Leakage from closed pressure relief valve caused by surface imperfections – analytical model and measurement

Wyciek z zamkniętego zaworu bezpieczeństwa spowodowany niedoskonałościami powierzchni – model analityczny i pomiary

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The article presents a way to obtain a mathematical model enabling the calculation of leakage between the steel head and the steel seat of the Pressure Relief Valve. Local contact conditions described by the roughness parameters were taken into account. To verify the mathematical model, experimental tests of valve tightness were carried out using the helium detection method. The tests were carried out in the gas pressure range from 0 to 1 MPa. The contact pressure between the head and the seat ranged from 0 to 5 MPa. The analytical model showed convergence with the experiment for the recommended values of contact pressure for the head and seat made of metal. It seems that the constructed computational model can find engineering applications due to its simplicity.

Keywords: leakage, calculations, roughness, valve

W artykule przedstawiono sposób uzyskania modelu matematycznego umożliwiającego obliczenie nieszczelności pomiędzy stalowym grzybem a stalowym gniazdem zaworu bezpieczeństwa. Uwzględniono lokalne warunki stykowe opisane parametrami chropowatości. W celu weryfikacji modelu matematycznego przeprowadzono eksperymentalne badania szczelności zaworów metodą detekcji helowej. Badania przeprowadzono w zakresie ciśnień gazu od 0 do 1 MPa. Nacisk stykowy głowicy z gniazdem wahał się od 0 do 5 MPa. Model analityczny wykazał zbieżność z eksperymentem dla zalecanych wartości docisku dla głowicy i gniazda wykonanego z metalu. Wydaje się, że skonstruowany model obliczeniowy ze względu na swoją prostotę może znaleźć zastosowania inżynierskie

Słowa kluczowe: wyciek, obliczenia, chropowatość, zawór

Acronyms

PRV – pressure relief valve
Ra – roughness average, µm
Rz – maximum peak to valley height of the profile, µm
Rmr – material ratio at a given depth, %
F_{spring} – force caused by spring, N
F_{open} – opening force, N
p_1 – inside pressure, Pa
A_{eff} – surface area of the head affected by the pressure inside the installation, m^2
p_{spring} – pressure of the head on the seat, Pa
A_{seat} – area of contact between the head and the seat, m^2
Q – volume flow, m^3/s
v – velocity, m/s
A – area, m^2
p_2 – barometric pressure, Pa
ρ – density of medium, kg/m^3
p_d – initial contact pressure, Pa
Pn – effective pressure force (force resulting from the pressure of the medium on the head), N
d – internal diameter of the contact zone, mm
D – external diameter of the contact zone, mm
D_{mean} – mean diameter of the contact zone, mm
Pu – real pressure force between head and seat after partial relief resulting from medium pressure, N
pd_{real} – seat-head contact pressure after taking into account partial relief due to medium pressure, Pa

Introduction

The safety valve (or pressure relief valve) is one of the basic elements of industrial installations, the tightness of which directly or indirectly determines the amount of pollutant emissions into the atmosphere. The safety valve opens only when the pressure in the installation increases excessively, so the normal operating state of such a valve is closed. If the medium discharge system is open to the atmosphere, such a leak cannot be negligible. Valves are responsible for 60% of fugitive emission, and pressure relief valves (PRV) – for 15% [1]. In the case of valves, the main path of leakage is the stem seal, while in the case of PRV, the source of leakage is located in the seat-head contact. A possible situation described by document

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EPA-453 R95 [2] when a leakage from safety valves occurs is the improper reseating of the valve after its activation and another one is operation at a pressure too close to the opening pressure. The tightness depends on the local contact conditions between the head and the seat. The type of valve considered was a full-lift angle spring safety valve with flanged ends and a metallic head and seat. Since the head and the seat are made of steel, their surface topography on a micro-scale depends on the surface treatment technology. Roughness and waviness have a basic influence on contact parameters of surfaces, especially metallic [3]. When examining the contact of two rough surfaces, it is essential to understand the meaning of the profile roughness parameters like amplitude parameters, spacing parameters, hybrid parameters, curves and related parameters, and also areal parameters like height parameters, spatial parameters, hybrid parameters, miscellaneous parameters, functions and related parameters [4].

One can find many mathematical models of rough surfaces contact. The typical approach is to use simplifications to enable the creation of a mathematical description and subsequent numerical calculations. It enables to examine of the relationship between the deformation of the contacting surfaces, determined by the applied spring force, and the resulting micro-flow of gas through any existing gaps, ultimately leading to overall leakage [3, 5]. Through industry experience and metrology measurements, it was determined that the main factor contributing to leakage is the form of the surface (waviness), rather than its roughness [6]. Channels created by surface irregularities under load, partly elastically and partly plastically deformed, constitute the medium flow path. The problem of metal to metal in a ball valve with metallic sealing was studied in [7]. The simulation with/without considering plastic effects is presented and verified by the experiment. The results indicate that the magnification-based model, with the consideration of plastic effects, can provide a better coincidence with experimental results. The study [8] contributes to a better understanding of the sealing mechanism of metallic ball seat valves and provides a reliable method for calculating fluid leakage using anisotropic surfaces. The obtained results provide information about the maximum leakage at a certain liquid pressure. The problem of the evaluation of gas leakage in metallic sealing surfaces with annular morphology is described in [9]. The analysis involves the use of anisotropic rough surfaces to assess the contact between the sealing surfaces. By analyzing the contact model, the leak channels are identified and then used in gas slip nanofluidic simulations to quantify the leakage. Finally, the evaluation is validated through leakage experiments. The publication [10] presents a simulative investigation of how surface roughness and geometry affect the sealing contact in pneumatic applications. The research [11] enables an understanding of the sealing mechanism of metallic ball seat valves. The surface scans of the investigated seats provide data on the contact area and roughness, which is used in the simulations performed using the finite element method. The paper [12] presents the model of predicting the leakage rate of tubing and casing premium connections quantitatively. The results of the study indicate that the average contact pressure, circumferential leakage width, and radial average leakage height between sealing surfaces are non-uniformly distributed. Furthermore, the leakage rate of a premium connection decreases exponentially as the radial interference between sealing surfaces increases. Hence, to minimize leakage, it is advantageous to increase the radial interference and reduce the roughness of the sealing surfaces.

The authors of the article attempted to estimate the leakage through the head-seat system in a closed position using a computational method taking under consideration the roughness parameters of contacting surfaces and carried out experimental verification of the obtained calculations.

Methodology

Background of the problem

The tightness of safety valves in closed position is related to the pressure of the head with the seat (Fig. 1).

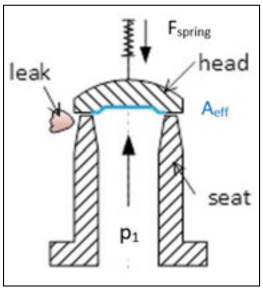

Fig.1. Leakage from the safety valve when the system pressure is lower than the limit
Rys.1. Wyciek z zaworu bezpieczeństwa przy ciśnieniu niższym od granicznego

A closed safety valve does not mean that the medium pressure inside the installation or vessel does not leak to the outside.

Leakage may occur because the spring force F_{spring} of the head pressure on the seat is limited by the opening force F_{open}.

$$F_{open} = p_1 \cdot A_{eff} \qquad (1)$$

Where:
p_1 – pressure inside the installation, Pa
A_{eff} – the surface area of the head affected by the pressure inside the installation, m^2

The pressure force of the head against the seat is constant, and if we divide this force by the area of contact between the head and the seat, we obtain the contact pressure of the head on the seat:

$$p_{spring} = F_{spring}/A_{seat} \qquad (2)$$

The seat-to-head contact area can be calculated as follows:

$$A_{seat} = \frac{\pi}{4} \cdot \left(De^2 - Di^2\right) \qquad (3)$$

Where:
De – external diameter of seat-to-head contact area, m
Di – internal diameter of seat-to-head contact area, m

Leakage in the steel head – steel seat connection in a safety valve requires the use of a leakage model that takes into account the pressure of the head against the seat by the spring and the impact of the medium pressure on the valve seat.

Analytical model of internal leakage

Continuity equation from which the leak volume flow can be calculated:

$$Q = v \cdot A \qquad (4)$$

Where:
Q – volume flow, m^3/s
v – velocity, m/s
A – area, m^2

One can find following equation for gas velocity, consistent with the formula for flow through the orifice with a hole approaching to 0:

$$v = \sqrt{\frac{2(p_1 - p_2)}{\rho}} \qquad (5)$$

Where:
p_1 – pressure inside the valve, Pa
p_2 – barometric pressure, Pa
ρ – density of medium, kg/m^3

When analyzing the surface layers of the head and the roughness of the valve seat, the interesting linear parameters are: Ra and Rz. Fig.2 presents the exemplary results of the roughness measurement of the valve head surface layer.

Ra (roughness average) measures the deviation of a surface from a mean height within the evaluation length. Rz (mean roughness depth) is the average of the maximum peak-to-valley depths within the

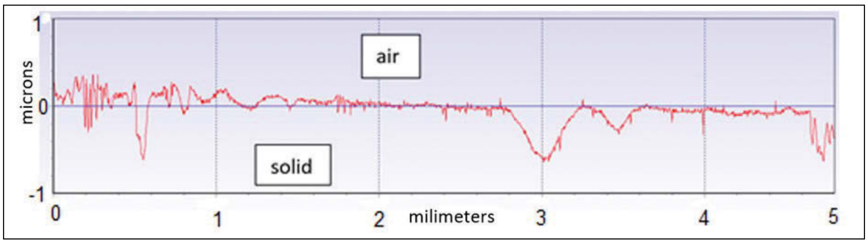

Fig.2.
Profile of the valve head
Rys.2. Profil grzybka zaworu

evaluation length. Rmr (relative material ratio at given depth) gives the percentage of material cut at a given depth from the top of the profile.

Additionally, important information about the surface layer is the material proportion of the roughness profile (Abott-Firestone curve) as the ratio of roughness peaks to roughness valleys. It is the most suitable method for estimating the surface capacity (load). For exemplary profile (fig. 2) Abott's curve is presented in Fig. 3.

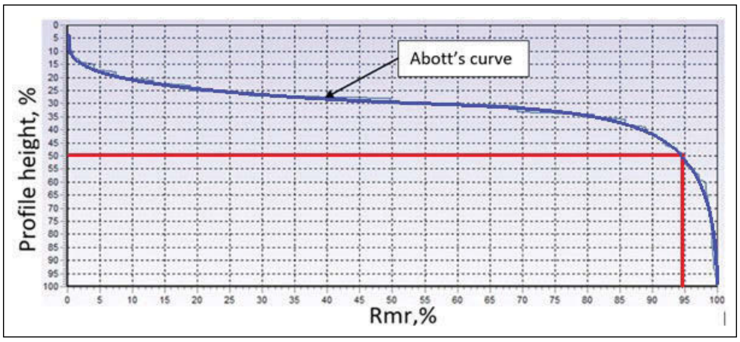

Fig.3.
Roughness profile load curve
Rys.3. Profil chropowatości i krzywa nośności

Rmr of the valve hear layer is equal to 94.7%. It means that the surface layer of the valve head has a small number of roughness valleys (5.3%) in relation to the number of peaks.

Contact between solids materials looks like in Fig. 4.

The actual contact areas and actual channel widths can only be approximate. There is no information about real contact, which should be treated as random.

The model assumes that the channels obtained between the peaks depend on Rz parameters of both valve head and seat roughness profiles and the profile load.

Having this model (Fig.4) of solid surfaces contact one can see that some valve roughness head peaks contact with roughness peaks of the valve seat directly and peaks slope and fill the spaces between the peaks called channels. The cross-section of the channels will decrease as the contact pressure increases. Then some roughness peaks will close the channels created between them, reducing leakage.

It seems that the size of the channels is mainly determined by the height between the roughness peak and roughness valley described as Rz parameter. The second parameter is the density (number) of channels which is described by the material proportion of the roughness profile (Abott-Firestone curve). Estimation of the number of channels and their total cross-section at the interface between the valve seat and valve head is the aim of this scientific work. Fig. 5 shows a part of the valve covering the seat with the head.

It has been proposed that the estimated total area of the channels is:

$$A = D_{mean} \cdot (R_{z(head)} + R_{z(seat)}) \\ ((1 - Rmr_{head}) \cdot (1 - Rmr_{seat})) \qquad (6)$$

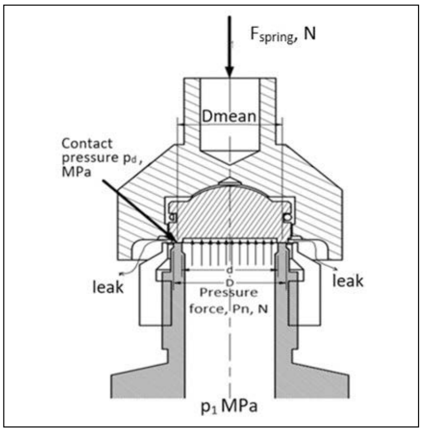

Fig.5.
A part of valve with seat and head; Pn – effective pressure force (force resulting from the pressure of the medium on the head), N; F_{spring} – spring force, N; d – internal diameter of the contact zone, mm; D – external diameter of the contact zone, mm; D_{mean} – mean diameter of the contact zone, mm; p_d – initial contact pressure in the contact zone between head and seat, MPa; p_1 – internal pressure MPa.
Rys.5. Fragment zaworu z gniazdem i grzybem, Pn – efektywna siła nacisku (siła pochodząca od medium działającego na grzyb), N; F_{spring} – siła sprężyny, N; d – średnica wewnętrzna obszaru styku, mm; D – średnica zewnętrzna obszaru styku, mm; D_{mean} – średnica średnia obszaru styku, mm; p_d – wstępny nacisk stykowy w obszarze styku między grzybem i gniazdem, MPa; p_1 – ciśnienie wewnętrzne MPa

where:
Rz – maximum height of profile, μm
Rmr – material ratio of the profile, %

The model of leakage through the head and seat in contact is as follows:

$$Q = \sqrt{\frac{2(p_1 - p_2)}{\rho}} \cdot (R_{z(head)} + \\ + R_{z(seat)})(D_{mean} \cdot \\ \cdot (1 - Rmr_{head}) \cdot (1 - Rmr_{seat})), \; {m^3}/{s} \qquad (7)$$

Tested object

In Fig.6 there is presented the balanced safety valve to be investigated. In this solution the valve seat and the valve head are interchangeable for research.

Scheme of test rig is shown in fig. 7. The helium with a known pressure valve it

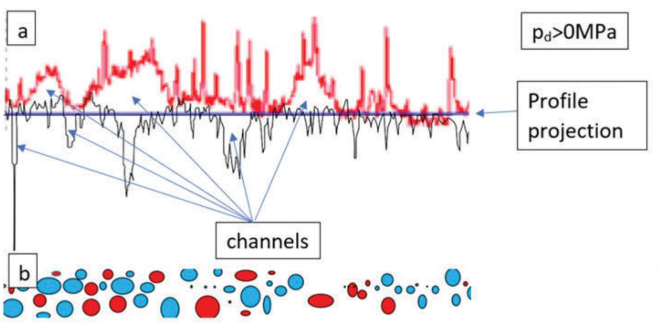

Fig.4.
Example of a solid contact with high load capacity shown in the cutting plane. Red figures – peaks of valve heads, blue figures – peaks of the valve seat, white areas – channels between cut roughness peaks, a) part of profiles under contact pressure, b) profiles cross-section under contact pressure
Rys.4. Przykład styku z dużym współczynnikiem obciążenia (naciskiem) pokazanym na płaszczyźnie przekroju. Czerwone obszary – wierzchołki grzyba zaworu, niebieskie obszary – wierzchołki gniazda zaworu, białe obszary – kanały pomiędzy przeciętymi wierzchołkami nierówności, a) część profilu pod naciskiem, b) przekrój profili pod naciskiem

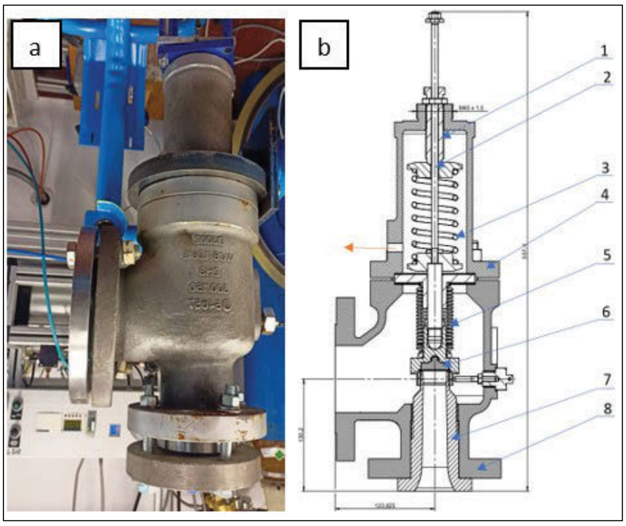

Fig.6.
Model of balanced safety valve design 2H3 300/150, a) overall view, b) cross-section; 1 – regulation screw, 2 – valve stem, 3 – spring, 4 – cap, 5 – bellows, 6 – valve head, 7 – screw-in valve seat, 8 – body;
Rys.6. Model zaworu bezpieczeństwa 2H3 300/150 a) widok ogólny, b) przekrój; 1 – śruba regulacyjna, 2 – trzpień zaworu, 3 – sprężyna, 4 – pokrywa, 5 – mieszek, 6 – grzyb zaworu, 7 – wkręcane gniazdo zaworu, 8 – korpus;

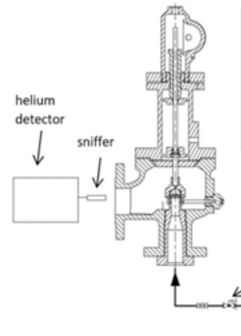

Fig.7.
Leakage measurements test rig
Rys.7. Stanowisko do pomiaru wycieku

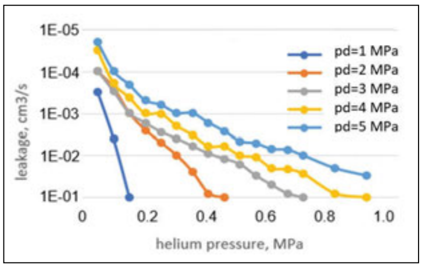

Fig.8.
Leakage curves – valve head contact pressure on valve seat p_d=1 MPa, p_d=2 MPa, p_d=3 MPa, p_d=4 MPa and p_d=5 MPa.
Rys.8. Krzywe wycieku – nacisk stykowy grzyb gniazdo p_d=1 MPa, p_d=2 MPa, p_d=3 MPa, p_d=4 MPa and p_d=5 MPa.

pressed under the valve head. Leak is collected using the sniffer of helium detector.

Roughness measurements

The roughness of the head and seat was measured in three places in the circumferential direction. Tightness research was conducted for hardened head and hardened seat. They were grounded and lapped, made with X2 steel.

Mean value of valve seat roughness measured in three places are: Ra= 0.048 μm, Rz=0.452 μm and Rmr=71.2%.

Mean value of valve seat roughness measured in three places are: Ra= 0.053 μm, Rz=0.563 μm and Rmr=70.6%.

Roughness measurements

Leakage tests were carried out for contact pressure p_d of valve head on seat equal to 1 MPa, 2 MPa, 3 MPa, 4 MPa and 5 MPa. Helium pressure p_1 acting on the valve head ranged from 0.05 MPa to the pressure at which the leak increased above the range of the helium detector.

Fig. 8 presents the closure tightness of the valve measured in accordance with the adopted procedure: set contact pressure p_d, helium pressure stabilized and after 2 minutes leakage measurement. Next step is helium pressure increase and its stabilization under valve head.

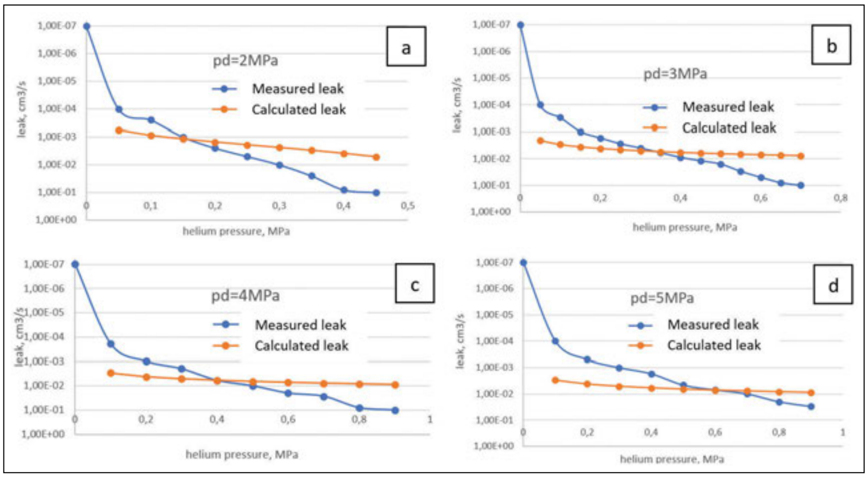

Fig.9.
Leakage curves – valve head contact pressure on valve seat p_d = 2 MPa (a), p_d = 3 MPa (b), p_d = 4 MPa (c), p_d = 5 MPa (d)
Rys.9. Krzywe wycieku – nacisk stykowy grzyb gniazdo p_d=2 MPa (a), p_d=3 MPa (b), p_d=4 MPa (c), and p_d=5 MPa (d)

Leakage calculation and comparison with the experiment

For the adopted leakage model:

$$Q=\sqrt{\frac{2\left(p_1-p_2\right)}{\rho}}\cdot\left(R_{z(head)}+\right.$$
$$\left.+R_{z(seat)}\right)\left(D_{mean}\cdot\right.$$
$$\left.\cdot\left(1-Rmr_{head}\right)\cdot\left(1-Rmr_{seat}\right)\right),\ {m^3}/{s}$$

Average (mean) values of profile roughness Rz and material ratio of the profile Rmr presented in Tables 1 and 2 were taken into account for calculations. Pressure p_1 means the helium stabilized pressure actual value, p_2 – atmospheric pressure

In Fig. 9 are presented measured and calculated values of the leakage.

Results

– roughness parameters

The measured roughness values parameters are lower than normative values to be obtained for the valve head and valve seat which is Ra=0.6mm.

In the case of the seat – measurements at three locations around the circumference revealed differences in roughness values. For the Rz parameter used in model equation Rz(mean)=0.452 mm, for Rmr(mean)=71.2%.

In the case of the head – measurements at three locations around the circumference revealed differences in roughness values. For the Rz parameter used in model equation Rz(mean)=0.563 mm, for Rmr(mean)=70.6%.

Average values of roughness parameter allows to random contact between solid surfaces making closer to real contact. Relying on one roughness measurement can dramatically change the width and number of channels and consequently, amount of leakage.

– leakage measurements

Helium is a gas with a high permeability. It means that a small gap produces a clear flow.

Table 1 presents the results of force values fluctuations, pressures changes acting

Table 1. Tightness class
Tabela 1. Klasa szczelności

	p_d, MPa				
Tightness class	1	2	3	4	5
L0.0001	p_{He}=0.04	p_{He}=0.05	p_{He}=0.06	p_{He}=0.08	p_{He}=0.10
L0.001	p_{He}=0.07	p_{He}=0.15	p_{He}=0.16	p_{He}=0.20	p_{He}=0.30
L0.01	p_{He}=0.12	p_{He}=0.30	p_{He}=0.43	p_{He}=0.50	p_{He}=0.70
L0.1	p_{He}=0.15	p_{He}=0.45	p_{He}=0.70	p_{He}=0.90	p_{He}=1.00

Table 2. Calculated values of a force and contact pressure between the valve head and the valve seat
Tabela 2. Obliczone wartości siły i nacisku stykowego pomiędzy grzybem i gniazdem

	4 MPa				5 MPa			
	F_{spring}	Pn	Pu	pd_{real}	F_{spring}	Pn	Pu	pd_{real}
	N	N	N	MPa	N	N	N	MPa
L0.0001	911.85	56.55	855.30	3.75	1139.81	70.69	1069.12	4.69
L0.001	911.85	141.37	770.48	3.38	1139.81	212.06	927.75	4.07
L0.01	911.85	353.43	558.42	2.45	1139.81	494.80	645.01	2.83
L0.1	911.85	636.17	275.67	1.21	1139.81	706.86	432.95	1.90

between valve head and seat. It allowed to calculate contact pressures and tightness class according with EN ISO 15848-1.

In Table 2 there are presented calculated force values for p_d =4 MPa and p_d =5 MPa. Descriptions as in Fig.5.

Where: $Pu = F_{spring} - Pn$ (8)

and $Pu \cdot A_{eff} = pd_{real}$ (9)

pd_{real} means the real value of seat-head contact pressure after taking into account partial relief due to pressure from the bottom of the head.

It obtained high tightness class L0.0001 at an initial contact pressure of 5 MPa at a helium pressure below 0.05 MPa. This helium pressure gives an equal force on the valve head Pn=70.69 N. Then equilibrium contact pressure is 4.69 MPa. It gives a 0.31 MPa reduction of the contact pressure in the safety valve. This means a reduction in contact pressure between the peaks of the valve head and the valve seat. Ratio: contact pressure to helium pressure is 46.9.

The worst tightness class L0.1 (initial pressure p_d=5 MPa) was achieved at the helium pressure of 1.0 MPa. Ratio: contact pressure to helium pressure is 1.9. In this situation the valve head is constantly in contact with the valve seat and the leakage is 1.5×10-1 cm^3/s.

– test results and calculation results

The model leak curve intersects the experimental leak curve. Helium pressure 0.4 MPa at contact pressure 4 MPa, helium pressure 0.6 MPa at contact pressure 5 MPa. For this valve-seat pair, the Rmr is around 70-80%. The discrepancy between the model and the experiment at lower and higher pressure values results from the assumption of non-deformability of surface irregularities peaks during load changes caused by gas pressure.

Summary

1) The analytical model used allows us to estimate the leakage at a contact pressure to a helium pressure ratio of 5-10 with the Rmr of 70-80% (typical for standard surface machining).

2) The model does not take into account the uplift of the valve head as the helium pressure increases. One can see the significant discrepancies between the model and measurement results as the pressure increases.

3) Including only one profile roughness measurement in the model may significantly distort the modelling results.

4) For recommended head-seat contact pressure (for metallic materials) there is an achievable desirable tightness class.

5) For recommended head-seat contact pressure (for metallic materials) there is a noticeable convergence of the mathematical model with the experiment.

6) The mathematical model has engineering potential for calculating leakage for other gases by substituting the appropriate density in the formula (7).

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