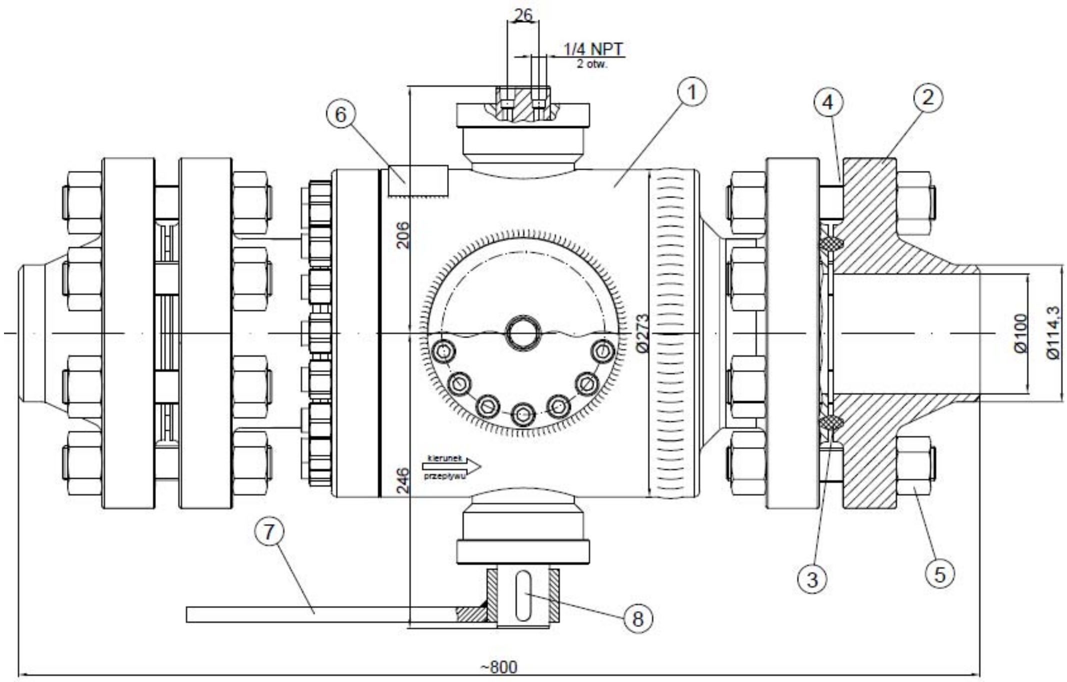


Fig.1. Prototype valve with built-in orifice, 1 – housing, 2 – flange, 3 – metal seal, 4 – bolts, 5 – nuts, 6 – rating plate, 7 – handle, 8 – stem key.

The valve parameters are the following: DN 100, PN 160. The manufacturer's description: KP100. Valve parameters demand special materials: ball - X20Cr13, stem – X6CrNiTi 18-10, valve housing P355NH, seal set housing - X6CrNiTi 18-10; they allow natural gas transportation.

3. Durability tests

The durability tests were performed in the Laboratory of Sealing Technology at the Wroclaw University of Technology. The study consisted of two procedures: making the cycles of open/close the ball channel and measurement of external and internal leakage before and after operation of the prototype. The leakage value can be treated as the level of wear of cooperating elements. Tests were carried out at ambient temperature conditions and in a temperature chamber to get lowered or elevated temperatures.

A schematic drawing of internal leakage measurement is presented in Fig.2. The examined prototype is placed in the temperature chamber. The temperature chamber provides stable conditions in the range of temperatures from -*70*°C to +*100*°C.

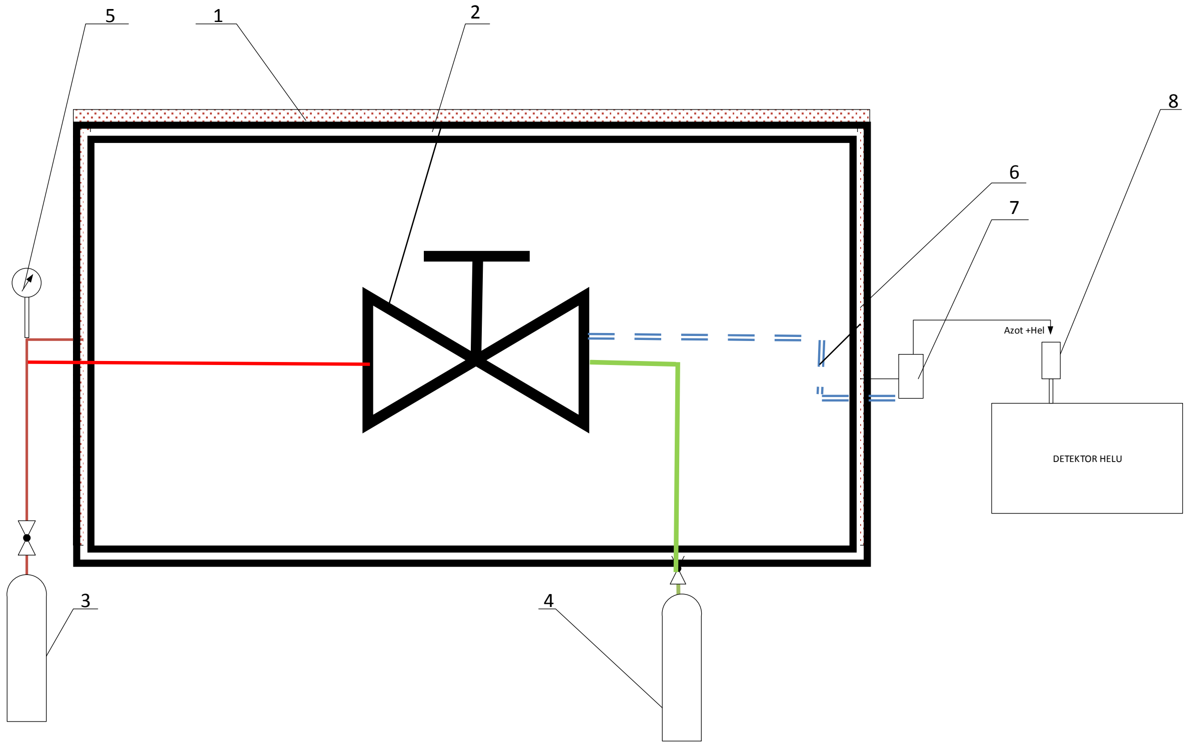


Fig.2. Schematic drawing of internal leakage measurement, 1 – temperature chamber, 2 – valve to be tested, 3 – helium gas cylinder, 4 – nitrogen gas cylinder, 5 – pressure gauge, 6 – pipe of helium-nitrogen mixture, 7 – gas mixture heater, 8 – sniffer.

An internal leakage test is carried out at the closed position of the valve prototype 2. The test chamber 1 makes it possible to set the temperature and heat or cool the object. At the outlet of one cylinder, nitrogen is supplied from the cylinder 4 (up to $15\ cm^3/min$) as an inert gas allowing removal of the helium contained within the valve chamber that has been found there after previous attempts or simply from the surroundings. From the direction of the inlet of the medium to the valve, helium with a pressure of *10* MPa was introduced from the pressure gas container 3. A leak appears in the chamber behind the ball of the valve as the nitrogen-helium mixture is sucked up by the helium detector sensor. The sample composition is analyzed in the detector continuously (Fig.3). Results are presented in a digital form as well as graphically.

Fig.3. The helium detector screen during leakage measurement.

An external leakage measurement was carried out in the same temperature chamber, however, after an application of covers insulating the stuffing box from the environment, as it is presented in Fig.4.

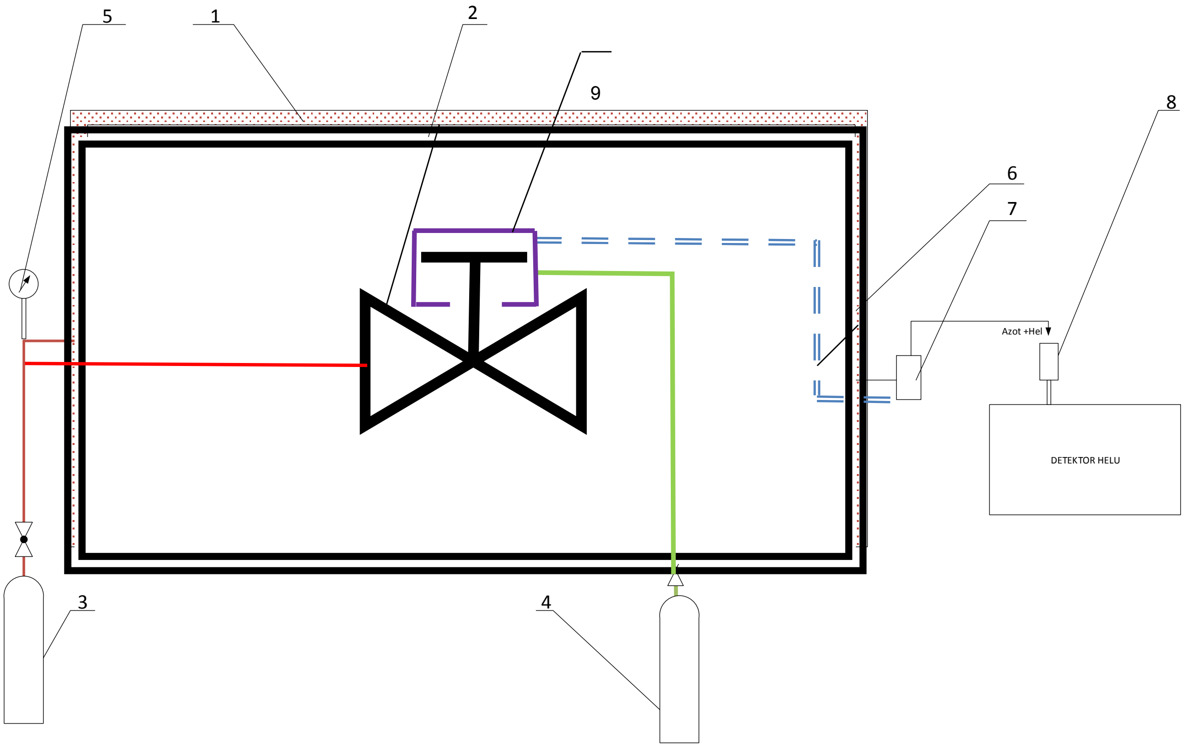


Fig.4. Schematic drawing of external leakage measurement, 1 – temperature chamber, 2 – valve to be tested, 3 – helium gas cylinder, 4 – nitrogen gas cylinder, 5 – pressure gauge, 6 – pipe of helium-nitrogen mixture, 7 – gas mixture heater, 8 – sniffer, 9 – insulating cover

The external tightness test is carried out at partially opened valve. Such position allows helium to enter the valve stems. A cover is provided on the stem to isolate the stuffing box from outside air. In this way, the gas emitted by leaks can be brought to the helium detector in the form of a nitrogen-helium mixture. After measuring the leakage on one side of the stem (connection side), the same is done on the second gland (hand side) after removing the handle.

The friction torque of the seals against the ball and the stems was measured with a (± *100 Nm*) tensometric torquemeter cooperating with the Peltron strain gauge. The torquemeter was calibrated before tests.

3.1. Test procedure

Before and after tests crucial elements of the valve were measured, i.e.: the roughness parameters of the ball and seals, the profile parameters of the cooperating elements.

Opening and closing cycles were carried out at ambient temperature (first 1000 cycles), then at -*30*°C (1000 cycles) and at (+ *100*°C). After every 1000 cycles of opening and closing of the valve, leakage and ball torque were measured. The valve was tested at a stable temperature. Leakage, as a parameter of tightness, was measured before operation at ambient temperature and after 1000 cycles. Then, leakage was measured for the valve chilled to -*30*°C and next after 1000 cycles of opening and closing of the passage (at that temperature). The leakage of the valve after heating it to + *100* ° C was measured and further measurements were made after the next 1000 cycles, but after 10 cycles of opening, the valve handle was blocked and hence continuation of the tests was not possible. It was decided to complete the research and disassembly the prototype at the company headquarters.

The method of leak measurement is proposed in the EN 15848: 2012 and in the TA-Luft-VDI 2440 standards. Helium leakage was measured with a helium detector [9].

3.2. Test results of leakage

The results of internal and external leakage measurement from the valve are shown in Tab.1. Helium pressure was equal to *10* MPa; tests were performed at ambient temperature. Results presented in Tabs 1-3 are counted in units of helium detector – the first column. In the second column, the unit of leakage is divided by the average seal length. The third column shows the values in cubic centimeters per minute. The unit mg/s×m of leakage value (forth column) was calculated for the average length of the spherical ball seal $\pi^x dk = \pi^x\ 120\ mm$ and the diameter of the stem $dt = 44\ mm$. It is possible to classify the valve in accordance with the presented units.

Table 1. Measurement results of the leakage from the valve KP 100, ambient temperature.

	Leakage mbar×l/s	Leakage mbar×l/m×s	Leakage cm^3/min	Leakage mg/s×m
Internal leakage; before tests	2.1×10^{-2}	5.5×10^{-2}	*1.2*	9.8×10^{-2}
Internal leakage; after 1000 cycles	2.8×10^{-4}	7.4×10^{-4}	1.6×10^{-2}	1.3×10^{-4}
External leakage; handle side; before tests	7.7×10^{-3}	5.5×10^{-2}	*0.45*	9.8×10^{-3}
External leakage; handle side, after 1000 cycles	4.3×10^{0}	*31.1*	*254*	*5.4*
External leakage; orifice port side; before tests	3.2×10^{-3}	2.3×10^{-2}	*0.18*	4.1×10^{-3}
External leakage; orifice port side; after 1000 cycles	9.8×10^{0}	*70.9*	*580*	*12.5*

At lowered temperature (-*30*°C) tightness tests were carried out with the same procedure.

Table 2 presents results of the measurements. Helium pressure was equal to *10* MPa.

Table 2. Measurement results of the leakage from the valve KP 100, -*30*°C.

	Leakage mbar×l/s	Leakage mbar×l/m×s	Leakage cm³/min	Leakage mg/s×m
Internal leakage; after 1000 cycles	$>1\times10^{+2}$ (*)	*>265*	*>5920*	*>46*
Internal leakage; after 2000 cycles	$>1\times10^{+2}$ (*)	*>265*	*>5920*	*>46*
External leakage; handle side; after 1000 cycles	$1.6\times10^{+1}$	*115*	*947*	*20.4*
External leakage; handle side, after 2000 cycles	$1.5\times10^{+1}$ (at *6* MPa**)	*108*	*888*	*19.1*
External leakage; orifice port side; after 1000 cycles	$2.6\times10^{+1}$	*122*	*1539*	*33.1*
External leakage; orifice port side; after 2000 cycles	$1.7\times10^{+1}$ (at *6* MPa**)	*123*	*1006*	*21.6*

(*) – leakage beyond the range of the helium detector, (**) – at *10* MPa – beyond the range of the helium detector

At elevated temperature (+*100*°C) the tests were performed following the procedure identical with the one described previously. Test results are presented in Tab.3.

Table 3. Measurement results of the leakage from the valve KP 100, +*100*°C.

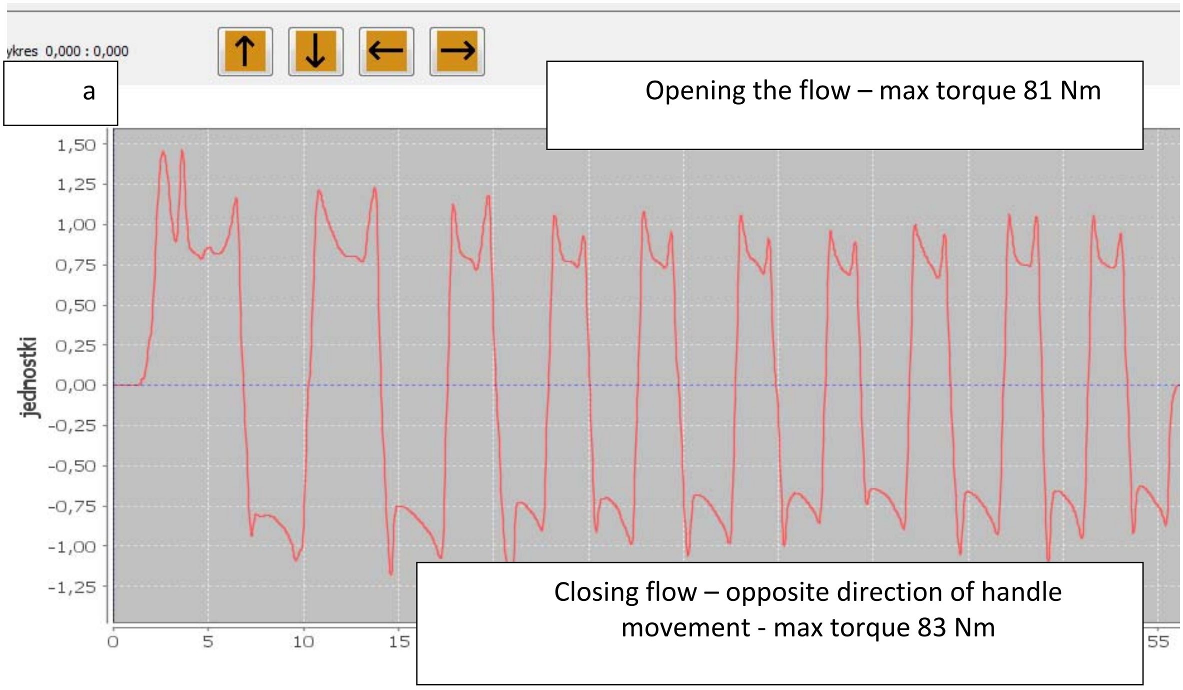
	Leakage mbar×l/s	Leakage mbar×l/m×s	Leakage cm³/min	Leakage mg/s×m
Internal leakage; after 2000 cycles	4.6×10^{-6}	1.2×10^{-5}	2.7×10^{-4}	2.1×10^{-6}
Internal leakage; after 3000 cycles	Not measured	-	-	-
External leakage; handle side; after 2000 cycles	$1.1\times10^{+1}$ (at 6 MPa**)	*79.6*	*651*	*14.0*
External leakage; handle side, after 3000 cycles	Not measured	-	-	-
External leakage; orifice port side; after 2000 cycles	$2.2\times10^{+1}$ (at 6 MPa**)	*159*	*1302*	*28.0*
External leakage; orifice port side; after 3000 cycles	Not measured	-	-	-

(**) – at *10* MPa – beyond the range of the helium detector.

4. Open/close torque measurement

Torque measurement at ambient temperature without pressure was conducted to check the range of friction values.

Figure 5 shows a screenshot of the change of the torque value during opening and closing of the valve.



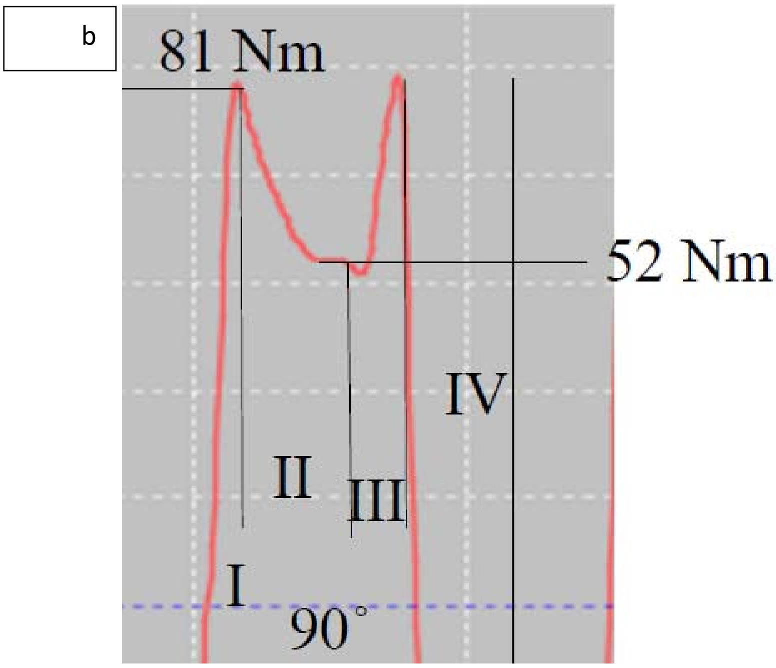


Fig.5. Friction torque diagram open/close, without pressure; a) first 9 cycles for the new prototype, b) analysis of friction zones.

The maximum torque required to turn the ball was *83 Nm*. Then, as it rotated, the friction resistance decreased to *50 Nm*. Four zones can be distinguished in one cycle (Fig.5b). Zone I – shows the transition from static friction to dynamic friction. Zone II is the change of torque value during ball rotation. Zone III presents the end of rotation, and zone IV – the change of force direction.

In the absence of pressure, the characteristics show the total friction resistance due to the friction of the seals of the ball and the sealing ring on the stem.

After filling the closed valve with gas at pressure *10* MPa, it was not possible to rotate the ball in the valve with the prepared torque gauge, as the torque was greater than allowed for the gauge. Consequently, a Zemic Load Force sensor was used to measure the torque mounted on the arm of known length.

Figure 6 presents the friction torque change during the valve opening at gas pressure equal to *10* MPa for the prototype.

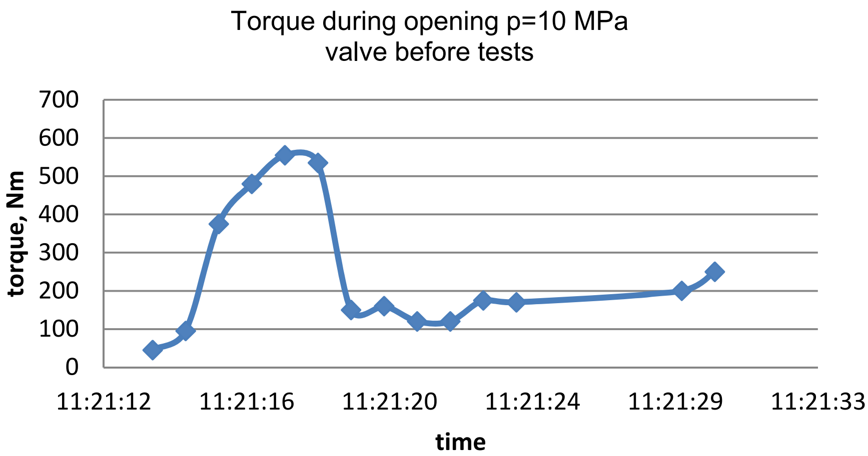


Fig.6. Friction torque change in the valve for the first opening at pressure *10* MPa; ambient temperature.

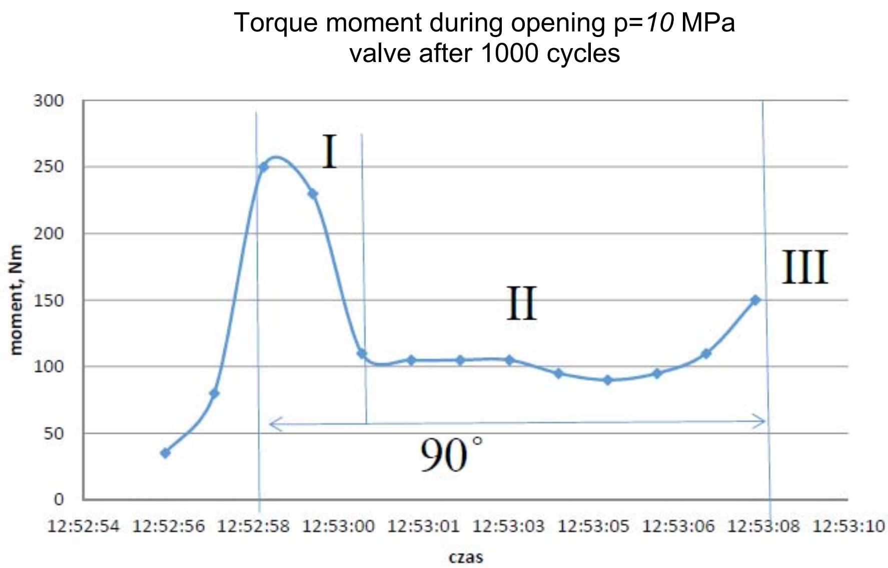


Fig.7. Friction torque analysis during the valve opening after 1000 cycles at pressure *10* MPa; ambient temperature.

The torque necessary to rotate the ball was *550 Nm* during the first opening of the valve. During the opening process (the start of flow through the ball) there was a pressure drop, and therefore the frictional resistance decreased to about *150 Nm*. The increase in torque at the end of the curve was due to reaching the extreme position. During the next openings the maximum torque required to turn the ball was *250 Nm*. Then, during its rotation, the friction resistance decreased to *100 Nm*. The opening process can be divided into 3 zones (Fig.7). Zone I – shows the value of the moment of transition from static friction to sliding friction until the gas flows from one side of the ball to the other. Zone II – further opening with the flow of the medium, changes in gas pressure and the change of pressure on the seal on the inlet side. Zone III – reaching the dead point. The fluid pressure moves the seal and presses it against the ball on one side. At the same time the pressure on the stem is increased. The maximum torque required to rotate the new ball valve is *320 Nm* when opening the flow. Then, as it rotates, the friction resistance decreases to *170 Nm*. When closing the valve at medium flow, the torque is *190 Nm* to *240 Nm*. The pressure value on both sides of the ball is similar. The ball on both sides is clamped with seals. The maximum torque required to turn the ball after 1000 cycles is *210 Nm* during opening. Then, as the ball rotates, the friction resistance decreases to *140 Nm*. When the valve is closed at medium flow, the torque value is *170 Nm* (transition from static friction to sliding friction). The pressure value on both sides of the sphere is similar. The ball on both sides is sealed with seals, but the stem is relieved.

Measurement at -30°C

After tests at ambient temperature the valve was chilled in the temperature chamber. The tested valve is after 1000 cycles of operation. In this way, the initial state is defined before proceeding with further tests. The change of friction force at chilled temperature is presented in Fig.8 (before cold tests). Gas pressure was equal to *10* MPa.

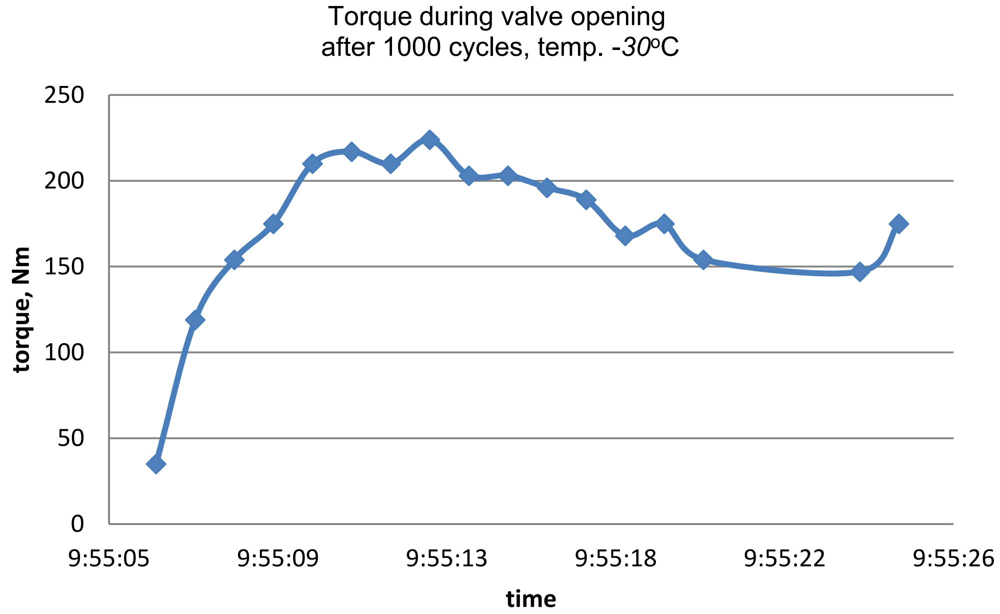


Fig.8. Friction torque change during the valve opening after 1000 cycles at pressure *10* MPa; -*30*°C.

The torque necessary to move the ball was *240 Nm* at the first opening of the valve at sub-zero temperatures. At the beginning of the flow through the ball due to the pressure drop, the friction resistance decreased to approximately *140 Nm*. The maximum torque required to turn the ball was *380 Nm*. Then, as it rotated, the friction resistance decreased to *145 Nm*. Leakage and opening torque measurements were made the next day after overnight cooling. After 1200 cycles, i.e., after 200 cycles of chilled valve testing, the torque needed to open the valve was between *150-250 Nm*. After 1400 cycles it changed from *150* to *220 Nm*, followed by 200 cycles of *180-130 Nm*, after the next 200 cycles the torque increased and reached *120-220 Nm*. After 2000 cycles, i.e. 1000 cycles of chilled valve operation at medium flow of at *-30*˚C, the torque range was *100-170 Nm*.

Measurement at +100°C

After tests at chilled temperature the valve was heated in the temperature chamber. The tested valve is after 2000 cycles of operation. In this way, the initial state is defined before the next stage of the tests. The change of the friction force at elevated temperature is presented in Fig.9 (before hot tests). Gas pressure was equal to *10* MPa.

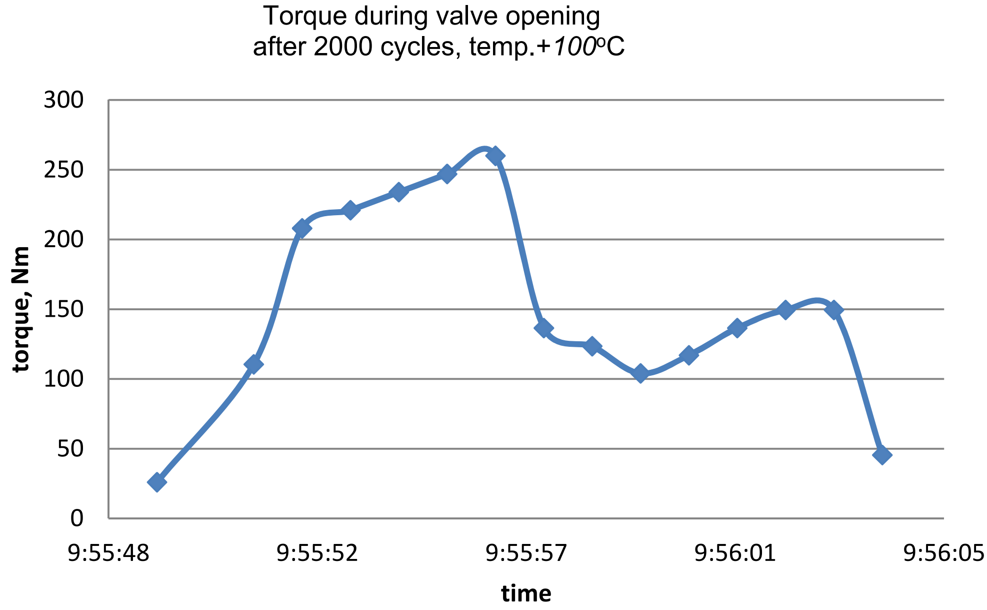


Fig.9. Friction torque change during the valve opening after 2000 cycles at pressure *10* MPa; +*100*°C.

The maximum torque required to open the hot valve was *260 Nm*, and during the gas flow the torque value was reduced to *100 Nm*. The opening and closing cycles of the valve were then performed. The torque value necessary to open the heated valve was in the range of *220-160 Nm*.

5. Roughness measurements

In order to complete the data needed for the analysis of the valve prototype, ball roughness was measured in four locations at the perimeter before and after operation. Measurements of the PTFE seal cooperating with the ball from inlet side were taken. The common profile of the sealing set cooperating with ball was made.

5.1. Ball roughness

The ball surface as an element that cooperates with the sealing set wears out. The frictional pair consisted of a steel ball (2H13, X20Cr13 hardened 800 HV), and sealing set: the sealing ring was made of 90 IHRD hardness rubber and a PTFE ring. The roughness measurements were made according to the diagram in Fig.10.

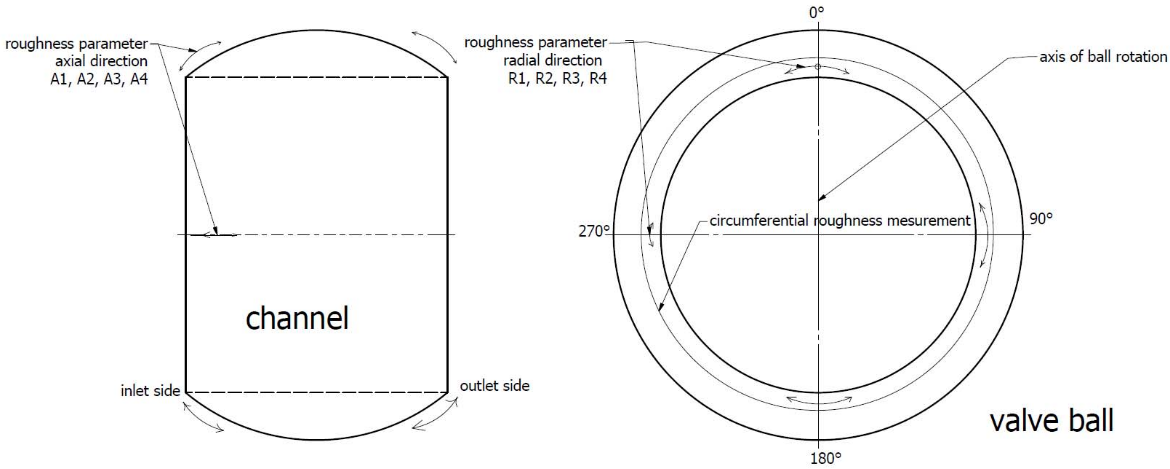


Fig.10. The directions of the ball roughness measurement.

The data of Ra, Rz and Rmax of radial ball roughness measurements are presented in Tab.4. The Ra and Rz of axial ball roughness measurements are presented in Tab.5.

Table 4. Roughness measured on the periphery of the ball before and after operation – radial direction.

	Ra, *mm*		Rz, *mm*		Rmax, *mm*	
	before	after	before	after	before	after
Position 0˚	*0.68*	*0.46*	*6.59*	*2.72*	*8.50*	*3.95*
Position 90˚	*0.42*	*0.58*	*3.73*	*4.02*	*4.31*	*5.86*
Position 180˚	*0.54*	*0.88*	*4.88*	*4.96*	*5.85*	*7.75*
Position 270˚	*0.51*	*0.72*	*4.37*	*3.60*	*5.70*	*4.80*
Roughness in circumferential direction	*0.54*	*0.59*	*11.14*	*8.26*	*13.84*	*11.34*

The ball circumferential roughness profile is presented in Fig.11.

a) b)

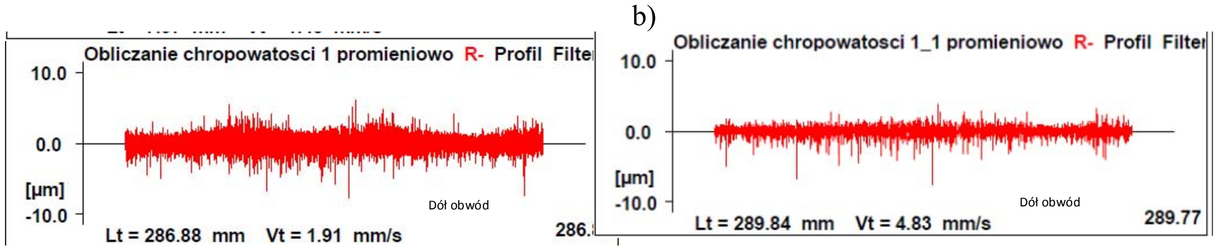


Fig.11. Profile of the circumferential ball roughness; a) before and b) after operation.

Table 5. Axial roughness parameters of the valve ball measured before and after cycles.

	Ra, *mm*		Rz, *mm*	
	before	after	before	after
Position 1	*0.61*	*0.54*	*6.30*	*3.72*
Position 2	*0.64*	*0.40*	*5.16*	*4.25*
Position 3	*0.61*	*0.61*	*4.50*	*5.86*
Position 4	*0.57*	*0.54*	*4.65*	*4.16*

5.2. Seal roughness

The sealing set consists of a PTFE ring supporting the ball and a rubber ring to increase tightness. The results of PTFE rings roughness measurements are shown in Tab.6.

Table 6. Roughness in radial direction measured on the periphery of the PTFE sealing ring before and after operation (inlet side).

	Ra, *mm*		Rz, *mm*		Rmax, *mm*	
	before	after	before	after	before	after
Position 0˚	*3.43*	*0.91*	*36.47*	*5.50*	*51.56*	*11.97*
Position 90˚	*0.55*	*0.66*	*5.51*	*3.25*	*10.29*	*4.31*
Position 180˚	*0.89*	*1.03*	*5.57*	*5.47*	*6.45*	*8.38*
Position 270˚	*0.71*	*0.97*	*5.68*	*5.00*	*13.47*	*8.74*
Roughness in circumferential direction	*1.40*	*0.96*	*51.59*	*31.18*	*90.97*	*56.40*

The PTFE ring radial roughness profile is presented in Fig.12.

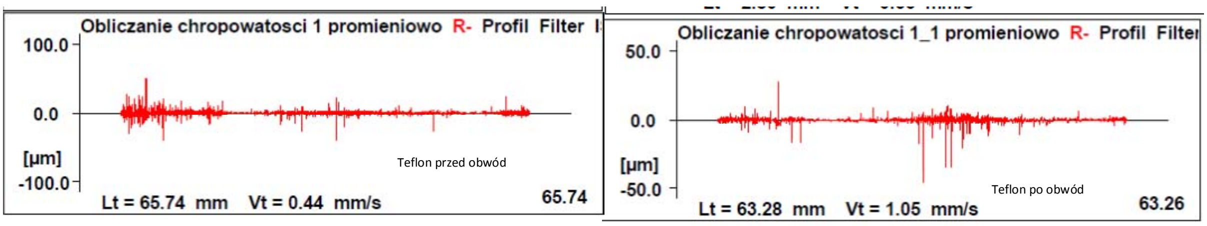


Fig.12. Profile of the PTFE ring radial roughness profile; a) before and b) after operation.

The cross-section of the sealing set is presented in Fig.13.

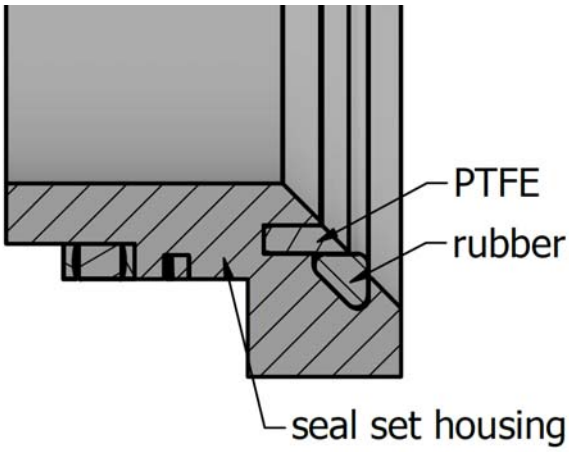


Fig.13. A part of cross-section of the PTFE and rubber ring installed in the housing.

The stylus of profilometer went axially through the seal set. The profile shapes before and after operation are presented in Fig.14.

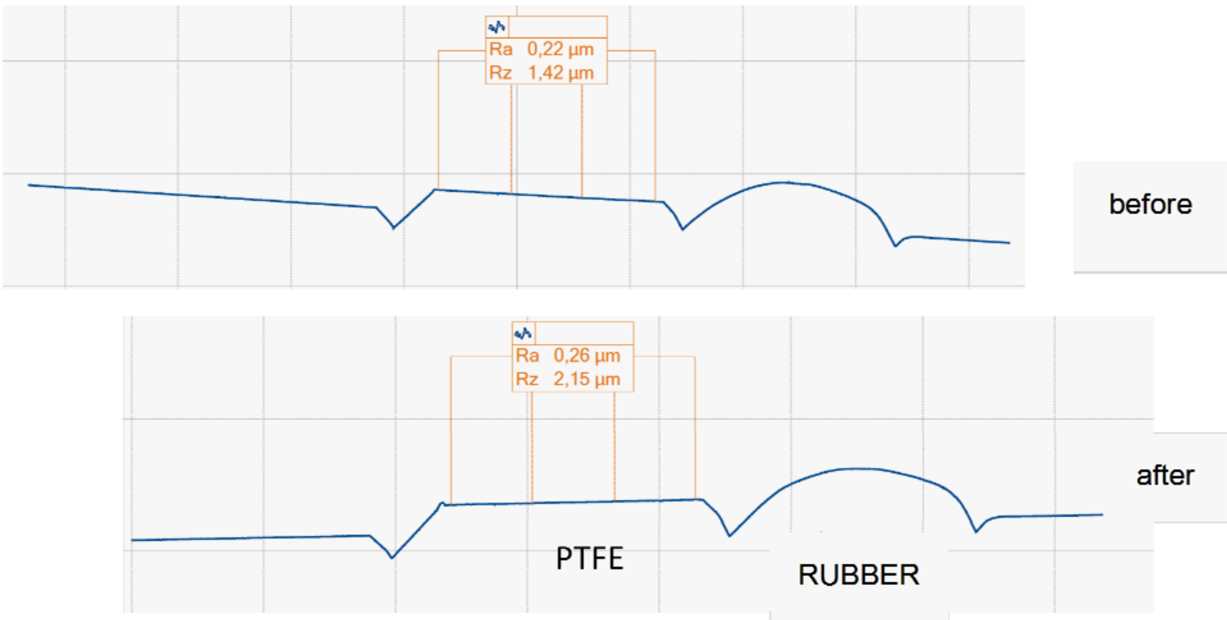


Fig.14. Profile shape before and after operation.

An analysis of the shape of the profile shows that the width of the PTFE ring has increased slightly (about *0.1 mm*) and the position of the rubber ring relative to the PTFE ring has changed. The rubber ring radius after work increased by approx. *0.2 mm*.

6. Discussion

The results of durability tests of the prototype valve were obtained with different methods. Information about leakage values, roughness profile after and before open/close cycles, torque with and without medium pressure at temperature range +*100*°C to -*30*°C provides inputs for discussion.

Internal leakage is the most important information that verifies the suitability of the valve as the flowmeter. Increased tightness after 1000 cycles at ambient temperature indicates that there is no flow between the ball and the valve housing when the channel in the ball is opened; it means that measurement uncertainty can be negligible. The higher leakage at sub-zero temperatures can be minimalized by the growth of the springs force that presses the seal set to the ball. The seal set polished the ball surface, the rubber ring additionally worked as a wiper. It allows operation of the prototype in contaminated environment.

When the valve is closed and there is a large pressure difference, a high torque value occurs. Therefore, the modification of sliding bearings supporting the stems is required.

The external leakage growth with the number of cycles was noticed. It is required to improve the design of stuffing- boxes .

7. Conclusions

The study can be summarized by the following conclusions:

1. After performing 1000 cycles at ambient temperature, the valve internal tightness increased - the use of seals pressed against the ball by springs made running-in possible
2. The leakage of the new valve stems seal from the level of 10^{-3} *mg/s·m* increased by 4 orders of magnitude to *101 mg/s·m* after 1000 cycles of opening and closing of the valve.
3. The cooling of the valve till -*30*°C, resulted in the internal leakage of *5920* cm^3/min (before operation at chilled temperature), comparing to leakage in the same valve at ambient temperature 1.6×10^{-2} cm^3/min. A change in temperature of approx. *50*°C is associated with a change in the dimensions of the elements that cooperate with one another. Dimensional analyses of the cooperating elements shall be carried out.
4. After the valve was heated to *100*°C, the internal leakage was 2.7×10^{-4} cm^3/min and was lower than at the ambient temperature (1.6×10^{-2} cm^3/min). Dimensional analyses of the cooperating elements shall be carried out.
5. The leakage through the seals of the stems at elevated temperatures is high.
6. The mean friction torque of the unloaded valve before operation was *80 Nm*, and about *50 Nm* under sliding friction conditions. This is the friction resistance resulting from the pressure of the integrated seal made of rubber and PTFE contained in the housing, and the stem seal rings friction.
7. The friction torque necessary to open the new valve before operation at ambient temperature was *550 Nm* (maximal pressure difference), and after the flow of gas from one side to the other, the friction torque was diminished to *150 Nm*. The pressure of *10* MPa on the ball from the inlet side generates the seal frictional force and causes the ball guide stems to load through the sliding sleeves.
8. The torque required for the rotation of the ball when closing the flow with equal pressure on both sides, i.e. when the friction resistance is determined by the friction of the sealing set is high, and is between *250* and *150 Nm*.
9. After 1000 cycles of operation at ambient temperature at $p=10$ MPa, the friction resistance decreased by approx. *50 Nm* on average.
10. Cooling of the valve did not cause a significant decrease in the torque value, although it can be seen that the torque value decreases with the number of cycles. Heating the valve to *100*°C also has no significant effect on the value of friction resistance.
11. An analysis of the shape of the profile shows a slight wear on the PTFE ring and the rubber profile.
12. Cooperation between the ball - PTFE is not evenly distributed on the periphery. The presented profiles show differences in the roughness on the circumference.
13. The construction of stems in sliding bearings should be changed.
14. The durability tests have demonstrated the need for comprehensive research.

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