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Stuttgart, Germany
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18th ISC

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October 08–09, 2014

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ISBN 978-3-00-046879-7

Bidirectional PTFE Lip Seals – Superior to Elastomeric Seals?

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High temperatures, high shaft speeds, dry run and aggressive fluids can harm and destroy elastomeric radial lip seals [1]. Seals made of polytetrafluoroethylene (PTFE) compounds can cope with the problems such demanding applications pose. Its outstanding material properties enable PTFE to function at temperatures up to 200 °C, with nearly every fluid and in dry running condition. However, unlike elastomeric radial lip seals, PTFE lip seals do not automatically pump back fluid [2]. To solve this problem PTFE lip seals with a spiral groove, which are widely used to seal crankshafts, were developed. As such seals work in only one rotational direction, bidirectional PTFE lip seals are necessary for universal application.

Research at the Institute of Machine Components of the University of Stuttgart led to leak-tight bidirectional PTFE lip seals. In this paper, application conditions and limits of the current design of bidirectional PTFE lip seals are presented. Finally, the question asked in the title will be discussed, taking into account the recent results.

1 Prior investigations and sealing mechanism

Development and manufacturing of the seals is done at the institute. Plain PTFE lips are first stamped and then mounted in housings. Recent publications cover investigations on the production and the function of various designs of PTFE lip seals with bidirectional sealing aids [3], [4], [5]. These investigations led to seals that are leak-tight in both rotational directions. The current design was described in depth and a hypothesis on the sealing mechanism was established [6].

Bidirectional PTFE lip seals of the current design consist of two closed rings with sealing aids in between. The second closed ring is essential for the sealing mechanism to work, as all earlier designs without a second closed ring leaked in dynamic tests. Figure 1 shows the closed rings and sealing aids and illustrates the sealing mechanism in dynamic condition. The sealing mechanism is described in more detail at the end of this chapter.

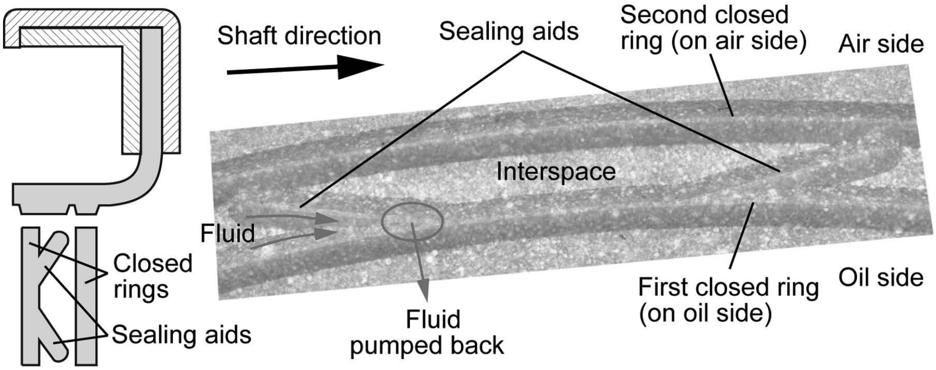

Figure 1: Sealing mechanism – dynamic condition

Different variants of this design were analyzed. Ones with a connection between sealing aids and second closed ring, as well as ones with a gap in between. Both are depicted in Figure 2.

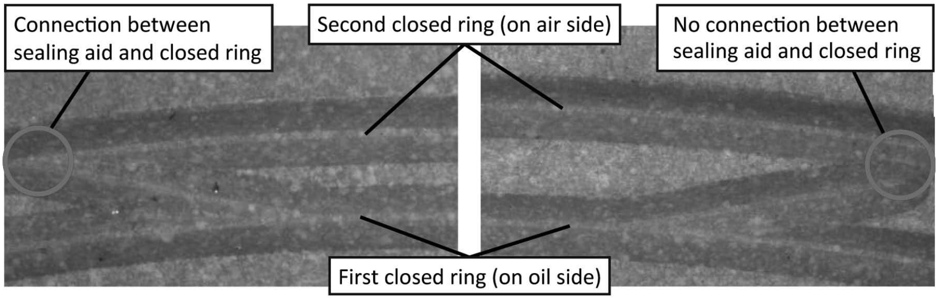

Figure 2: Comparison of variants – connection (left) and no connection (right)

The sealing mechanism in static condition was analyzed at a flow analysis test rig. At this test rig, the contact of the sealing aids and the shaft is observed through a glass hollow-shaft. Figure 3 shows pictures from investigations at the flow analysis test rig. The variant where sealing aids and closed ring are connected leads to leakage. This is shown in Figure 3 on the left, as the second closed ring is wetted, one minute after oil was filled in. The variant with the gap in between leads to an improved static leak-tightness, as the fluid is stopped at the sealing aid and the second closed ring is not wetted. This in exemplified in Figure 3 on the right, which shows the sealing contact three day after oil was filled in.

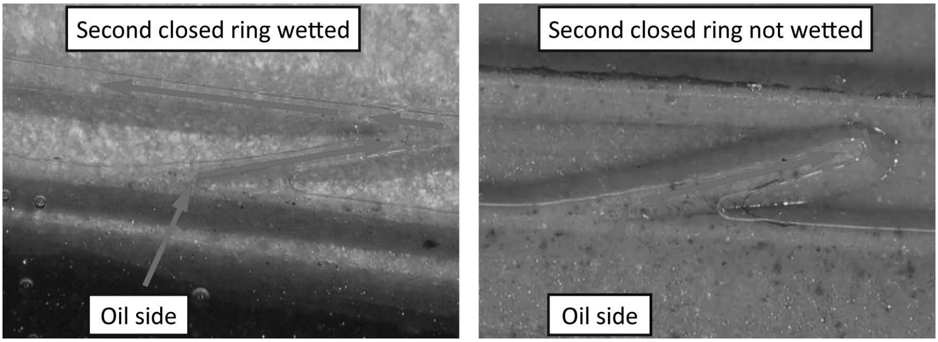

Figure 3: Function in static condition

During dynamic tests, the variant with a gap between the sealing aids and the second closed ring showed better results as well. The back pumping in dynamic condition was observed at the flow analysis test rig and presented in prior publications [7]. During basic endurance test runs, the seals were leak-tight in both rotational directions. The hypothesis on the sealing mechanism is derived from these and further investigations, detailed in earlier publications. It is subsequently described for static and dynamic condition.

1.1 Sealing mechanism in static condition (standstill of shaft):

- Fluid wets the first closed ring due to capillary forces in the rough contact surfaces of seal and shaft. Cohesive forces at the steep wall of the first closed ring prevent the fluid from flowing out of the contact area. This steep wall is essential [8].
- The fluid wets the area underneath the sealing aids due to capillary forces. It does not flow off the steep walls of the sealing aids due to cohesive forces.
- The second closed ring is not wetted, thus the seal is leak-tight in static condition.
- The second closed ring supports the function in static condition: If fluid accumulates in the interspace, the second closed ring stops it from flowing off.

1.2 Sealing mechanism in dynamic condition (rotating shaft):

- The first closed ring restricts fluid from penetrating into the interspace between the two closed rings.
- If fluid reaches the interspace it is dragged along by the shaft. A sealing aid deflects the fluid flow and collects fluid. At the intersection of sealing aid and first closed ring, a hydrodynamic pressure builds up, which pumps the fluid back to the oil side (Figure 1) [5].
- The second closed ring prevents fluid, not collected immediately, from exiting the interspace to the air side (i.e. leakage). A following sealing aid collects and pumps back the fluid. Therefore, the seals are leak-tight in dynamic condition.

2 Basic endurance test runs

The basic endurance test run is the fundamental test for all bidirectional PTFE lip seals. The shaft speed is 3000 rpm (12.6 m/s at the utilized shaft diameter of 80 mm), the oil temperature 120 °C and the rotational direction alternates every five hours. After 20 hours of runtime, the shaft stands still for 4 hours and the oil cools down at ambient temperature (~ 23 °C). This cycle is repeated 10 times, resulting in a total duration of 10 days. An engine oil (Fuchs SuperSyn 0W-30) with a kinematic viscosity of 68 mm^2/s at 40 °C is used. The fluid is filled to the middle of the shaft, which means a fluid volume of 1.2 l. Table 1 shows the operational conditions.

Table 1: Operational conditions – basic endurance test run

Speed [rpm]	Rotational direction	Duration [h]	Oil Temp [°C]	Oil level	Total duration
3000	left	5	120	middle of shaft	10 days
3000	right	5			
3000	left	5			
3000	right	5			
0	-	4	cool down		

Figure 4 shows leak rates measured during basic endurance test runs. Three bidirectional PTFE lip seals of the current design (PNJ), one earlier design (1st design) without a second closed ring and a PTFE seal with plain lip are compared. The seal with the plain lip and the first design seal show continuously high leak rates. Two seals of the current design show high leak rates at the beginning of the runs. Each day the leak rate reduces and after five days, the seals are completely leak-tight. One of the seals was leak-tight during the whole test run.

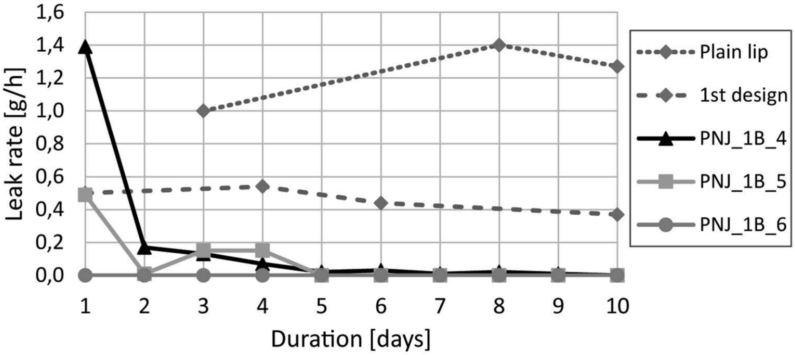

Figure 4: Comparison of leak rates in basic endurance test runs

3 Variation of operational conditions

Results of the basic endurance test runs were described in detail in prior publications [7], [8]. This paper presents latest investigations, which expand the frame of the basic endurance test runs to different operational conditions. They range from low speeds of 100 rpm (0.42 m/s) to high speeds of 8000 rpm (33.5 m/s). In addition, test runs with frequent changes of rotational direction and start-stop cycles are presented as well as runs with eccentric shafts. In all of these test runs, one parameter is varied, compared to the basic endurance test runs. If not specifically mentioned the other operational conditions remain unaltered. For each test run a table containing the operational conditions is given. The leakage at the beginning of the test runs, as described above, was avoided almost entirely, due to better manufacturing techniques and a better centered PTFE lip in the housing.

The main criterion for the function of the seals during all test runs is leakage. If leakage occurs repeatedly and reproducible, the seals are not suitable for the respective operational condition. Minor, not repeatedly occurring leak rates up to 0.05 g/h are tolerated. By using this approach, the limits of the current design of bidirectional PTFE lip seals are defined. Knowledge of these limits helps to identify areas where improvement is necessary.

The following paragraphs describe the test runs and results at the different operational conditions. The leak rate during all test runs was measured daily. If functionally important leak rates occurred (> 0.05 g/h), they are illustrated in a diagram, minor leak rates are mentioned in the text. For better comparison, all diagrams are scaled equal to the diagram of the basic endurance test runs (Figure 4). Interpretations relating to the sealing mechanism and plans for further development are detailed in chapter 4.

3.1 Function at low speed

The test runs at low speed aim to find out if the seals work at a speed of 100 rpm (0.42 m/s). Possibly, a critical low speed exists where the hydrodynamic pressure is not sufficient to pump back fluid. Table 2 shows the operational conditions of the test.

Table 2: Operational conditions – low speed

Speed [rpm]	Rotational direction	Duration [h]	Oil Temp [°C]	Oil level	Total duration
100	left	5	120	middle of shaft	10 days
100	right	5			
100	left	5			
100	right	5			
0	-	4	cool down		

Two seals were tested at low speed. One seal was completely leak-tight, the other seal showed minor leak rates with a maximum of 0.03 g/h.

3.2 Function at frequent start-stop of the shaft

The test runs with start-stop cycle consist of 30 minutes of shaft rotation and 30 minutes of standstill. The rotational direction was not changed after each stop but remained the same for five hours and changed thereafter, see Table 3.

Table 3: Operational conditions – start-stop

Speed [rpm]	Rotational direction	Duration [h]	Oil Temp [°C]	Oil level	Total duration
3000	left	0.5	120	middle of shaft	10 days
0	-	0.5			
Cycle repeated for 5 hours					
3000	right	0.5			
0	-	0.5			
Cycle repeated for 5 hours					
0	-	4	cool down		

Two seals were tested with the start-stop cycle. Both were completely leak-tight during the runs.

3.3 Function at frequent change of direction

During the runs with frequent changes of direction, the direction was altered every 10 minutes, see Table 4.

Table 4: Operational conditions – frequent change of direction

Speed [rpm]	Rotational direction	Duration	Oil Temp [°C]	Oil level	Total duration
3000	left	10 min	120	middle of shaft	10 days
3000	right	10 min			
Cycles repeated for 20 hours					
0	-	4 h	cool down		

Figure 5 illustrates the leak rates of the four seals tested. Two seals show a high leak rate during the first day. This run-in process occurred solely for those two seals, but was otherwise avoided. Afterwards the seals were leak-tight or had minor leak rates of maximally 0.05 g/h.

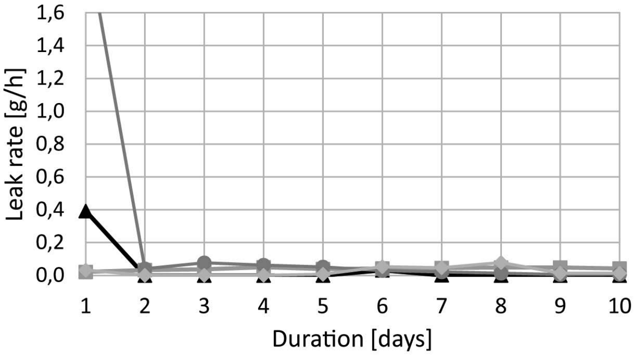

Figure 5: Leak rate – frequent changes of direction

3.4 *Function at increasing speed*

During the runs with increasing speed, the speed increased daily, from 500 rpm (2.1 m/s) to 8000 rpm (33.5 m/s). The runs stopped after nine days (8000 rpm), as all seals showed leakage. The test sequence is shown in Table 5.

Table 5: Operational conditions – increasing speed

Speed [rpm]	Rotational direction	Duration [h]	Oil Temp [°C]	Oil level	Total duration
500	left	5	120	middle of shaft	9 days
500	right	5			
500	left	5			
500	right	5			
0	-	4	cool down		
Speed increased each day to 1000/ 2000/… / 8000 rpm					

Figure 6 shows the leak rates of the four seals tested at increasing speed. All four were leak-tight up to 2000 rpm (8.4 m/s). Three seals were leak-tight up to 5000 rpm (20.9 m/s), which is at day six of the run. One seal was leak-tight up to 7000 rpm (29.3 m/s). At higher speeds, all seals showed leakage.

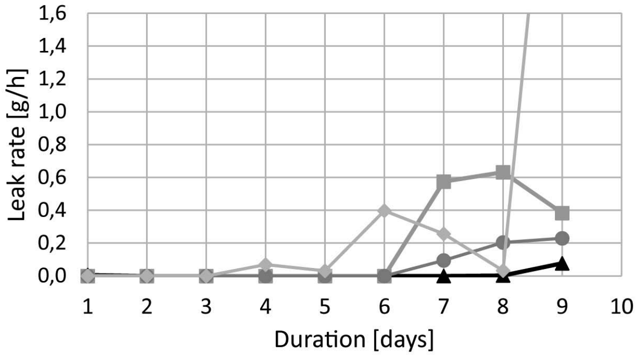

Figure 6: Leak rate – increasing speed

3.5 *Function with eccentricity of the shaft*

In addition to centered shafts used before, six seals were tested with eccentric shafts. Shaft eccentricity means the radial offset of the shaft axis. Accordingly, shaft eccentricity of 0.1 mm means a displacement of the shaft surface of 0.2 mm in one revolution. Eccentricities of 0.1, 0.2 and 0.3 mm were tested. Apart from the shaft eccentricity, the duration differed from the basic endurance test runs. Runs with shaft eccentricities of 0.2 and 0.3 mm were stopped after 7 and 6 days. The test sequence is shown in Table 6.

Table 6: Operational conditions – shaft eccentricity

Speed [rpm]	Rotational direction	Duration [h]	Oil Temp [°C]	Oil level	Total duration
3000	left	5	120	middle of shaft	6 to 10 days
3000	right	5			
3000	left	5			
3000	right	5			
0	-	4	cool down		
Shaft eccentricity 0.1/ 0.2/ 0.3mm					

Two seals for each shaft eccentricity were tested. Seals tested with an eccentricity of 0.1 mm were completely leak-tight during the test runs. An eccentricity of 0.2 mm caused minor leak rates of a drop of fluid on some days, on other days the seals were completely leak-tight. At an eccentricity of 0.3 mm, the seals showed repeatable but minor leak rates of 0.004 g/h as a maximum.

4 Interpretation of the results and further development

During the tests at low speed (100 rpm/ 0.42 m/s), one seal was completely leak-tight, which shows that the sealing mechanism works and a hydrodynamic pressure builds up at the sealing aids. To prove if a critical low speed exists, where the sealing mechanism breaks down, tests with lower speeds are scheduled.

No leakage appeared during the start-stop cycles. The sealing mechanism works for short periods (30 min) of shaft rotation and standstill. During shaft standstill, fluid is contained and pumped back in the periods when the shaft rotates. Test runs with shorter intervals, as well as start-stop cycles at lower speeds are scheduled.

Frequent changes in rotational direction led in some cases to a minor, but repeatable leak rate. The reason for this is probably a very small amount of fluid that leaks at every change in direction. The cause of the leakage will be analyzed further. Therefore, test runs with more and with fewer changes in direction are scheduled. If the leakage results from the changes in direction, the leak rate will correlate to the amount of changes.

During test runs with eccentricities of 0.1 mm, the seals were completely leak-tight, while eccentricities of 0.2 mm led to occasional minor leak rates. Shaft eccentricities of 0.3 mm led to minor leak rates which were still remarkably low (0.004 g/h maximal), as a higher amount was expected. The sealing mechanism works because of the accurate contact of the sealing aids and the shaft. If the eccentricity is too high, the sealing aids do not contact the shaft as intended and the sealing mechanism does not work. The higher the eccentricity, the worse is the contact of sealing aids and shaft. Another definite influence on the function is the combination of the shaft speed and the eccentricity. The PTFE lip cannot follow large displacements of the shaft surface at high speeds, which leads to leakage. Therefore, test runs with eccentricity and increasing speed are planned. That way a critical speed for each eccentricity will be defined.

Overall, the seals worked well at the conditions described above. Although some seals showed minor leak rates, the sealing mechanism works essentially. The main limit are high shaft speeds. At a critical speed of 5000 rpm (20.9 m/s) the seals begin to leak distinctly with high leak rates. Generally, plain PTFE lip seals trend to increased leak rates at high speeds [9]. Various influences could cause this effect: a change of the fluid film height in the sealing gap, reduced fluid viscosity or changes in the fluid flow. The bidirectional PTFE lip seals of the current design avoid leakage up to the critical speed because they actively pump back fluid. At the critical speed, the leak rate exceeds the pumping rate. The fluid between the closed rings cannot be pumped back, passes the second closed ring and leaks to the air side. This corresponds with the hypothesis of the sealing mechanism in dynamic condition. The closed rings act as barriers that retain fluid, so the sealing aids can collect it and pump it back. More seals will be tested at speeds of 4000 to 6000 rpm to analyze the behavior at critical speed more precisely.

Additionally, new test runs to broaden the range of operational conditions even further, are planned. In these, temperatures will be varied between - 20 °C and 170 °C. Due to the high thermal expansion of PTFE, these temperature differences could influence the contact of sealing aids and shaft and therefore the sealing mechanism. Tests with other fluids, primarily oils of other viscosities are planned. The viscosity could influence the sealing mechanism, especially the hydrodynamic pressure at the sealing aids and the fluid film in the contact area. Furthermore, test runs at operational conditions presented in this paper, will be combined with eccentric shafts. In addition to tests with eccentric shafts, tests with static displacement of the seal are planned. To test the sealing mechanism for smaller applications, the current design was scaled down to a shaft diameter of 50 mm. Seals for this shaft diameter will be stamped and tested.

5 Conclusion

This paper presents the current design of bidirectional PTFE lip seals and explains the hypothesis on the sealing mechanism. According to the function at various operational conditions, limits of the seals were determined. The seals work leak-tight in both rotational directions up to 5000 rpm (20.9 m/s) at an oil temperature of 120 °C. Additionally they are leak-tight during start-stop operation and frequent changes in rotational direction. They can also cope with shaft eccentricities of at least 0.2 mm at 3000 rpm (12.6 m/s).

Are bidirectional PTFE lip seals superior to elastomeric radial lip seals? The answer to that question is not simple.
For “standard” operational conditions, elastomeric seals are clearly the best choice. They are proven, reliable-working seals, used in a multitude of different applications. The current state of technology for bidirectional PTFE lip seals cannot rival this enormous advantage in knowledge. However, PTFE is superior when it comes to chemical and thermal resistance. At high temperatures and in combination with chemically aggressive fluids, plain PTFE lip seals are in use today. In this area, bidirectional PTFE lip seals can provide leak-tight operation.

One day it might be possible to replace elastomeric seals with ones made of PTFE compounds. A main benefit would be the universal chemical compatibility. Prior to this, a large amount of development and testing is necessary and even so elastomeric seals might never be obsolete. However, just two years ago, it was not possible at all, to achieve complete leak-tightness with PTFE lip seals in applications dictating alternating shaft rotation. The work presented is another step towards the goal of reliable-working bidirectional PTFE lip seals. With the knowledge gained, the design of the seals will be optimized to further improve the function of the seals. The goal of all investigations is to gain a better understanding of the sealing mechanism and to achieve complete leak-tightness at a wide range of operational conditions.

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