Determination of a face seal’s operational parameters on test bench

Abstract

The paper presents a method for determination of static characteristics of a gas lubricated face seal on the basis of experiment performed on the test bench. It has been developed a mathematical model $Q_N = f(t_g, p_g, n)$ depicting effect of temperature of the gas $t_g$, pressure of the gas $p_g$ and rotational speed of the shaft $n$ on flow rate value of the gas $Q_N$. This dependency was used to determine pressure of the gas required for a selected operational parameters of the machine. To assess correctness of functioning of the seal it has been performed measurements of a selected operational parameters of the machine. To assess correctness of functioning of the seal it has been performed measurements of a selected operational parameters of the machine. To assess correctness of functioning of the seal it has been performed measurements of a selected operational parameters of the machine.

Keywords: face seals, testing of the seals.

1. Introduction

Mechanical face seals belong to devices serving to eliminate a leakage in area where the shaft passes through opening in casing of a machine (e.g. impeller pump). Principle of operation consists in throttling of leakage in a slot created by end faces of being in contact mating rings, from which one ring is mounted in the casing, while the second ring rotates together with the shaft [1]. The rings of the seal are characterized by very small flatness deviation of working end faces (of about 0.3–0.6 µm) obtained through lapping operation, the most often using a single disc lapping machines [2].

The face seals are counted among critical components of many fluid-flow machines, because the seals determine operational life and reliability. For this reason, the manufacturers perform tests of the seals, simulating real operational conditions of the seal. Determination of allowable operational parameters of a given type of the seal belongs to key factors for correct application of the seal in a particular machine.

Special type face seals, implemented in case of very high rotational speeds, are so called gas lubricated mechanical seals. As lubricating film, which prevents friction, serves gas cushion formed during rotational movement of the seal, through hydrodynamic compression of the gas in shallow, spiral grooves machined on surface of one from the rings [3]. Seals of such type are characterized by predetermined flow rate of the gas through the gap created by the cushion of the gas. On value of the flow rate (except features of the design structure) the biggest effect have: rotational speed of the shaft, pressure and temperature of the gas. Experimental tests of prototype enable verification of conceptual design, capability to generation of the gas cushion and determination of static and stepwise characteristics [4]. The experimental tests also enable determination of mathematical relations between parameters having effect on operation of the device.

2. Methodology and techniques of the tests

The tests were aimed at determination of the characteristics and definition of optimal operational parameters of prototype gas lubricated seal of the 30GSL/A5-I439 type (Fig. 1) manufactured by the ANGA Uszczelnienia Mechaniczne Sp. z o.o. Company having its premises in Kozy.

Throttling of leaking process gas in the seal of the 30GSL/A5-I439 type takes place in the gap created by faces of the rings 1 and 3. On scaling surface of the ring 1 are machined spiral unidirectional grooves, where occurs hydrodynamic compression of the gas, resulting in formation of gas cushion and acting as lubricating film.

Fig. 1. The essential parts of the tested face seal [5]: 1 – stationary ring, 2 – static O-ring, 3 – rotating ring, 4 – dynamic O-ring, 5 – springs, 6 – seal housing, 7 – set screws, 8 – thrust plate, 9 – snap spring ring, 10 – protective sleeve, 11 – static O-ring

The input values $x_i$ connected with operational parameters of the seal are:
- temperature of the process gas $t_g$, °C,
- pressure of the process gas $p_g$, MPa,
- rotational speed of the shaft $n$, rpm.

The output value $z_n$ is:
- flow rate of the gas $Q_N$, normal l/min.

To the most important disturbances $h_i$ belong: vibrations of the test bench during its operation, pressure fluctuation of the process gas, temperature fluctuations of the process gas, fluctuation of the rotational speed.

In turn, as a constant values $c_i$ can be assumed: test bench, ambient temperature, ambient pressure, chemical composition of the process gas.

General scheme of the tested object is shown in the Fig. 2.
The tests comprised determination of an effect of selected operational parameters, i.e. temperature of the process gas \( T_g \), pressure of the process gas \( p_g \) and rotational speed \( n \) on value of the flow rate of the gas through the seal \( Q_g \). Volumetric flow rate of the gas is expressed in normal liters per minute, describing volume of the gas in normal conditions, i.e. absolute pressure 1013.25 hPa and temperature 0°C, flowing through gap of the seal during 1 minute. Adopted unit of measure corresponds to mass flow rate of the gas, what eliminates uncertainty of the measurement, resulted from variability of parameters of condition of the gas.

Tests of the prototype seal were performed on a special purpose test bench (Fig. 3).

The test bench was equipped with pneumatic system having incorporated instruments to monitor parameters of the working gas, which flows through the seal during the tests. To the most important from them belong: pressure transducer of the PT016R (Turck) type and transducer of mass flow rate of the EL-FLOW F-111B (Bronkhorst) type connected with the Metronic MPI-G recorder, and thermo-resistant sensor of the TOP-PKGKbm-21 type (ALF-SENSOR) with the A/D converter and the Simex SRD-99 recorder. Additionally, there were used standard rotameters and manometers to controlling changes of the measured quantities.

Changes of temperature of the gas in the measuring chamber of the seal were performed by swilling of its front wall with water of specified temperature. The water was heated/cooled in the heat exchanger, feeding its heating/cooling coil with hot steam or cold water.

3. Results of the tests and analysis

According to general scheme of the model of the tested object (Fig. 2), it has been assumed [8]:

\[ z = Q_g, \text{ in normal l/min}, \]
\[ x_1 = T_g - \text{variability range: } 22\text{°C} - 80\text{°C}, \]
\[ x_2 = p_g - \text{variability range: } 0.5\text{÷1.2 MPa}, \]
\[ x_3 = n - \text{variability range: } 3000\text{÷12000 rpm}, \]

It has been elaborated mathematic model of flow rate of the gas in form of second-order polynomial with dual interaction [7]:

\[
z = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \quad (1)
\]

where: \( b_0, b_1, b_2, b_3, b_{11}, b_{22}, b_{33}, b_{12}, b_{13}, b_{23} \) – regression coefficients.

In course of the tests it has been implemented the PS/DS-P: \( a[1.2154/3\times5] \) plan (static-determined-orthogonal-selective-multifactorial plan), in which every quantity takes five values. In the calculations for \( i=3 \) was taken value of \( a=1.2154 \) [6]. Levels and values of the independent variables for accomplishment of the PS/DS-P: \( a[1.2154/3\times5] \) plan are compiled in the Table 1.

### Tab. 1. Levels and values of the independent variables for implementation of the plan PS/DS-P: \( a[1.2154/3\times5] \)

<table>
<thead>
<tr>
<th>Input values</th>
<th>Values for the codes (( \alpha = 1.2154 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_1 ) ( T_g ) °C</td>
<td>24 22 27 50 75 80</td>
</tr>
<tr>
<td>( x_2 ) ( p_g ) MPa</td>
<td>0.29 0.50 0.56 0.85 1.14 1.20</td>
</tr>
<tr>
<td>( x_3 ) ( n ) rpm</td>
<td>3700 3000 3800 7500 11200 12000</td>
</tr>
</tbody>
</table>

Succession of individual tests, implemented parameters and values of the flow rate \( Q_g \) are specified in the Table 2.

### Tab. 2. Levels and values of the independent variables for implementation of the plan PS/DS-P: \( a[1.2154/3\times5] \)

<table>
<thead>
<tr>
<th>No</th>
<th>Code values</th>
<th>Set values</th>
<th>Value measured in successive repetitions</th>
<th>Average value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{x}_1 ) ( x_1 ) ( \hat{x}_2 ) ( x_2 ) ( \hat{x}_3 ) ( x_3 )</td>
<td>( z = Q_g )</td>
<td>( \hat{z} = \overline{Q}_g )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>( -1 ) ( -1 ) ( -1 )</td>
<td>27 0.56 3798</td>
<td>0.032; 0.033; 0.035; 0.032; ( 0.031; )</td>
<td>0.032</td>
</tr>
<tr>
<td>2</td>
<td>( +1 ) ( -1 ) ( -1 )</td>
<td>75 0.56 3798</td>
<td>0.006; 0.007; 0.008; 0.009; ( 0.007; )</td>
<td>0.007</td>
</tr>
<tr>
<td>3</td>
<td>( -1 ) ( +1 ) ( -1 )</td>
<td>27 1.14 3798</td>
<td>1.298; 1.301; 1.294; 1.289; ( 1.293; )</td>
<td>1.295</td>
</tr>
</tbody>
</table>
All obtained measurement results were tested with the Grubbs test to eliminate coarse errors. Critical value of the Grubbs test was assumed as $T_{kr}=1.869$ for the significance level of 0.05 and $n_{ptn}=1324.7$. If $P_{F}=0.05$ then term of the regression equation is significant at significance level of $\alpha$. However, significance of individual terms of the regression equation was calculated with use of the Student’s $t$-test, computing value of the $P=F_{(t,\infty)}$. If $P_{F}=0.05$ then term of the regression equation is significant at significance level of $\alpha$. Negative results were obtained for 2 components: free term (which doesn’t undergo elimination) and the term $t_{g}^{2}$. After elimination of the $t_{g}^{2}$, values of the regression coefficients of remaining terms have been corrected.

The result is incomplete model of the tested object in form of:

$$Q_{N} = 0.0584578101 + 0.01454240697 t_{g}^{2} - 1.8856649749 p_{g}^{2},$$  

(3)

$$+ 2.2334545079 t_{g}^{2} p_{g}^{2} - 0.0000000027 n^{2} - 0.0216738506 t_{g}^{2} p_{g}^{2} - 0.0000003568 t_{g}^{2} n + 0.0002204733 p_{g}^{2} n,$$

(2)

Values of the regression coefficients were calculated with accuracy to 10 decimal places due to big differences in numerical values (even up to 6 orders of magnitude).

Statistical analysis of the regression equation (2) was performed using the STATISTICA computer software (Tab. 3).
Developed form of the incomplete model of the tested object is significant, and all terms of the equation (except the free term which doesn’t undergo elimination) are significant.

Correct operation of the tested seal is connected with maintenance of the gas flow rate $Q_n$ within a certain interval. Lower limiting value of this interval denotes minimal value of the flow rate occurring when contactless operation of the seal is maintained. On the basis of preliminary tests of the 30GSL/A5-1.439 type seal, minimal value of the flow rate $Q_n$ was estimated as about 0.2 normal l/min. In turn, upper limiting value of the interval (called as allowable leak of the gas) results from necessity of limitation of excessive consumption of the gas, depending on individual application. In case of the tested seal, value of allowable leak was assumed at the level 1.6 normal l/min.

Effect of temperature $t_g$, pressure $p_g$ of the gas, and rotational speed of the shaft $n$ on flow of the gas $Q_n$ through prototype seal of the 30GSL/A5-1.439 type is presented in form of diagrams in Figs. 4–6. Due to the fact that the model comprises independent variables, the spatial diagrams depict dependency of the gas flow $Q_n$ in function of two parameters (temperature $t_g$ and pressure $p_g$ of the gas), at constant value of the third parameter (rotational speed $n$). The diagrams were developed with consideration of limitation of the parameters which comply with condition of maintaining flow rate value within allowable interval of 0.2–1.6 normal l/min.

On the basis of the developed mathematical model it is possible to determine if the seal can operate correctly with a given values of the parameters $t_g$, $p_g$, $n$, by substitution of these values to the equation 3. Simultaneously, knowing rotational speed of the device and the temperature, it is possible to select pressure of the gas which would assure correct operation of the seal. For example, wanting to install the seal in a machine operated with rotational speed 3000 rpm at temperature not exceeding 50°C, the pressure not lower than 0.85 MPa should be assured.

4. Assessment of wear on end faces of the rings of the seal

Except allowable range of the gas flow rate values $Q_n$ it is also important to maintain contactless character of the gaso-dynamic seal operation during its rotational motion. Presence of contact of the faces results in friction forces between the stationary ring and the rotating ring of the seal, what can cause wear of the rings.

Wear of the end faces of the tested gas lubricated seal was assessed by comparison of selected 3D surface roughness parameters of the rings before and after dynamic operation. The following parameters of the 3D roughness have been selected: amplitude parameters of the surface – arithmetic mean height of the surface $Sa$, root mean square height of the surface $Sq$, maximum peak height of the surface $Sp$, maximum pit height of the surface $Sv$, maximum height $Sht$, and parameters of the areal material ratio curve – core height $Sk$, reduced peak height $Spk$, reduced dale height [9, 10].

The measurements were carried out using the Form Talysurf 120 contour measurement system produced by the Taylor Hobson Company. Conical gauging point of the K501/1685 type with fillet radius 2 µm and angle 60° was used. Measurements of the surface roughness and topography were performed in four uniformly spaced locations on sealing surfaces of the both rings. Measurements of the topography have been performed on the surfaces with dimension 2 mm × 2 mm, performing 401 linear runs distant from each other with 5 µm. In course of the measurements the following parameters have been used: sampling length $l_i=0.25$ mm, evaluation length $l_f=2.8$ mm, number of sampling lengths $i=5$. It has been adopted sampling step $A_i=0.35$ µm, number of recorded points $N_x=8000$, feed rate of the gauging point $v_f=0.5$ mm/s, and Gauss filter.

In the Table 5 are written the following parameters of the 3D surface roughness 3D: $Sa$, $Sq$, $Sp$, $Sv$, $St$, $Sk$, $Spk$, before and after 25 operational hours of the seal. During this time there were performed in total 75 cycles of start and stop of drive system of the bench.
Tab. 5. The results of measurements of selected parameters of 3D surface roughness of the sealing rings (before and after 25 h of operation)

| Parameter, µm | Stationary ring | | | | Rotating ring | | | |
| | measured values | average | measured values | | average | measured values | | average |
| | before operation | | after 25 h of operation | | | before operation | | after 25 h of operation |
| Sa | 0.0343; 0.0361; 0.0339; 0.0361; 0.0351 | 0.0385; 0.0401; 0.0429; 0.0420; 0.0409 | 0.0559; 0.0589; 0.0578; 0.0568; 0.0574 | 0.0605; 0.0623; 0.0617; 0.0600; 0.0611 |
| Sq | 0.2831; 0.2294; 0.2975; 0.2631; 0.2683 | 0.2239; 0.2745; 0.2508; 0.2473; 0.2491 | 0.0978; 0.0914; 0.3195; 0.0962; 0.9468 | 0.9846; 0.9546; 0.9771; 0.9602; 0.9691 |
| Sp | 0.6219; 0.6685; 0.6501; 0.6759; 0.6541 | 0.7592; 0.6985; 0.7218; 0.7563; 0.7340 | 0.0368; 0.0372; 0.0394; 0.0368; 0.0376 | 0.0360; 0.0372; 0.0370; 0.0362; 0.0366 |
| Sv | 0.9738; 0.0372; 0.0394; 0.0368; 0.0376 | 0.0360; 0.0372; 0.0370; 0.0362; 0.0366 |
| St | 0.9738; 0.0372; 0.0394; 0.0368; 0.0376 | 0.0360; 0.0372; 0.0370; 0.0362; 0.0366 |
| Sk | 0.0495; 0.0464; 0.0460; 0.0500; 0.0480 | 0.0467; 0.0481; 0.0475; 0.0470; 0.0473 |
| Spk | 0.0559; 0.0548; 0.0578; 0.0551; 0.0559 | 0.0604; 0.0599; 0.0557; 0.0589; 0.0591 |
| Svk | 0.0559; 0.0548; 0.0578; 0.0551; 0.0559 | 0.0604; 0.0599; 0.0557; 0.0589; 0.0591 |

Obtained results in case of the stationary ring are pointing at a slight increase of such 3D surface roughness parameter values like: Sa, Sq, Sv and St. However, values of such roughness parameters like: Sp, Sk, Spk and Srk undergo a slight decrease in result of operation of the seal.

In case of the rotating ring, in result of operation of the seal, it is seen a distinct decrease of the following parameters Sv and Sr, while the following parameters undergo a slight decrease only: Sq and Sp; the parameters of the areal material ratio curve: Sk, Spk and Srk remain practically at the same level.

Differences in changes of the 3D surface roughness parameter values, for the stationary and rotating rings, in result of operation of the seal, should probably be explained by different types of materials of the both rings.

This can be confirmed by images of surface topography shown in the Figs. 7–10.
5. Summary

Experimental tests of the prototype gas lubricated face seal have allowed elaboration of mathematical model, which describes selected static characteristics. The model enables determination of recommended and allowable operational parameters of the tested gas lubricated face seal for a specific industrial application.

In addition to allowable flow rate of the gas $Q_N$ flowing through the seal, it was also necessary to maintain contactless character of the operation during rotational motion. Changes in values of most 3D surface roughness parameters of the sealing rings resulted from operation of the seals are pointing at a slight (infinitesimal) wear. In connection with aggregate time of the tests and changing values of the input parameters (rotational speed $n$, temperature $t_g$ and pressure $p_g$ of the gas) it can be concluded that in the whole analyzed range of variability of these parameters, during rotational movement of the seal, it was formed the gas cushion to prevent friction. A slight wear mentioned above is probably connected with presence of a contact during start and stop of the seal only.

Adopted methodology of the research can be implemented to determination of static characteristics, also in case of other type gas-lubricated seals, inclusive of a duplex seals in face-to-face and tandem systems.

6. References


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