INFLUENCE ON THE LEAKAGE FLOW RATE OF THE STATIONARY SEAL RING SHAPE OF THE MECHANICAL SEAL SYSTEMS USED IN FEED PUMPS IN THE POWER PLANTS

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Abstract: The tendency to use high-capacity pumps especially in power plants raised the need to reduce the leakage flow rate of the mechanical seals and to increase their lifetime. During this study the influence of the geometric shape of the stationary seal ring under the action of the axial forces on the leakage flow rate between the active front surfaces was investigated. Hydrostatic and hydrodynamic measurements were carried out in order to confirm the results.

Keywords: end face mechanical seal, flatness deviation, leakage flow rate, axial forces, stationary seal ring, clearance gap

1. INTRODUCTION

Due to the increase of the installation power (up to 700 MW) the need for using high-capacity pumps, especially in Nuclear Power Plants, shows an increasing tendency.

The operating parameters of these pumps were extended as it follows: flow rate up to 4000 tons/hour, diameter up to 450 mm, pressure up to 100 bars and peripheral speed up to 70 m/s. Proper sealing of these pumps is essential and therefore the mechanical seal systems must ensure long life-time and reduced leakage flow rate [1] (5 ÷ 10 l/hour).

In this study we analyze the influence of the geometric shape of the stationary seal ring under the action of axial forces on the leakage flow rate between the active front surfaces.
Present investigations were carried out using a sealing system composed by three mechanical face seals (Figure 1).

2. ELASTIC DEFORMATION OF SEAL RINGS UNDER THE ACTION OF THE AXIAL FORCES

Stationary and rotating seal rings are mechanically deformed under the action of the axial forces. These deformations can reach a value of 30 μm in case of the stationary seal ring made from carbographitic material (in function of the constructive shape) and 1 μm in case of the rotating seal ring made form wolfram carbide material (Figure 2).

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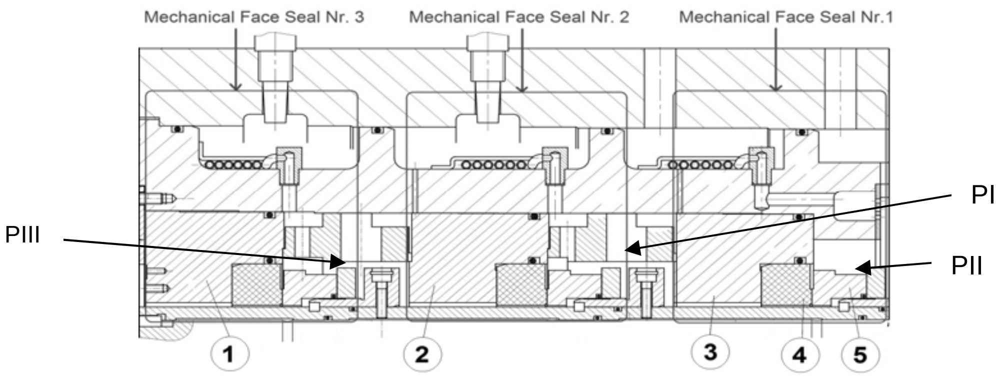


Fig.1. Partial drawing of the mechanical face seal system: 1 - superior stationary ring holder; 2 – middle stationary ring holder; 3 – inferior stationary ring holder; 4 – stationary ring; 5 – rotating ring.

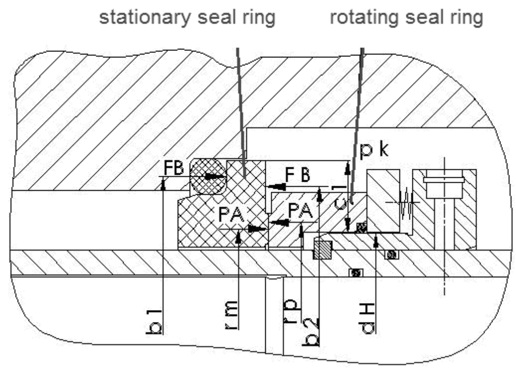


Fig. 2. Partial draw of the end face mechanical seal with the corresponding axial forces: F_B – normal force due to the hydraulic and bow pressure which act on the stationary seal ring; P_A – normal force due to the hydraulic and bow pressure which act on the rotating seal ring; p_k – sealed pressure; b_1 – effective reaction radius of the normal force F_b; b_2 – effective action radius of the normal force F_b; r_m – mean radius of the sliding surface; r_p – effective action radius of the normal force Pa; d_H – hydraulic diameter [2].

Constructive shape of the stationary seal ring which presents the less significant deformation under the action of the axial forces represents the simple shape ring (Figure 1) [2].

According to the model of Gemma [3] the rotational angle of the simple shape ring (Figure 3) is given by the equation:

$$\varphi = \frac{12\overline{M}r_m}{El^3 \ln \frac{r_e}{r_i}} \qquad (1)$$

where *M* [N·mm/mm] is the relative moment, *E* [N/mm^2] are the elasticity modulus , *l* [mm] are the axial length, r_m [mm] are the medium radius, r_e [mm] are the outer radius, r_i [mm] are the inner radius.

The mechanical deformation of the seal ring is given by the equation:

$$S_{Ma} = \varphi \cdot b \cdot C_F \qquad (2)$$

where *b* [mm] is the ring width and C_F is the shape coefficient.

The gap deformation and the resulting shape are given by the sum of deformations caused by the axial forces:

$$S_{Ma} = S_{AMa} + S_{BMa} \quad (3)$$

where S_{AMa} is the mechanical deformation of the stationary seal ring and S_{BMa} is the mechanical deformation of the rotating seal ring.

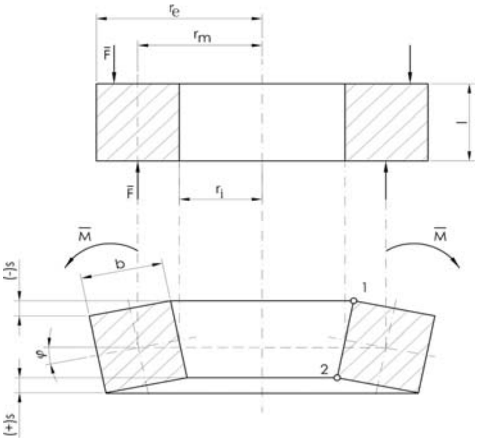


Fig. 3. Elastic deformation of the rings under the action of the moment M of the eccentric force [2].

Thus the deformations can be influenced by the adequate construction of the rings and by selecting the right material with the corresponding elasticity modulus.

As a consequence, the imperfect shape of the seal rings together with the axial forces lead to the deformation of the stationary and rotating seal rings, which also lead to the increase of the leakage flow rate.

In this paper we investigated the influence on the leakage flow rate of the flatness deviation of the primary and secondary surfaces of the stationary seal ring (Figure 4) made from carbographitic material having an elasticity modulus equal to 21000 N/mm^2 together with the rotating seal ring flatness deviation with a much harder face.

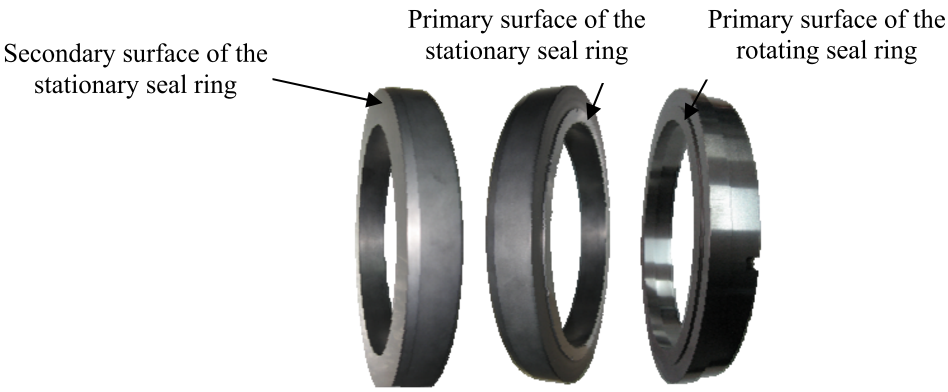


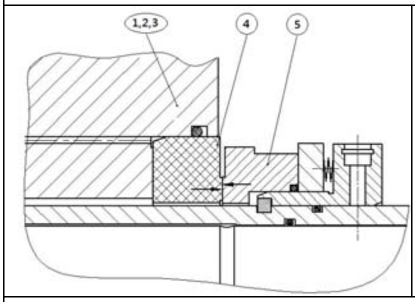
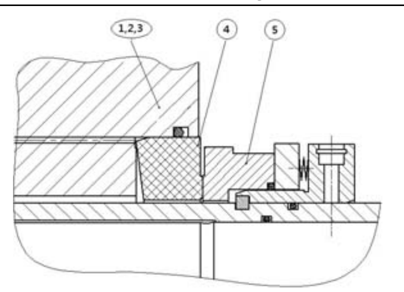
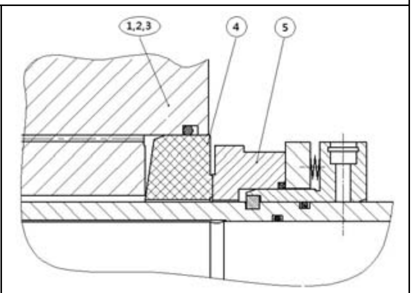
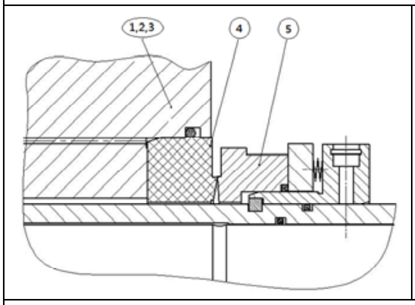
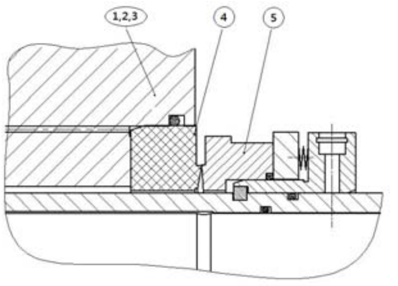
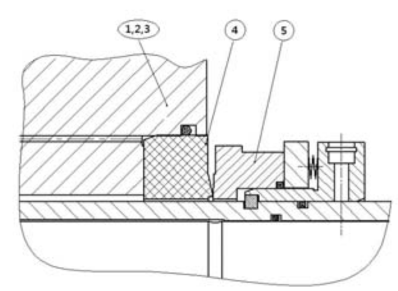
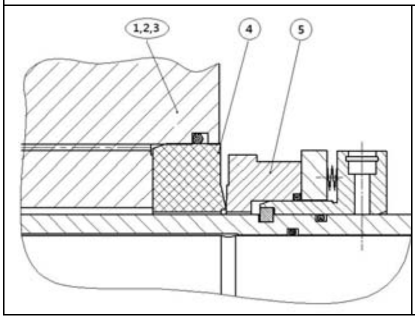
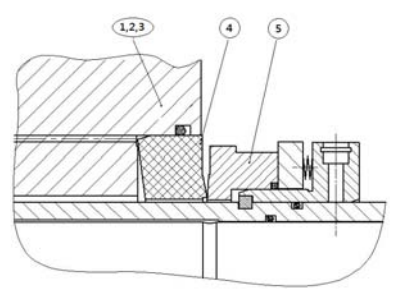
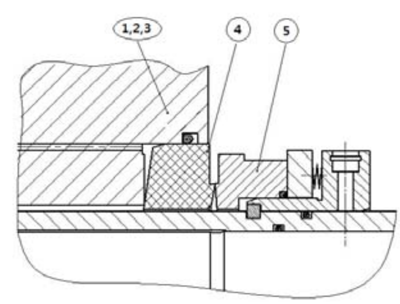
Fig. 4. Surfaces of the stationary and rotating seal rings.

3. DEVIATIONS OF THE STATIONARY AND ROTATING SEAL SHAPES AND THE INFLUENCE OF THE AXIAL FORCES ON THE CLEARANCE GAP BETWEEN THE PRIMARY SEAL SURFACES

Taking in consideration that the mechanical seal must withstand a pressure difference up to 99 bars, their construction must be performed in order to obtain minimum deformation of the seal rings under the action of the axial forces. The stationary rings (pos. 4 on Figure 1) are mounted in the holders (pos. 1, 2, 3 on Figure 1) in order to seat on a flat surface, taking over the deformations due to the moments which act on the seal surfaces. The secondary surface of the stationary seal ring and the surface of the holder must have proper flatness.

Three variations of the seal ring surface flatness deviations are presented in Table 1.

Table 1. Variations of the flatness deviation of the seal ring faces:
1, 2, 3 – ring holders; 4 – stationary ring; 5 – rotating ring.

Variations of the secondary surface of the seal ring with ***proper*** flatness deviation.	Variations of the secondary surface of the seal ring with ***inappropriate*** flatness deviation. –**CONVEX-**	Variations of the secondary surface of the seal ring with ***inappropriate*** flatness deviation. –**CONCAV-**
At mounting:		
		
At the action of increasing pressure:		
		
After reducing the pressure - after operation:		
		

To prevent the mechanical deformations of the carbographitic stationary seal rings, caused by the axial forces, we use a special construction containing a metallic holder with lapped surface having 0.6 − 0.9 μm flatness, in which the ring is mounted to avoid the stationary seal ring deformations over 0.6 − 0.9 μm.

4. LEAKAGE FLOW RATE

According to [4, 5], the biggest influence on the leakage flow rate between the seal surfaces has the clearance gap *h* between the flat surfaces, being related to the third power of *h*:

$$Q = \frac{h^3}{\eta \cdot \ln\left(\frac{D}{d}\right)}\left[1.885 \cdot 10^{-4} \cdot \Delta P - 7.752 \cdot 10^{-19} \cdot \rho \cdot n^2 \left(D^2 - d^2\right)\right] \qquad (4)$$

where: h [μm] – clearance gap between the active surfaces;
Q [ml/h] – leakage flow rate;
D [mm] – outer diameter of the friction surface;
d [mm] – inner diameter of the friction surface;
η [Pa·s] – dynamic viscosity of the sealed medium;
ρ [kg/m^3] – density of the sealed medium;
n [1/min] – rotational speed of the shaft of the pump;
ΔP = [bar] – pressure difference

5. MEASUREMENTS AND COMPUTING

Dimensions and characteristic of the materials of the investigated mechanical end face seal system.

Dimensions and characteristic of the material of the stationary seal ring:

- D = Ø 228.9 mm, d = Ø 207.85 mm;
- E = 21000 N/mm^2, l = 31.8 mm, r_m = 109.18 mm, r_e = 133.35 mm, r_i = 102.85 mm.

Dimensions and characteristic of the material of the rotating seal ring:

- D = Ø 229.8 mm, d = Ø 205.6 mm;
- E = 620000 N/mm^2, l = 34.8 mm, r_m = 108.85 mm, r_e = 128.5 mm, r_i = 102.85 mm.

Working conditions:

- PI = 99 bar – pressure at the first sealing stage;
- PII = 63 bar – pressure at the second sealing stage;
- $PIII$ = 33 bar – pressure at the third sealing stage;
- η = 1.25 *10^{-3} Pa·s;
- ρ = 1000 kg/m^3;
- n = 1499 rot/min.

Flatness and shape deviations:

- Flatness deviation of the surface of the holder (pos. 1,2,3 on Figure1) is 0.9 μm;
- Flatness deviation of the primary surface of the stationary sealing ring (pos. 4 on Figure1) is 0.9 μm;
- Flatness deviation of the secondary surface of the stationary sealing ring (pos. 4 on Figure1) is between 0.9 – 10 μm;
- Flatness deviation of the primary surface of the rotating sealing ring (pos. 5 on Fig. 1) is 0.6 μm (Figure 5).

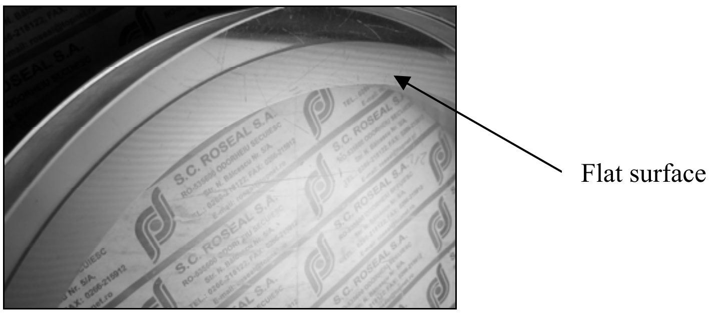


Fig. 5. Measurement of the flatness of the surface.

During the investigation, the flatness deviation of the secondary surface of the stationary sealing ring was varied between 0.9 μm, 5 μm and 10 μm, other deviations and dimensions were kept constant.

Deformations were computed for two cases: for the active surface and for the overall dimensions. According to (1, 2, 3) the computed mechanical deformations of the stationary and rotating seal rings are given in Figures 6 and 7.

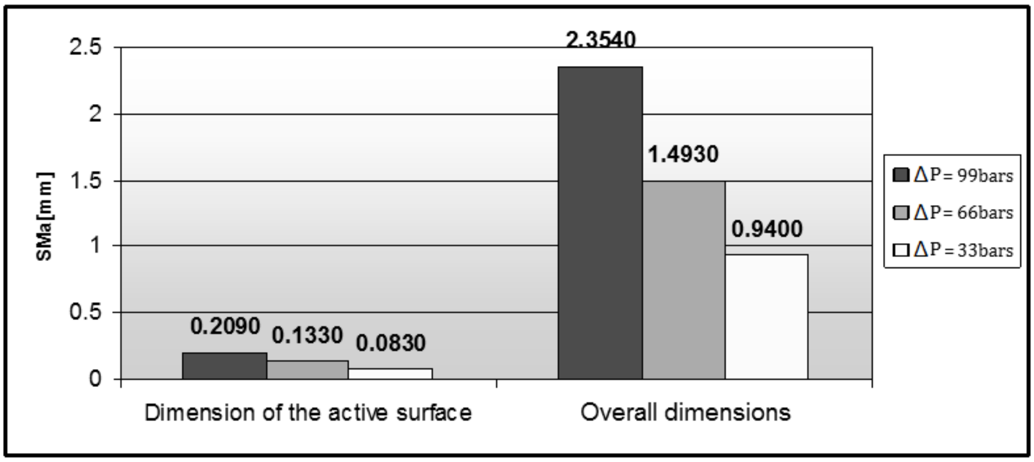


Fig. 6. Mechanical deformation of the stationary seal ring.

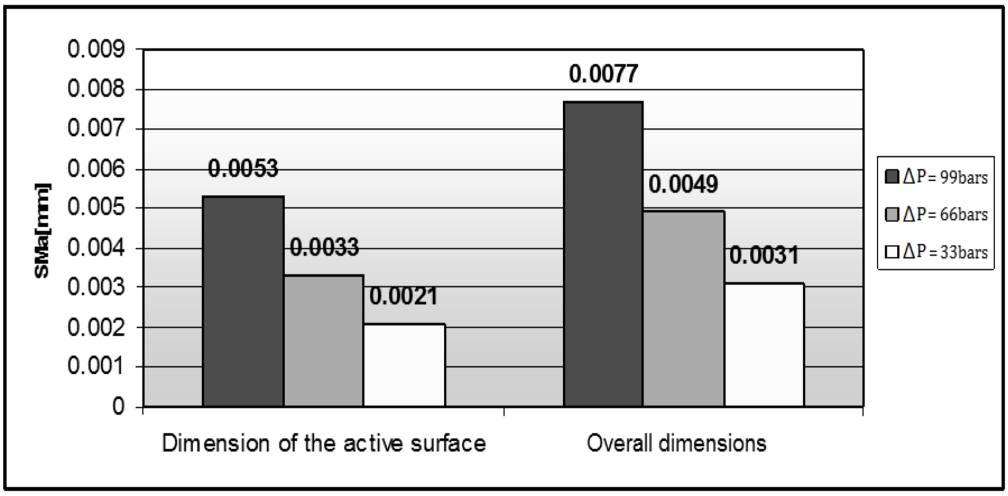


Fig. 7. Mechanical deformation of the rotating seal ring.

It can be observed that the deformations are much higher than the flatness deviations of the secondary surface of the stationary sealing ring cumulated from the deviations of the surfaces of the holders (pos.1, 2, 3 on Figure 1), therefore the clearance gap *h* between the two surfaces was determined taking in consideration the executive flatness deviations of the secondary surface of the stationary sealing ring.

Variation a) - flatness deviations of the secondary surface of the stationary sealing ring (pos. 4 on Figure 1) is 0.9 μm;
- $h = 0.9\ \mu m$ +0.9 μm +0.9 μm +0.6 μm = 3.3 μm.

Variation b) - flatness deviations of the secondary surface of the stationary sealing ring (pos. 4 on Figure 1) is 5 μm;
- $h = 5\ \mu m$ +0.9 μm +0.9 μm +0.6 μm = 7.4 μm.

Variation c) - flatness deviations of the secondary surface of the stationary sealing ring (pos. 4 on Figure 1) is 10 μm;
- $h = 10\ \mu m$ +0.9 μm +0.9 μm +0.6 μm = 12.4 μm.

Leakage flow rates for the different sealing stages in function of the clearance gap are given in Figure 8.

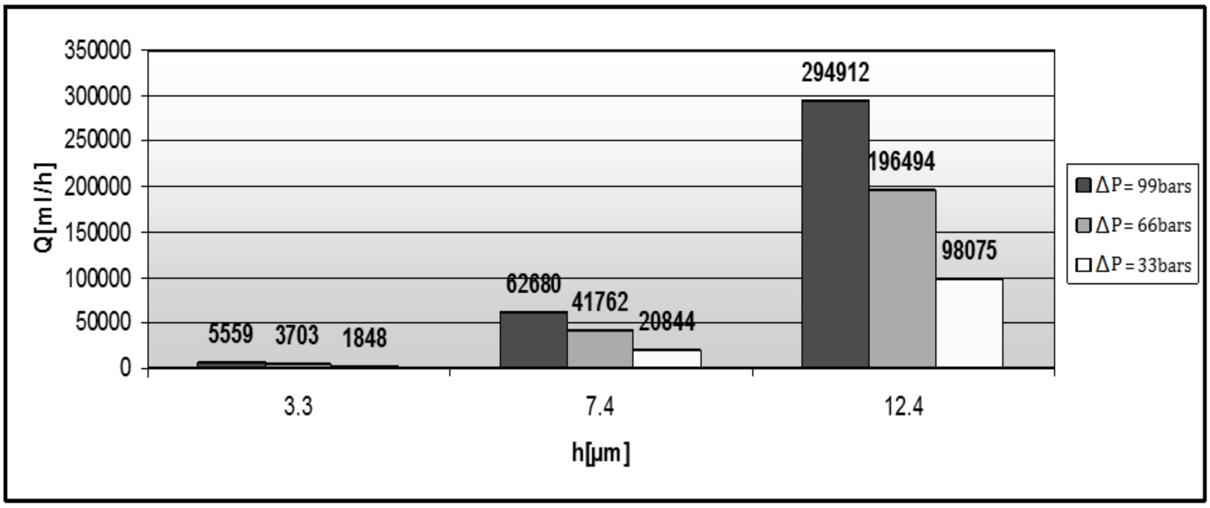


Fig. 8. Leakage flow rate vs. clearance gap for three sealing stages.

It can be observed that the leakage flow rate can increase by a factor of 160 due to the deviations of the secondary surface of the stationary sealing ring.

6. HYDROSTATIC AND HYDRODYNAMIC TESTS

During the investigations, two kinds of measurements were carried out: hydrostatic test (mineralized water) and hydrodynamic test (heavy water) using a seal system composed by three mechanical face seals (Figure 1).

6.1. Hydrostatic test using mineralized water

The first step of testing the mechanical seal systems was to elaborate hydrostatic tests. Pressures were measured at each sealing stage (see Figure 1). Four combinations of the different flatness deviations of the secondary surface of the stationary sealing ring were tested.

At the first test for the first sealing stage the flatness deviation of the secondary surface of the stationary sealing ring is equal to 5 μm. The results are as follows:

Test 1:

- Mechanical face seal 1 having stationary seal ring according to variation b.
- Mechanical face seal 2 having stationary seal ring according to variation a.
- Mechanical face seal 3 having stationary seal ring according to variation a.

The measured pressures at the different sealing stages are:

PI = 98 bar; PII = 74 bar; PII = 48 bar

The leakage flow rate at the first sealing stage is:

Q = 13126 ml/h – leakage flow rate (inadmissible value for seal 1)

The leakage flow rate to the atmosphere:

Q [ml/h] – insignificant leakage flow rate

For the second test the flatness deviation of the secondary surface of the stationary sealing ring for the first sealing stage is equal to 10 μm. The results are as follows:

Test 2:

- Mechanical face seal 1 having stationary seal ring according to variation c.
- Mechanical face seal 2 having stationary seal ring according to variation a.
- Mechanical face seal 3 having stationary seal ring according to variation a.

The measured pressures at the different sealing stages are:

PI = 98 bar; *PII* = 82 bar; *PIII* = 46 bar

The leakage flow rate at the first sealing stage is:

Q =41090 ml/h – leakage flow rate (inadmissible value for seal 1)

The leakage flow rate to the atmosphere:

Q [ml/h] – insignificant leakage flow rate

Using proper flatness deviation (0.9 μm) of the secondary surface of the stationary sealing ring for all sealing stages the measured pressures and the corresponding leakage flow rate are as follow:

Test 3:

- Mechanical face seal 1 having stationary seal ring according to variation a.
- Mechanical face seal 2 having stationary seal ring according to variation a.
- Mechanical face seal 3 having stationary seal ring according to variation a.

The measured pressures at the different sealing stages are:

PI = 99 bar; *PII*= 66 bar; *PIII*= 34 bar

The leakage flow rate to the atmosphere:

Q [ml/h] – insignificant leakage flow rate

The last test contained only secondary sealing rings with flatness deviation equal to 10 μm:

Test 4:

- Mechanical face seal 1 having stationary seal ring according to variation c.
- Mechanical face seal 2 having stationary seal ring according to variation c.
- Mechanical face seal 3 having stationary seal ring according to variation c.

The measured pressures at the different sealing stages are:

PI = 99 bar; *PII* = 62 bar; *PIII*= 37 bar

The leakage flow rate to the atmosphere:

Q = 120000 ml/h – leakage flow rate (inadmissible value)

6.2. Hydrodynamic test using heavy water

Hydrodynamic tests were elaborated for three combinations of the different flatness deviations of the secondary surface of the stationary sealing ring were tested. Pressures were measured at each sealing stages (see Figure 1).

The first test was done using flatness deviation of the secondary surface of the stationary sealing ring for the first sealing stage equal to 5 μm. The results are as follows (see Figure 9):

Test 1:

- Mechanical face seal 1 having stationary seal ring according to variation b.
- Mechanical face seal 2 having stationary seal ring according to variation a.
- Mechanical face seal 3 having stationary seal ring according to variation a.

The measured pressures at the different sealing stages are:

PI = 95 bar; *PII* = 72 bar; *PIII* = 39 bar

The leakage flow rate at the first sealing stage is:

Q = 12600 ml/h – leakage flow rate (inadmissible value for seal 1)

The leakage flow rate to the atmosphere:

Q = 1890 ml/h – leakage flow rate (admissible value)

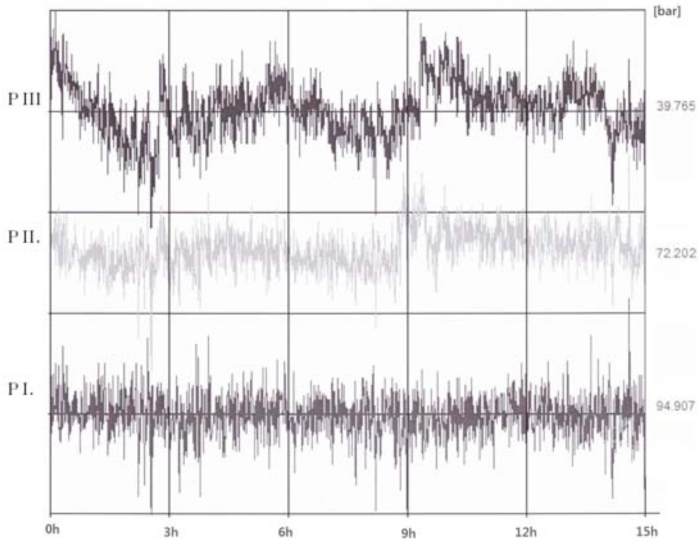


Fig. 9. Pressure variation in time of the three mechanical face seals of the seal system for test 1.

At the second test for the first sealing stage the flatness deviation of the secondary surface of the stationary sealing ring is equal to 10 μm. The results are as follows (see Figure 10):

Test 2:

- Mechanical face seal 1 having stationary seal ring according to variation c.
- Mechanical face seal 2 having stationary seal ring according to variation a.
- Mechanical face seal 3 having stationary seal ring according to variation a.

The measured pressures at the different sealing stages are:

PI = 96 bar; PII = 76 bar; $PIII$ = 42 bar

The leakage flow rate at the first sealing stage is:

Q = 51400 ml/h – leakage flow rate (inadmissible value for seal 1)

The leakage flow rate to the atmosphere is:

Q = 2040 ml/h – leakage flow rate (admissible value)

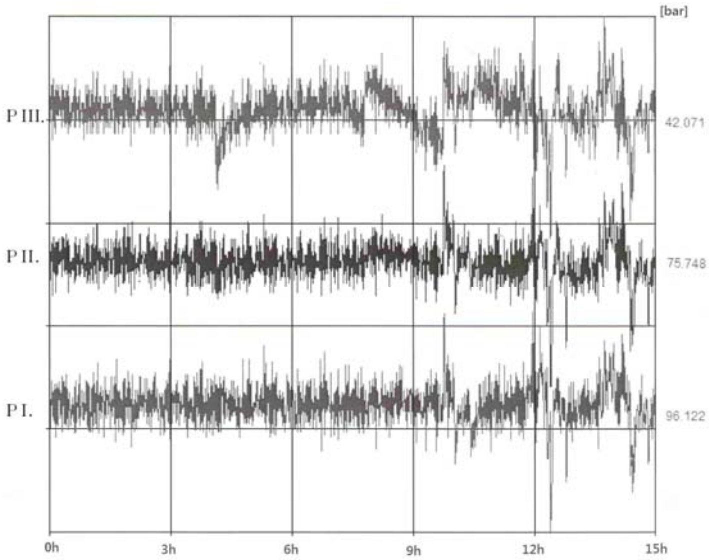


Fig. 10. Pressure variation in time of the three mechanical face seals of the seal system for test 2.

The last test was elaborated using stationary sealing rings with proper flatness deviation (0.9 µm) of the secondary surfaces for all sealing stages. The measured pressures and the corresponding leakage flow rate are as follow (see Figure 11):

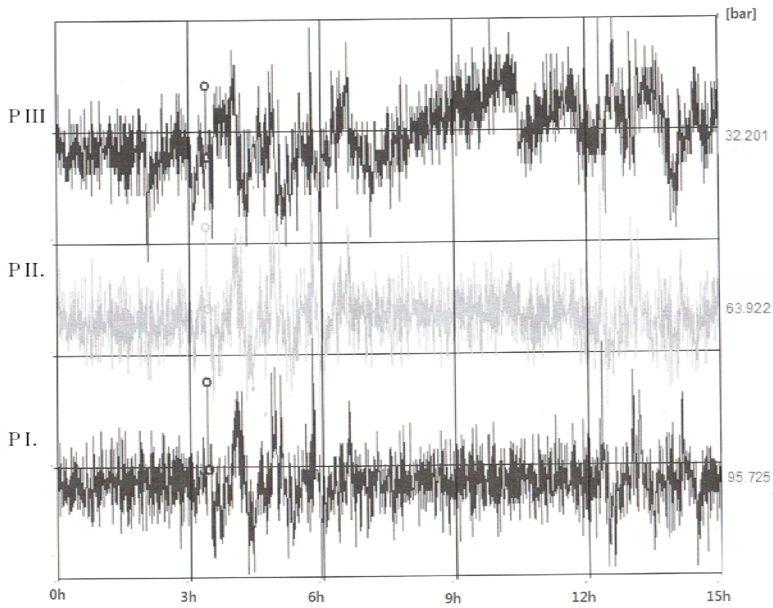


Fig. 11. Pressure variation in time of the three mechanical face seals of the seal system for test 3.

Test 3:

- Mechanical face seal 1 having stationary seal ring according to variation a.
- Mechanical face seal 2 having stationary seal ring according to variation a.
- Mechanical face seal 3 having stationary seal ring according to variation a.

The measured pressures at the different sealing stages are:

PI = 96 bar; *PII* = 64 bar; *PIII* = 32 bar

The leakage flow rate to the atmosphere is:

Q = 1533 ml/h – leakage flow rate (admissible value)

7. CONCLUSIONS

Through the execution of mechanical seal systems it must ensure to obtain clearance gaps between the two active surfaces less than 3.3 µm in order to have mixed or boundary friction and thus according to (4) to achieve low leakage flow rate and long lifetime.

In this study we demonstrated through theoretical calculations and experiments that the surface flatness deviation of the secondary seal ring has a big influence on the gap *h* due to the fact that the axial forces compel this to be "copied" and transmitted to the active surface of the seal and thus the clearance gap is increased. The obtained experimental results are in a good correlation to the theoretical results, the difference of about 15% is due to the assumed simplifications, not taking in consideration the other influencing factors such as radial forces and temperature gradients.

Finally we can conclude that the planning and execution phase of the sealing rings must provide proper flatness deviation not only for the active surfaces of the rotating sealing ring but for the secondary sealing ring, as well, in order to achieve low leakage flow rate and long lifetime.

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