Tribometer for the Investigation of Self-Lubricating Sealing Materials under Realistic Compression Conditions

Max JOSWIG[1], Konrad KLOTSCHE[1], Christiane THOMAS[1]

[1]Technische Universität Dresden,
Faculty of Mechanical Science and Engineering,
Institute of Power Engineering,
Schaufler Chair of Refrigeration, Cryogenics and Compressor Technology
Dresden Germany
max.joswig@tu-dresden.de

ABSTRACT

The transition to renewable energy sources poses various challenges. For instance, due to their volatility, there is a growing need for transporting and storing renewable energy. Hydrogen is often considered for this.

Compressor technology shows numerous applications that require oil-free compression to maintain high gas purity levels, including hydrogen in fuel cell applications. Reciprocating crosshead compressors can deliver and store hydrogen at high pressure. However, relevant sealing materials such as fluoropolymers and thermoplastic polymers for rider bands and piston rings yield significant wear and friction under high loads. Additionally, concerns have been raised about the adverse effects of the bioaccumulation and persistence of per- and polyfluoroalkyl substances (PFAS) like many fluoropolymers once released into the environment. This has led to the proposal to ban these substances within the European Union. Therefore, it is necessary to experimentally investigate the tribological behavior of self-lubricating sealing materials under realistic compressor conditions to eventually find alternative PFAS-free sealing materials with suitable oil-free tribological properties.

The paper outlines a specialized tribometer designed to analyze friction and wear of sealing materials for reciprocating compressors. The tribological system components, including the forces, movements, and gas influence the frictional behavior of material pairings. The tribometer can provide a realistic compression atmosphere while continuously monitoring friction and wear. The research helps to identify materials that endure high-pressure compression, exhibit low friction and wear, and comply with PFAS-free requirements.

1. INTRODUCTION

1.1 Hydrogen Outlook and Compression Methods

According to the Intergovernmental Panel on Climate Change (IPCC) report, global temperatures are expected to continue increasing at an alarming rate, with a projected increase of 1.4 to 2.5 K in global surface temperature, leading to more frequent and severe heatwaves, flooding, and other extreme weather events (IPCC, 2023). As a result, there is a pressing need to transition to cleaner and more sustainable energy sources to mitigate the impact of climate change. This has sparked a renewed focus on hydrogen as a versatile and clean energy carrier that can be produced from renewable sources.

The demand for hydrogen is expected to increase significantly, driven by the transition to cleaner energy sources and the need for energy storage and transportation. According to a global estimation, the demand for hydrogen is projected to reach 125 to 585 Mt/a by 2050, up from the current approximately 90 Mt/a. This substantial increase is attributed to the growing significance of hydrogen in various sectors, including mobility, domestic heating, and electricity generation (McKinsey & Company, 2022).

Given the increasing demand for hydrogen and its significance as an energy carrier, there is a crucial need for pure (oil-free) compressed gas in various high-pressure applications. These applications include storage tanks operating at pressures ranging from 200 to 500 bar, trailers at 350 bar, grid operations at 100 bar, and passenger cars and trains requiring pressures of up to 700 bar and 350 bar, respectively (Töpler and Lehmann, 2017). Furthermore, high gas purity is essential for hydrogen fuel cell applications, requiring minimal residual hydrocarbons (2 ppm) as specified in, e.g., ISO 14687 (2019). It is preferable to use oil-free compression in these critical applications to prevent impurities from being transferred into the downstream application.

Numerous compression principles, such as piston, hydraulic, ionic, and diaphragm compressors, achieve high-pressure compression without compromising gas purity, as depicted in Figure 1. However, it is essential to consider each compression principle's specific characteristics and requirements. Hydraulic, ionic, and diaphragm compressors usually provide low volume flows. Upscaling can increase the volumetric flow for these compressors but comes with the drawback of higher installation and maintenance costs compared to piston compressors (Harder et al., 2021). On the other hand, piston compressors offer high volumetric flows and efficiencies, making them well-suited for applications where high-pressure gas delivery is required.

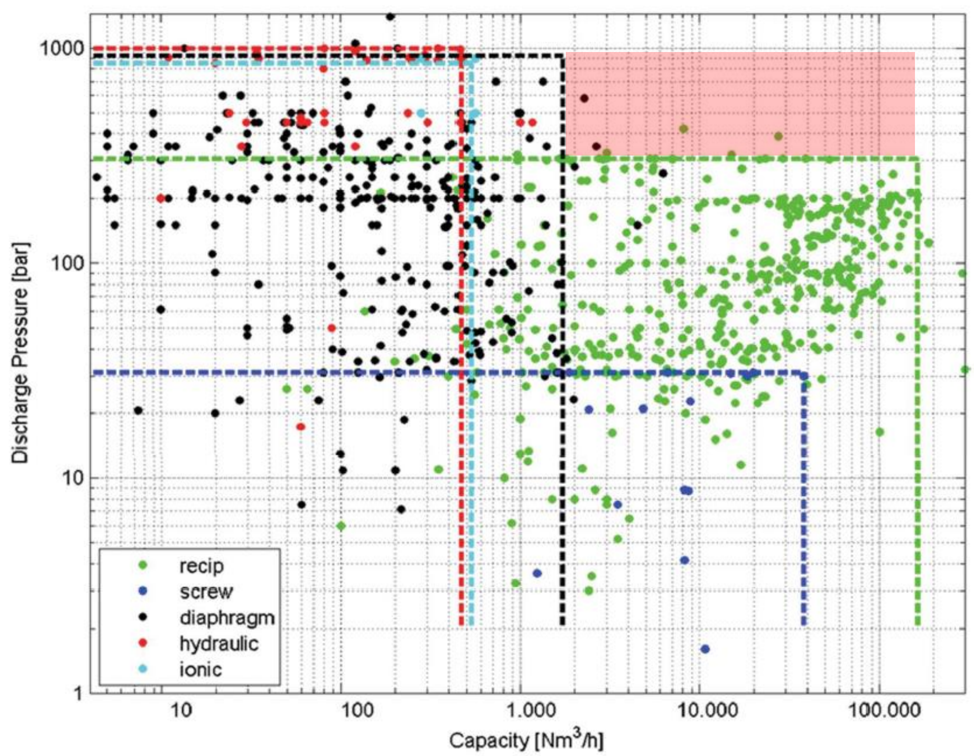

Figure 1: Compressor map with current industrial references (dots) and performance ranges (dashed lines) for pure hydrogen applications (EFRC, 2022)

The red area in Figure 1 illustrates that reciprocating compressors are limited to discharge pressures in the low hundreds of bars, mainly because self-lubricating sealing materials have not been developed for high pressures. Additional research is needed to extend the range of application of oil-free reciprocating compressors into the highlighted area, as current self-lubricating materials still experience high wear.

1.2 State of the Art of Sealing Materials

The tribological requirements demand the so-called self-lubricating sealing materials for continuous sliding, low friction, minimal wear, good heat conduction, and chemical resistance. They must also show heat resistance, limited brittleness, adaptability to different forms, and minimal metallurgical flow and thermal expansion. Fluoropolymers like Polytetrafluorethylene (PTFE) and blends of polymers such as Polyphenylsulfide (PPS), Polyimide (PI), and high-temperature polymers such as Polyetheretherketone (PEEK) are commonly used for this purpose.

Furthermore, as the European Union seeks to regulate the use of PFAS the choice of materials may be further restricted. The European Chemicals Agency (ECHA) scientific committees are currently evaluating a restriction proposal and comments submitted until 25 September 2023, with the evaluation expected to continue until at least September 2024. If accepted, a ban on fluoropolymers for such applications would take immediate effect without derogation (ECHA, 2024).

This paper introduces a novel tribometer design specifically developed to investigate and analyze the tribological performance of sealing materials to meet regulatory standards.

2. TRIBOLOGICAL FUNDAMENTALS

2.1 Tribological System

A systematic approach is used to break down a tribological system into its constituent parts for detailed analysis. Figure 2 shows the system's structure and operating variables influencing surface changes, energy dissipation, and material loss.

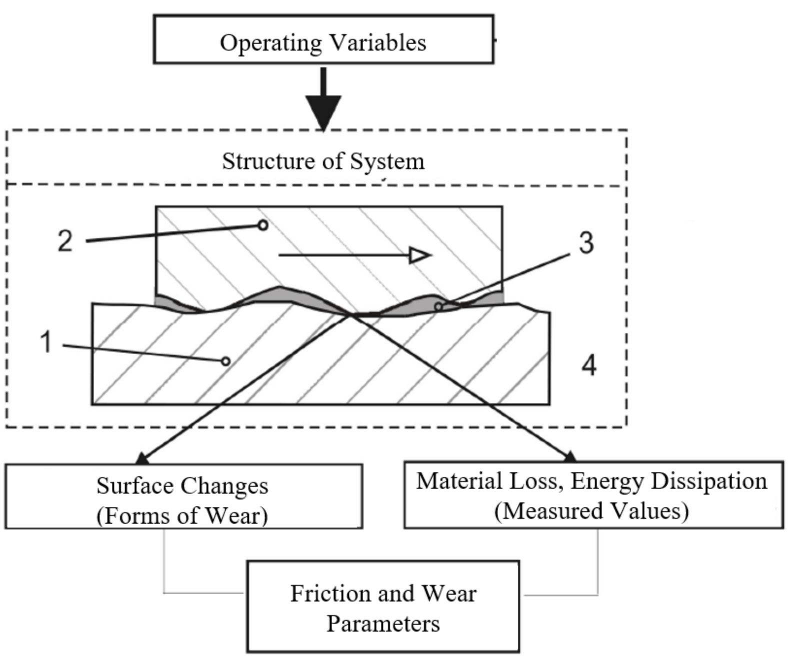

Figure 2: System structure of a tribological system (Czichos and Habig, 2015)

When comparing a tribological system, such as a piston ring-cylinder wall in an oil-free operating reciprocating hydrogen compressor, the analysis presented in Table 1 can aid system analysis and serve as a design concept for the present tribometer.

Table 1: Breakdown of the tribological system for a hydrogen compressor

	System Breakdown		**Counterpart Hydrogen Compressor**
Structure of System	(1)	Sliding body	Sealing element (piston ring, rod packing)
	(2)	Counter body	Cylinder wall
	(3)	Interfacial medium	None (not lubricated)
	(4)	Surrounding medium	Hydrogen
Operating variables	Load (progression, duration)		Following the working cycle of the piston
	Velocity		Defined by compressor drive
	Temperature		Gas and Body Temperature
	Type of Movement		Sliding
	Form of Movement		Oscillating

The friction between the two bodies depends on the tribological system and is described by the coefficient of friction:

$$\mu = \frac{F_F}{F_N}\,[1] \tag{1}$$

Where F_F and F_N represent the friction force and the normal force, respectively. The wear factor k is calculated by dividing the wear volume by the acting normal force F_N and the sliding distance s:

$$k = \frac{V}{F_N \cdot s}\ \left[\frac{m^3}{N \cdot m}\right] \tag{2}$$

The amount of worn material is also heavily dependent on the gas surrounding the sealing element, the roughness of the counter surface, the temperature and other material-dependent factors..

2.2 Established Tribometer Designs

Tribological investigations in hydrogen have been conducted with established tribometer designs. The following paragraphs aim to provide a summary of published information on hydrogen tribometers. This review is not exhaustive and represents the authors' understanding based on publicly available sources.

Table 2: Tribometer designs available in the public domain used for hydrogen applications

	Optimol SRV®5 (Optimol Instruments, 2024)	**Kyushu University** (Sawae et al., 2009, 2010; Sawae and Sugimura, 2010)	**Stasskol** (STASSKOL, 2024)	**BAM CT2** (BAM, 2024; Theiler and Gradt, 2021)	**BAM VT1** (BAM, 2024; Theiler and Gradt, 2015)	**Pacific Northwest National Laboratory** (Duranty et al., 2017, 2018)
Type	Oscillating	3-Pin on disc	Oscillating	Pin/ball on disc, contin./ recipr.	Pin/ball on disc, contin.	Steel ball on a plate, oscillating
Speed [m/s]	10^{-4}…0.5	0.1	< 6	10^{-5}…10	10-5…10	0.1
Geometry	-	58 mm disc diameter	130 mm stroke	-	-	-
Contact Force/ Pressure	1…5000 N	4 MPa	1…10 MPa	5…1000 N	1…500 N	-
Gas Pressure [MPa]	10.0	40.0	0.125	10^{-8}…10^{-1}	10^{-3}	34
Temperatures [°C]	-40…150	20	80…200 (counter body)	-269…23 (gas)	-80, 600 (gas)	-
Specimen	1	3	4	-	-	-

Only limited information is available on tribometers for hydrogen applications as the majority is custom-made. The typical design involves a pin-on-disc configuration at elevated gas pressure, which may allow mimicking an oscillating motion by continuously accelerating and decelerating the disc. However, limited disc diameters raise questions about reaching typical average piston speeds.

Few tribometers provide an actual oscillating movement. These are generally better for achieving average piston speeds but are often limited in the maximum gas pressure they can reach.

General observations indicate that both configurations can attain suitable contact pressures. Additionally, temperatures are often within the appropriate range for compressor applications. Established tribometers, however, have limitations in testing multiple specimens simultaneously. This restricts the efficiency of conducting tests at scale and may prolong the overall testing process.

However, current technology has room for improvement, including suitable temperature and gas pressure combinations, movement type and speed, and parallel specimen tests. This paper introduces a new tribometer design that addresses the key factors to meet these requirements.

3. PRESENT TRIBOMETER DESIGN

The tribometer is designed according to the tribological analysis in Table 1 and is based on compressor parts to ensure accurate and transferable tribological results. It uses a linear reciprocating principle focusing on average piston speeds, reciprocating movement, and sinusoidal velocity matching the application. This setup uses sealing material specimens instead of sealing rings to allow for measurement technology access and ensure a constant sliding area. The following paragraphs describe the design.

3.1 Friction and Wear Measurement Assembly

The assembly shown in Figure 3 includes a piston rod (1) that carries the exchangeable sealing material specimen (2). It oscillates according to the compressor drive and can accommodate four specimens simultaneously, with a dedicated assembly for each specimen on the tribometer.

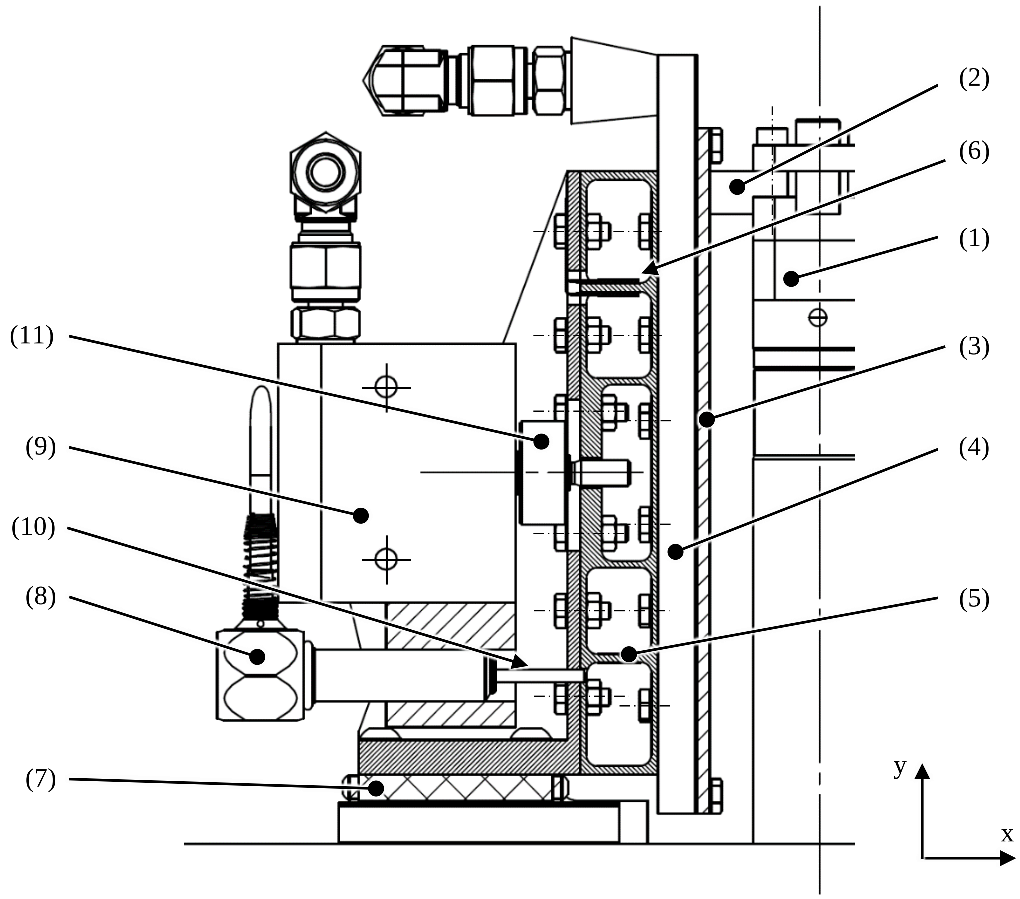

Figure 3: Friction and wear measurement assembly

The specimen rubs against a sliding counter body (3), which is exchangeable. It is placed on a cooling element (4) to dissipate the frictional heat through internal cooling channels. Each counter-sliding body has a temperature sensor on the side facing away from the frictional contact at mid-stroke and top dead center to measure the body temperature near the frictional contact point.

The spring body (5) holds the cooling element and the counter sliding body. It is designed to improve sensitivity for friction force-induced deformation with a reduced section modulus in the x-direction. Strain gauges (6) are attached in a full Wheatstone bridge circuit for strain measurement, specifically in the x-direction, and configured to exclude normal strain sensitivity. This enables the measurement of friction force in operation.

The mentioned parts are located on a slide bearing (7) to continuously move towards the specimen as it gradually reduces in volume due to wear. This is necessary to maintain a constant load on the frictional contact and enables continuous measurement of wear progression. The linear displacement in the x-direction is measured using a linear variable differential transformer (LVDT) (8) with its coils fixed underneath a hydraulic cylinder (9). At the same time, its core (10) is attached to the spring body to track linear displacement. According to Equation 2, this measurement delivers the values for the calculation of the wear volume based on the known specimen's section dimensions.

The hydraulic cylinder continuously maintains the normal load to replicate the pressure on the sealing elements. As the specimen wears, the hydraulic cylinder advances towards the piston rod. A force sensor (11) measures the acting force, which equals the normal force on the frictional contact. The measured forces can then be used to calculate the coefficient of friction of the tribological system using Equation 1.

Each sensor and part of the friction measurement assembly is compatible with hydrogen and withstands the gas pressures and temperatures mentioned in Table 3.

Table 3: Measurement technology of the tribometer

Physical Parameter	Instrument	Range	Uncertainty
Temperature Counter Body	Type K Thermocouple	< 1100 °C	+/2.5 °C or +/- 0.75 %
Temperature Gas	Type K Thermocouple	< 1100 °C	+/2.5 °C or +/- 0.75 %
Linear displacement due to wear	eddyLab SM10-S-KR-F14-X0254	0…10 mm	+/-0.30 %
Friction Force	HBM M-Series Strain Gauges	< 250 N	+/-3 %
Normal Force	Octogon H2AV4	-	-
Gas Pressure	Bronkhorst P-602CV	-	+/-0.5 %

3.2 Tribometer Assembly and Periphery

The containment encloses the friction and wear measurement assemblies in a completely sealed environment to control the atmosphere for tribological tests. It can be detached to allow easy application of specimens onto their holders for experiment preparation. The containment can be pressurized with hydrogen or other gases up to 20 bar(a), reaching maximum gas temperatures of 150 °C. Additionally, it is equipped with sight glasses.

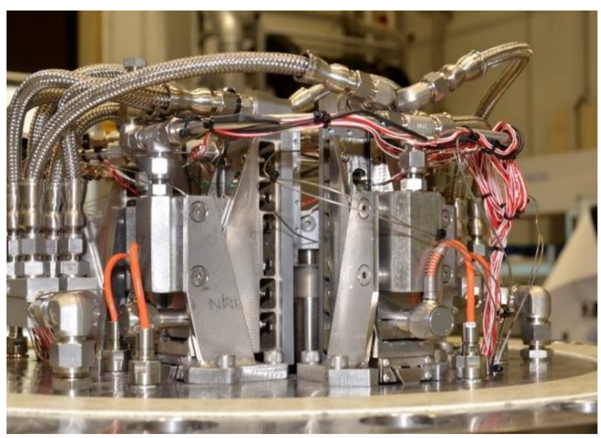

Figure 4: Tribometer assembly periphery (left), friction and wear measurement assemblies (right)

The drive (incl. the electric motor) is a standard model that simplifies the design and manufacturing of the tribometer. It provides a vertical crosshead-type movement for conducting tribological tests on specimens while minimizing the effects of gravitation on measurements.

The containment, including friction and wear measurement assemblies, is located at the top of the drive. The tribometer has two compressor drives with two piston rods each to accommodate specimen holders, allowing for 16 specimens equipped with individual friction and wear assemblies. This arrangement enables simultaneous testing of multiple samples, ensuring accurate statistical results. Table 4 provides a comprehensive overview of the tribometer design specifications, including key parameters and performance metrics.

Table 4: Tribometer specifications

Gases	Hydrogen, nitrogen, others
Gas pressure	< 20 bar(a)
Gas Temperatures	20 … 150 °C
Number of specimens	16
Measurement features	Continuous wear, friction, and counter-sliding body temperatures
Average piston speeds	1.5 … 3.1 m/s
Maximum normal load	850 N
Frictional Contact	Reciprocating, oil-free
Oscillating frequency	350…725 rpm
Stroke	130 mm

4. CONCLUSIONS

The presented tribometer facilitates thorough testing of sealing materials (especially PFAS-free) to identify optimal sealing solutions for oil-free reciprocating piston compressors. It enables reliable and efficient piston compressor technology for high-pressure applications by meeting the demand for pure, high-pressure hydrogen compression in line with tribological needs, climate goals, and regulatory limitations.

Associated research also focuses on other potential applications that require oil-free compression, such as in air or process gas compression with high purity standards. Introducing oil-free compression in areas where it has not yet been implemented presents further opportunities. For example, the challenge of using oil-lubricated compressors in refrigeration technology due to the miscibility of oil with refrigerants and resulting decreased heat exchanger and overall system efficiency performance can be addressed by transferring reliable oil-free technology and experiences from hydrogen compressors.

NOMENCLATURE

F	force	[N]
k	wear rate	[m^3/(N m)]
s	sliding distance	[m]

Subscript

F	friction
N	normal

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ACKNOWLEDGEMENT

The project is carried out in cooperation with Mehrer Compression GmbH, Balingen, Germany. It is supported by the Federal Ministry for Economic Affairs and Climate Action (BMWK) through the Zentrales Innovationsprogramm Mittelstand (ZIM) under the funding code KK5038002AB0.