Shaft Seal Systems of Rotary Equipment in Cryogenic Plants

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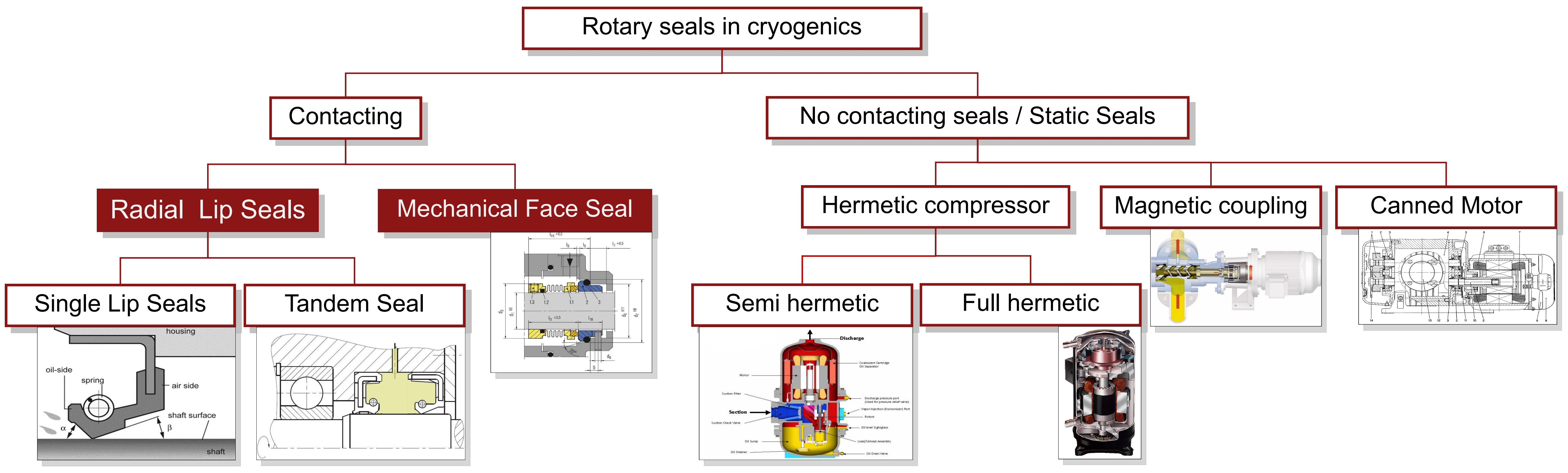
Cryogenic Operations 2016

SLAC-PUB-16847

Introduction

Rotating machinery such as compressors, vacuum pumps, oil pumps are widely used in cryogenics. Uninterrupted operation of these components is crucial for the overall system availability .

Leaking shaft seals are a major source of failure and require often high efforts and time consuming maintenance. A brief overview about the requirements, general designs and technical functionality of shaft seals in particular for cryogenic equipment will be given here. A classification of sealing systems is shown in the tree diagram. The focus in this presentation is set on contacting seals which are the most common used designs in current practice.



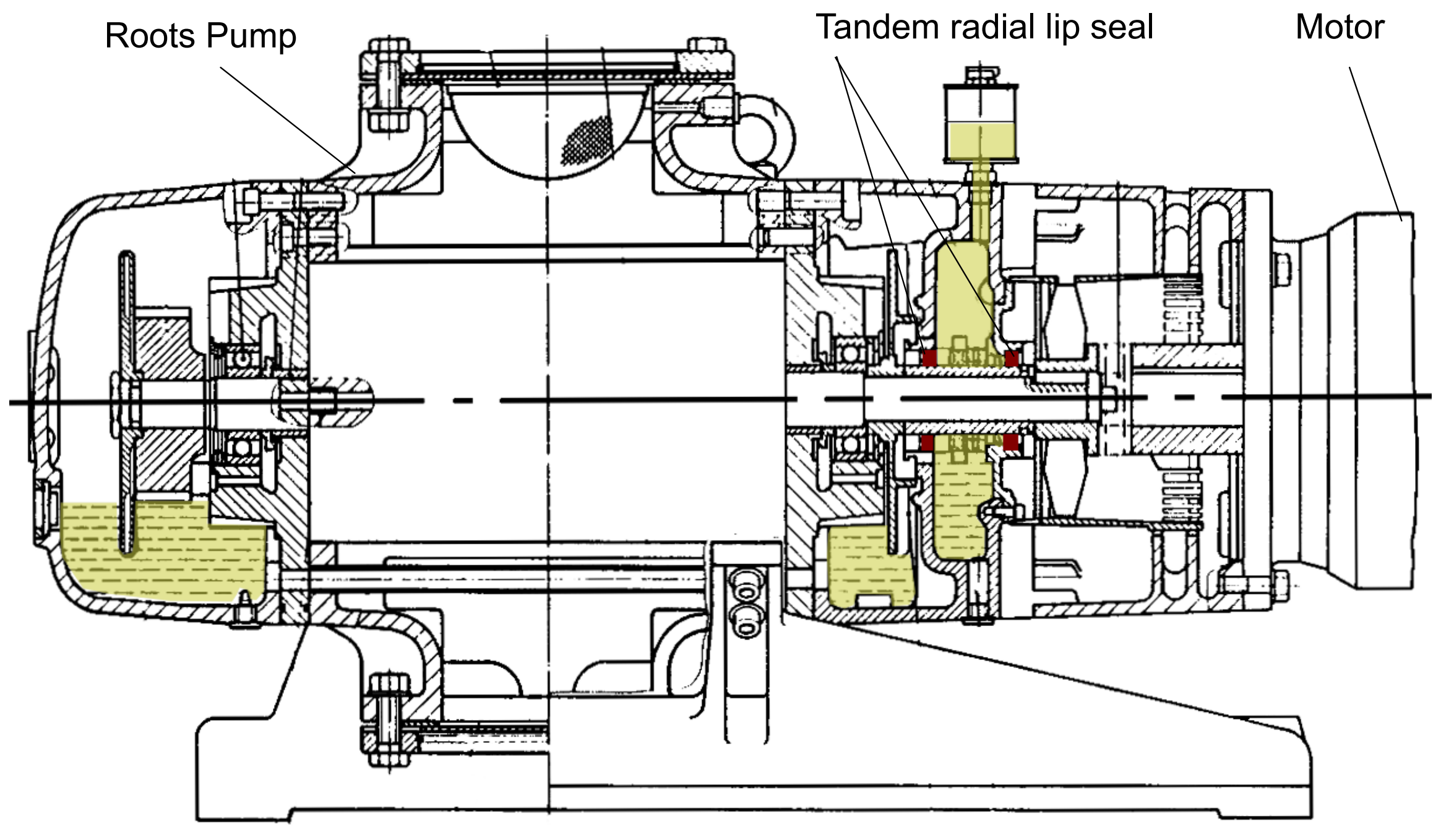
Rotary seals in cryogenics

- Contacting
  - Radial Lip Seals
    - Single Lip Seals
    - Tandem Seal
  - Mechanical Face Seal
- No contacting seals / Static Seals
  - Hermetic compressor
    - Semi hermetic
    - Full hermetic
  - Magnetic coupling
  - Canned Motor

Radial Lip Sealing

To seal **non-pressurized fluids** on a shaft passage the radial lip seal is used since the 1940s. The principle of sealing seems to be simple at the first sight but when looking to the hydrodynamic sealing mechanisms in detail, it is not fully understood even today.

The requirements for leak tightness to the shaft sealing on vacuum pumps generally and to cryogenic processes in particular are extraordinary. Among the demand to prevent the oil from leaking to the outside it also has to ensure that no air gets inside the process. While an air penetration to a common vacuum pump means in effect the degradation of the minimal suction pressure, pollution of a helium process gas stream can cause severe damage to the cryogenic system. To ensure air leak tightness of process vacuum pumps tandem radial lip sealing with a sealing fluid in between can be used.



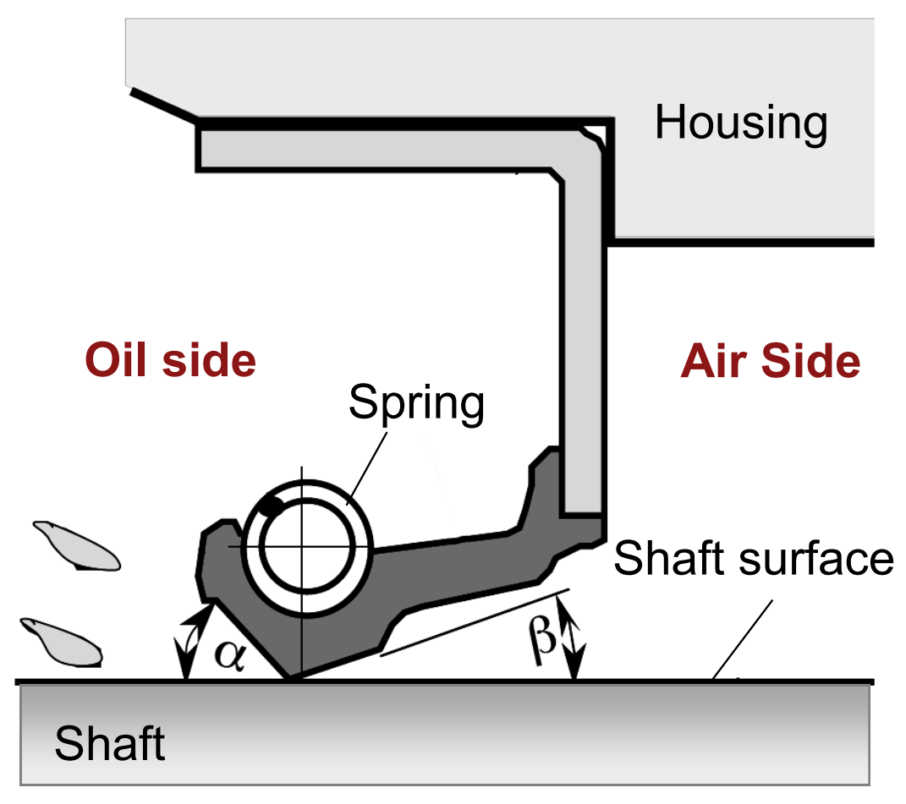
Roots Blower with a tandem radial lip seal and sealing fluid

A cross-section view of a typical radial lip seal is shown below. A large variety of different designs in detail exists on the market while the basic sealing principle stays the same. The sharp lip seal contacts the shaft surface, the radial forces are generated by a garter spring in combination with the elastic forces of the asymmetric seal design. The width of the contact surface is 0.1...0.15 mm and can increase due to normal wear up to 0.2...0.7 mm. The asymmetric contact angles α (40...60°) and β (20...35°) as well as the slight offset of the spring center to the lip center are essential for the dynamic sealing functionality.

Under normal operating conditions this design is able to be leak tight, which means no significant amount of oil drops from the shaft over a long period of operation time. The development of microstructures on the lip seal during the initial wear allows the formation of an elasto-hydrodynamic condition between sealing surface and shaft surface. In experiments it was demonstrated that a well-functioning lip seal is able to transport (pump) oil from the air side to the oil side.

The surface roughness of the shaft should be achieved in the range of R_z=1...5 µm with a hardness of 55 HRC minimum. Scratches especially in axial direction have to be avoided.

The **assembling of the lip seal is the most critical part** in the lifetime of a lip seal. Damage of the sharp sealing lip due to sharp burr and dust and fibers can cause leaks after very short operation time. To avoid any impurities the sealing surfaces should not be touched and no grease must be used for initial lubrication. Cleanliness, proper auxiliary tools and a good working environment is important for a successful assembling.

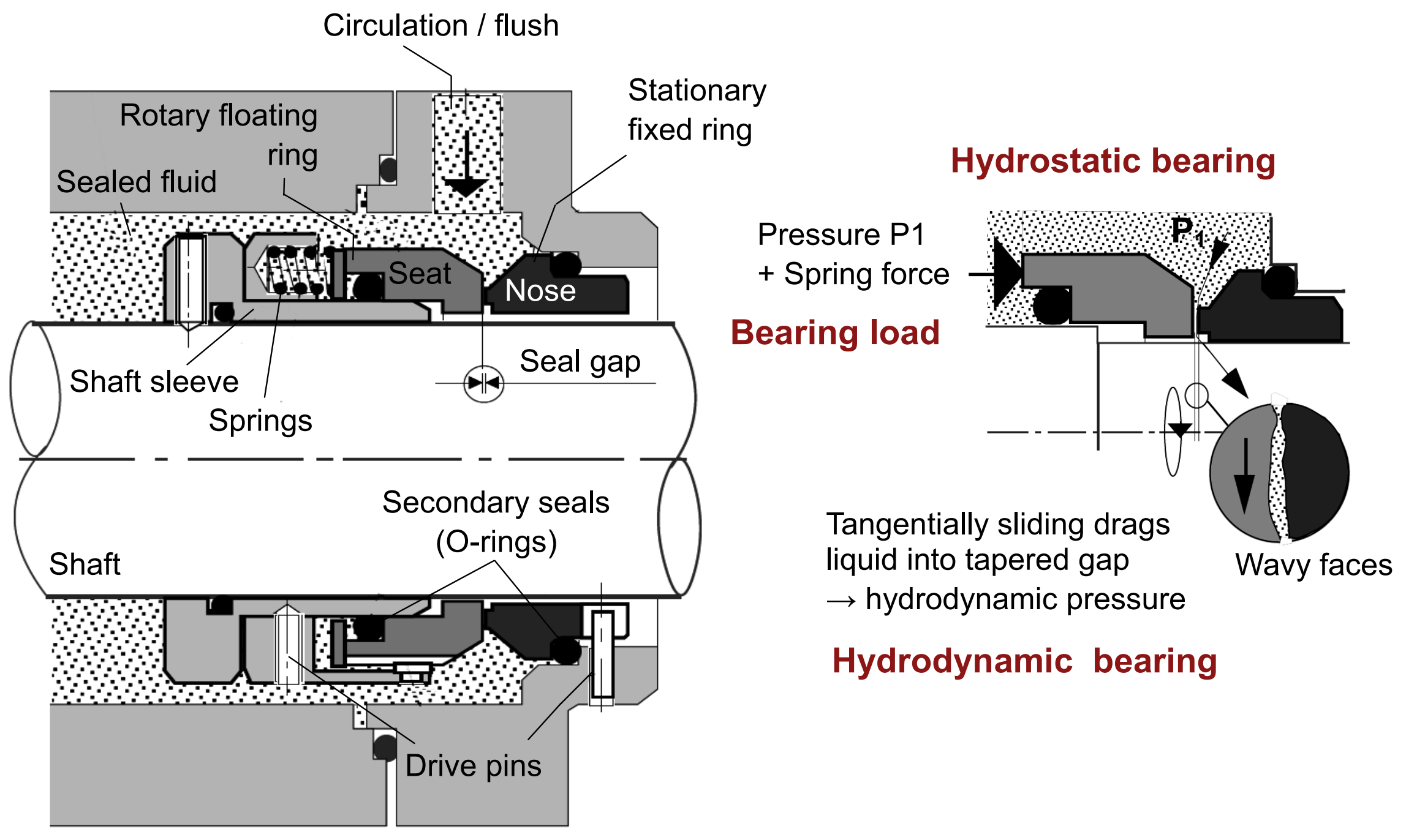


Typical design of radial lip seal

Mechanical Face Seal

Mechanical face seals are used to seal **pressurized fluids** on rotating shafts. This system is widely used on helium cycling compressors and associated lube oil pumps.

A typical design of a mechanical seal is shown in the picture below. The rotating seat is pressed against a fixed nose by static pressure and spring force. A reversed arrangement of seat and nose is possible as well.

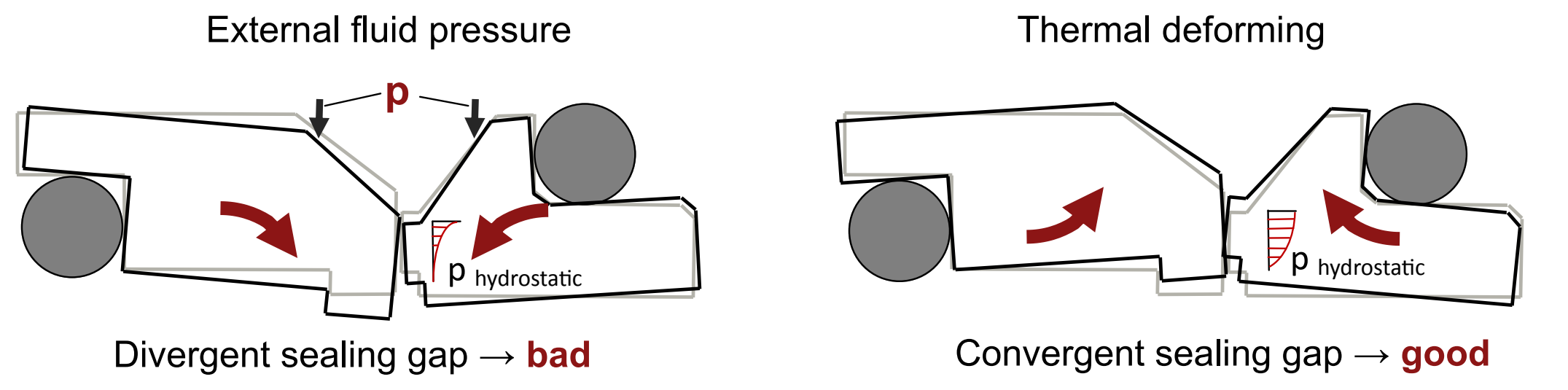


Cross-section of a typical mechanical seal

Due to the ability of the axial movement of the seat wear and thermal expansion are compensated automatically, both sealing parts stay in permanent contact. Carbon graphite rings in combination with a metal or ceramic counterpart are most common used materials. O-rings provide secondary static sealing. The sliding O-ring seal between the shaft sleeve and seat can be replaced by metallic or elastomer bellows.

Without rotation the flat and plane lapped surfaces of seat and nose touch each other to seal the fluid inside the pump body. When the rotation of the shaft starts, the surfaces separate from each other and form a fluid gap by hydrodynamic lubrication. In ideal conditions the fluid gap is in the order of 1 µm. The mechanism of sealing is working as a **combination of a hydrostatic and hydrodynamic system** (see figure above).

Deforming caused by thermal expansion and pressure forces can lead to a convergent or divergent gap between the sealing surfaces. A convergent gap has a positive influence on the hydrostatic pressure profile in terms of leak tightness while a divergent gap tends to leak. Adaptive wear can mitigate this deforming after certain operation time. However, a changing of operation conditions (fluid pressure and temperature) will force a new run–in wear which can increase the risk of excessive wear and leaks.



Deformation of a mechanical seal by pressure and thermal impact

Very complex mechanisms on a microscopic scale are responsible for a long term proper sealing. Failures can have many reasons, the most common are listed below:

1. Assembling failures

- Wrong spring load
- Wrong O-ring (size, material)
- Dirt particles between seal surfaces
- Skewed counter ring
- Damage on sealing ring
- Damage on secondary sealing

2. Operational failures

- Low cooling fluid circulation
- Oil degradation due to high temperatures
- Strong vibrations
- Depositions on sealing surfaces
- Abrasive wear
- Dry run (e.g. bubbles between sealing gap)

3. Fabrication failures

- Damaged secondary seals
- Casing lid askew
- Very wavy sealing surfaces
- Failure on bellows
- Rough surface on secondary seal

4. Design failures

- Choice of material pairing
- Surface ratio (balancing)
- Wrong spring force
- Deformation by wrong design
- Resonant vibration on bellows
- Rough surface on secondary seal

Conclusion / Outlook

Shaft sealing systems such as mechanical seals and radial lip seals may appear as proven technology since many decades. Practice in cryogenics shows that one of the major reasons for failures and high maintenance cost are leaking shaft seals on compressors, oil pumps and vacuum pumps. The causes for failing seals are often high local temperatures, vibrations, general design or assembly failures.

The picture below shows a mechanical face sealing damaged by local high temperatures and oil degradation (oil: Breox B35).

Sliding ring of an oil pump, despite moderate fluid temperatures local overheating lead to damage and fail

Alternative and new developed sealing principles like magnetic coupling, semi or full hermetic devices become more and more popular in the cryogenic field as they avoid any dynamic sealing and provide long term reliability. These technologies are today still limited to small or mid size units such as vacuum pumps and oil pumps. Helium Cycling compressors for large scale cryoplants are sealed with mechanical face sealing as the state of the art.

New materials as special ceramics as well as the better theoretical understanding of the principles and limits for these sealing systems should lead to an increase of reliability in the future.

Brief summary of recommendations for shaft sealing systems:

- **Choice of right sealing system for required operation case**
  - Pressurized / non pressurized fluid
  - Changing pressure ratios, risk of air in leaks
- **Choice of right materials and material pairings**
- **Minimize local temperatures on shaft sealing**
  - Optimize local fluid cooling
- **Condition of shaft and housing according to spec**
  - Surface roughness
  - No burrs, scratches
  - Roundness
  - Alignment, concentricity
- **Very careful handling during shaft seal assembling**
  - Tooling (mounting sleeve, press-in tools)
  - Proper cleaning, don't touch sealing surface
  - Cartridge sealing can avoid assembling errors

References / Acknowledgements

- www.fachwissen-dichtungstechnik.de
- Fluid sealing technology principles and applications, Muller, H. K., CRC Press 1998
- Seals and Sealing Handbook 6. edition, Flitney, R. K., Elsevier Science and Technology 2014
- Shaft Seals for dynamic applications, Horve, L. A., M. Dekker, Inc. 1996
- Fluid sealing, Nau, B.S., Springer-Science + Business Media Dordrecht 1992

Work supported by Department of Energy contract DE-AC02-76SF00515

Picture credits:

- Leybold RUVAC WS/WSU 251/501/1001/2001 operating instructions
- Dunham-Bush Prospect Vertical Medium Screw Compressors MSC 110mm series
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- KRAL magnetic coupled pressure lube oil pump
- Copeland full hermetic scroll compressor