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Magnetic nanofluids and magnetic composite fluids in rotating seal systems

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Abstract

Recent results are presented concerning the development of magnetofluidic leakage-free rotating seals for vacuum and high pressure gases, evidencing significant advantages compared to mechanical seals.

The micro-pilot scale production of various types of magnetizable sealing fluids is shortly reviewed, in particular the main steps of the chemical synthesis of magnetic nanofluids and magnetic composite fluids with light hydrocarbon, mineral oil and synthetic oil carrier liquids. The behavior of different types of magnetizable fluids in the rotating sealing systems is analyzed. Design concepts, some constructive details and testing procedures of magnetofluidic rotating seals are presented such as the testing equipment.

The main characteristics of several magnetofluidic sealing systems and their applications will be presented: vacuum deposition systems and liquefied gas pumps applications, mechanical and magnetic nanofluid combined seals, gas valves up to 40 bar equipped by rotating seal with magnetic nanofluids and magnetic composite fluids.

Keywords: Rotating Seal, Magnetic Nanofluids, Magnetic Composite Fluids, Gas Valves, Testing Procedures, Magnetofluidic Applications

1. Introduction

The properties of the magnetic nanoparticles, the magnetic component of magnetic nanofluids, may be tailored by varying their size and adapting their surface coating in order to meet the requirements of colloidal stability of magnetic nanofluids with non-polar and polar carrier liquids. Long-term stability of concentrated magnetic nanofluids in strong magnetic fields, e.g. in rotating seals or bearings [1, 2] imposes severe requirements on dispersion/stabilization of magnetic nanoparticles in various organic carriers.

Magnetic composite fluids [3] develop higher yield stress as conventional magnetorheological (MR) fluids [4], therefore these nano-micro structured magnetizable fluids to be considered here are envisaged beside high pressure magnetic seals, also for MR clutches and brakes [5] capable of transferring controllable high torques with a fast response time in special hydraulic turbine designs, without introducing noise and vibrations. Some of these MR brakes exploit also the magnetic sealing capabilities of MR fluids [6].

Mechanical-magnetofluidic seals [7] were developed for liquid sealing applications for hydraulic equipments, e.g. for special pumps or taps.

2. Synthesis of magnetic fluids

Details of the multi-step procedures developed at the Laboratory of magnetic fluids from Timisoara and applied on micropilot scale at the ROSEAL Co. from Odorheiu Secuiesc are given in [8, 9, 3]. These basic procedures were refined and optimized for synthesis of magnetic fluids for a given application, like rotating seals.

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Long-term colloidal stability of magnetic nanofluids in rotating MF seals, especially at high volume fraction of magnetic nanoparticles, is a complex issue connected to the synthesis procedure followed, including the nature of surfactant(s) and carrier liquid used [8, 9, 10]. The dimensionless coupling parameter λ, which is half the ratio of the dipolar energy of two aligned dipoles at close contact to the thermal energy, should be kept below 1 to ensure highly stable magnetic fluids. During preparation repulsive forces due to coating of magnetic cores are introduced to prevent irreversible aggregation of particles produced by attractive van der Waals and dipolar interactions. When the dipolar interactions are much stronger than the thermal energies, particle chains start growing and forming more complex structures, depending on the particle volume fraction, size distribution, temperature and magnetic field applied.

An interesting feature of magnetic nanofluid synthesis is that the relative strengths and ranges of various interaction potentials can be controlled by the diameter of magnetic cores and the thickness of the stabilizing layer [11]. Magnetic fluids for sealing applications [12, 7] have to be tailored in such a way to ensure high magnetization, low viscosity, low or very low vapor pressure and excellent colloidal stability in intense and strongly non-uniform magnetic field. Usually, magnetic fluids in a sealing stage have to withstand an intense and strongly non-uniform magnetic field, $H_{max} \sim 10^6$ A/m and $|\text{grad } H| \sim 10^9$ A/m^2. These requirements are sometimes difficult to fulfill simultaneously and impose special conditions on the stabilization procedure applied in MF preparation, to avoid irreversible magnetic field induced structural processes.

The basic procedure for chemical synthesis of *magnetite* nanoparticles, mostly used for magnetic fluid preparation, has the following steps: co-precipitation (at $t \approx 80^oC$) of magnetite from aqueous solutions of Fe^{3+} and Fe^{2+} ions in the presence of concentrated NH_4OH solution (25%) → subdomain magnetite particles → sterical stabilization (chemisorbtion of lauric acid (LA), myristic acid (MA) or oleic acid (OA); 80-82^{o}C) → phase separation → magnetic decantation and repeated washing → monolayer covered magnetite nanoparticles + free surfactant → extraction of monolayer covered magnetite nanoparticles (acetone added; flocculation) → stabilized magnetite nanoparticles used for magnetic nanofluid preparation.

Magnetic fluids for sealing applications synthesized at micropilot scale by ROSEAL Co.:

(a) organic non-polar carriers: dispersion of LA, MA or OA monolayer coated magnetite nanoparticles in various low vapor pressure non-polar carriers (transformer oil and various mineral oils) (Vekas et al, 2006) at $t \approx 120\text{-}130^oC$ → magnetic decantation/ filtration → repeated flocculation and redispersion of magnetic nanoparticles (elimination of free surfactant; advanced purification process) → non-polar magnetic nanofluid.

(b) organic polar carriers (such as diesters, mixtures of various mineral and synthetic oils (e.g., high vacuum oils, HVO): primary magnetic fluid on light hydrocarbon carrier → repeated flocculation and redispersion of magnetic nanoparticles (elimination of free surfactant; advanced purification) → monolayer stabilized magnetic nanoparticles → dispersion in polar solvent (stabilization with secondary surfactant, e.g. dodecylbenzensulphonic acid (DBS) or polymers (PIBSA), physically adsorbed to the first layer) → polar magnetic nanofluid.

The saturation magnetization M_s of these nanofluids, at very high volume concentration (hydrodynamic volume fraction ≈ 0.6) of surfactant coated magnetite nanoparticles, attains 80-100 kA/m.

According to [12, 7]

$$\Delta p = \mu_0 \int_0^{H_{max}} M dH - \mu_0 \int_0^{H_{min}} M dH = \mu_0 M_s (H_{max} - H_{min}) = M_s (B_{max} - B_{min}), \quad (1)$$

the sealing capacity Δp of a sealing stage is directly proportional to the saturation magnetization M_s. Here:

μ_0 – absolute permeability
M_s – magnetic saturation
H_{max} – maximum magnetic field intensity measured between the pole pieces and the shaft
H_{min} – minimum magnetic field intensity measured on the surface of the magnetic fluid
B_{max} – maximum magnetic induction
B_{min} – minimum magnetic induction

Some sealing applications, such as in compressors, special pumps, turbines and taps, require even higher saturation magnetization of the sealing fluid. For such applications nano-micro-structured composite magnetizable fluids (CMF) were designed [3] whose saturation magnetization is about one order of magnitude higher and attains 450-500 kA/m. These CMFs are high concentration magnetite nanofluid based micron range iron particle suspensions, which ensure high sealing capacity of low rotation speed magnetic seals.

The magnetic nanoparticle content significantly improves the magnetorheological behavior of the composite MF in comparison with a commercial MR fluid having the same magnetic solid content, but only micrometer sized particles [4]. The characteristic shear stress vs. magnetic interaction energy shows a much more pronounced increase with magnetic induction for the nano-microstructured magnetizable fluid sample, in comparison with the approximately linear increase observed for a conventional MR fluid. The magnetic and flow properties of CMFs make them suitable for low rotation speed and high pressure MF seal and also for semi-active MR brake and damping applications.

3. Constructive details

The main components of a magnetic fluid seal are shown on the Fig. 1.

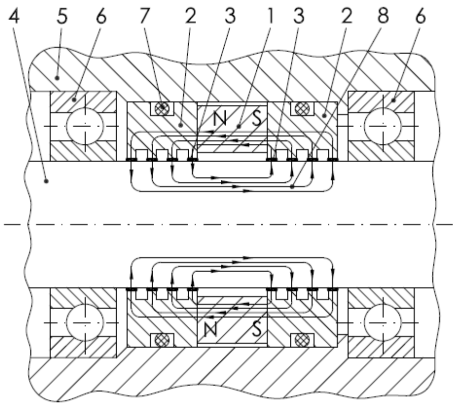


Fig. 1. Magnetic fluid seal: 1– permanent magnet; 2 – Pole pieces (soft magnetic materials); 3 – Magnetic nanofluid; 4 – Shaft (ferromagnetic material); 5 – Housing (nonmagnetic material); 6 – Bearings; 7 – "O" ring; 8 – Magnetic flux

A good magnetic fluid seal design involves careful selection of the materials and precise dimensioning. It is recommended to use low-carbon soft magnetic materials (such as OLC 10, OLC 15) for pole pieces, while for the rotating shaft is required to have soft magnetic material with high mechanical resistance, such as 13 CN 30 ~ 35.

To avoid magnetic flux dissipation the housing should be manufactured from nonmagnetic materials. The role of the bearings is to keep distance between the shaft and the housing and to assure high rotational accuracy.

After selecting the appropriate materials the magnetic field inside the seal must be determined. To obtain the useful magnetic flux that keeps the magnetic fluid in the air gap, the dissipated magnetic flux must be calculated, as well (see Fig. 2.).

$$\Phi_{useful} = \Phi_{magnet} - \Phi_{dissipated} \tag{2}$$

$$\Phi_{dissipated} = \Phi_{dissipated1} + \Phi_{dissipated2} + \Phi_{dissipated3}, \tag{3}$$

where:

$\Phi_{dissipated1}$ – dissipated flux through the housing

$\Phi_{dissipated2}$ – dissipated flux due to the bearings and pole pieces

$\Phi_{dissipated3}$ – dissipated flux through the air between the pole pieces

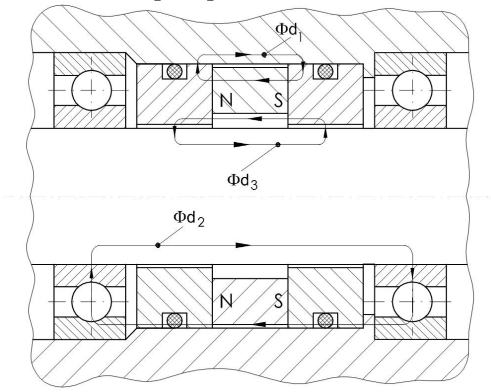


Fig. 2. Magnetic flux dissipation in magnetic fluid seals

Magnetic fluid seals are generally composed by multiple stages, i.e. multiple magnetic fluid rings maintained between the rotating shaft and stationary parts by a properly designed magnetic system [1].

The total differential pressure for n stages that a magnetic fluid seal can sustain is given by the sum of the pressure capacities of the individual stages:

$$\Delta p_{max\_total} = n \cdot \Delta p_{max\_stage} \tag{4}$$

Usual operating conditions, in particular rotation of sealed shaft, are related to viscous dissipation P_v at a sealing stage:

$$P_v = 2\pi R^3 \omega^2 \eta \, f(\delta, t, b), \tag{5}$$

where η is the viscosity of the sealing fluid, R the radius and ω the angular velocity of the shaft, t the width of a sealing stage at the tip. The viscous heating of the fluid should not exceed about 100-120ºC, in order to avoid stabilizant desorption and accelerated carrier liquid evaporation. At high peripheral velocity v of the rotating shaft, beside heating also the influence of centrifugal forces have to be taken into account, which reduce the sealing capacity [1]:

$$\Delta p(v) = \Delta p(0) - (1/2) \rho v^2 h/R, \tag{6}$$

where ρ is the density and h is the thickness of the magnetic fluid "O" ring.

The constrains related to *viscous heating* and *centrifugal forces* do not affect many of the applications of MF seals, which usually encounter relatively low rotating speed of the sealed shaft, up to v ~ 10 m/s.

The effectiveness of designing magnetic fluid seals was increased by developing a software program. It takes in consideration all the necessary information about materials and dimensions and calculates the maximum sustainable differential pressure of the magnetic fluid seal.

4. Magnetofluidic rotating seal systems

MF rotary seals offer hermetic sealing capabilities for a long lifetime, can be used at high speeds, are non-contaminating and present optimum torque direct drive transmission. Magnetic liquid seals are engineered for a wide range of applications and exposure but are generally limited to sealing gases, vapors and not direct pressurized liquids.

In order to avoid the practical limits with respect to temperature, differential pressure, speed, applied loads and operating environment, the software program for magnetic fluid rotating seals design takes into account the relations (5)-(7), the geometrical and magnetic characteristics of the magnetic circuit, as well as other material properties.

Some example of the custom engineered magnetic fluid seals designed and produced by the Roseal Co., as well as their applications are described below.

4.1 Vacuum deposition systems and liquefied gas pumps applications

4.1.1. Magnetic fluid feed-through for high power electric switches

This kind of feedthrough was designed especially for high power electric switches that use SF_6 gas to impede the formation of electric arc at switching-off. For safety reasons the leakage of SF_6 has to be avoided for the full operating period (several years) of the switch with rotating shaft (see Fig. 3a, b.) in a pressure range between 10^{-6} to 7 bar. Hundreds of MF feedthroughs of this type are in use for several years (over 5 years) without maintenance.

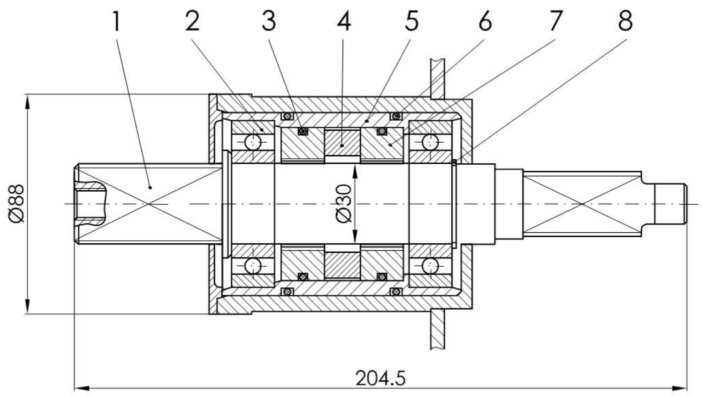


Fig. 3a. Sketch of magnetic fluid feedthrough for high power electric switches with SF_6. Components: 1- shaft; 2- ball bearing; 3,6- "O" ring; 4- permanent magnet; 5- non-magnetic casing; 7- polar piece; 8- safety ring.
Fig. 3b. Magnetic fluid feedthrough for high power electric switches

4.1.2. MF vacuum feedthrough for crystal growth equipment

The feedthrough presented was designed for vacuum sealing applications, in particular for crystal growth equipments. Several years experiments show maintenance free operational lifetime up to 5 years in high vacuum up to 10^{-6} Torr (see Fig.4.).

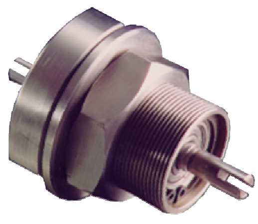


Fig. 4. MF vacuum feedthrough

4.1.3. MF feedthrough for mixers

This feedthrough was designed for applications such as boron-gadolinium mixers, which operates at a rotation speed up to 1000 rot/min in a radiation field up to 100mR/h (see Fig. 5.).

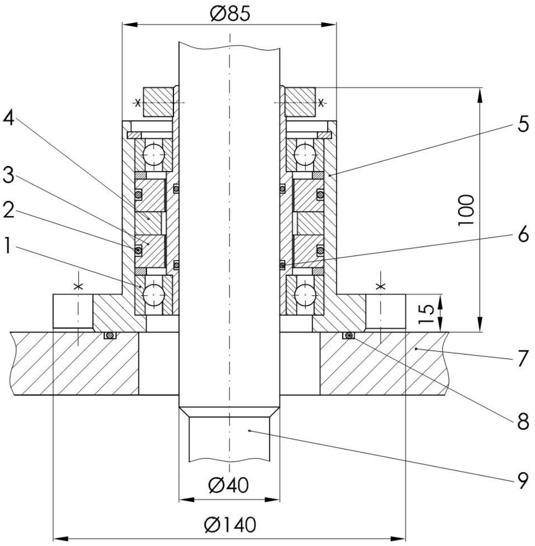


Fig. 5. MF feedthrough 1 – bearings; 2, 6, 8 - "O" ring; 3 – pole pieces; 4 – permanent magnet; 5 – seal casing; 7 – mixer casing; 9 - shaft

4.2 Tandem magnetic fluid seal – mechanical seal arrangements

To ensure leak-proof sealing of liquefied gases in a secure way a tandem seal was designed consisting in a mechanical seal and a magnetic fluid rotary seal, taking advantages of both types of seals, such as relatively high sealed pressure difference and long-term leakage-free operating regime.

4.2.1 Mechanical – magnetic fluid tandem seal for high vacuum deposition systems

The combined seal was designed for high vacuum (up to $5x10^{-7}$ Torr) deposition system (see Fig. 6.). To keep a low pressure difference on the primary MF seal, the chamber between the two seals is connected to a preliminary vacuum pump.

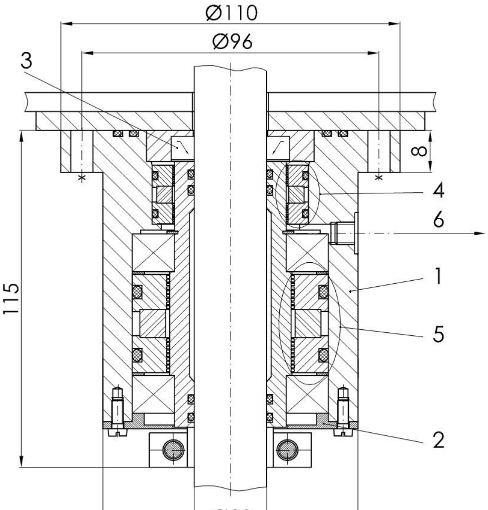


Fig. 6. Magnetic fluid – mechanical seal for high vacuum deposition system: 1- non-magnetic shaft; 2- magnetically soft sleeve; 3-friction seal; 4- primary magnetic fluid seal; 5- secondary magnetic fluid seal; 6- to preliminary vacuum pump.

4.2.2 Mechanical – magnetic fluid tandem seal for liquefied gas pump

Sealing liquids with MF seals can encounter serious difficulties, since the sealing capacity of the magnetic liquid sealing stages may be compromised when another liquid contacts them due to miscibility of the two liquids and/or due to foaming process, especially at high rotational speed. Consequently, when sealing liquids, the magnetic fluid can be diluted or even washed out and the seal fails. To avoid these limitations, tandem seals were engineered for vertical axis pumps for liquefied gas. While the mechanical seal retains up to 25 (40) bars, for up to 3000 rot/min rotation speed of the shaft, the leakage-free magnetic fluid seal prevent any escape of gases from the chamber between the two seals, up to 3 bars. The accumulated gas in the chamber is evacuated to an external recovery system or flame (see Fig. 7a, b.).

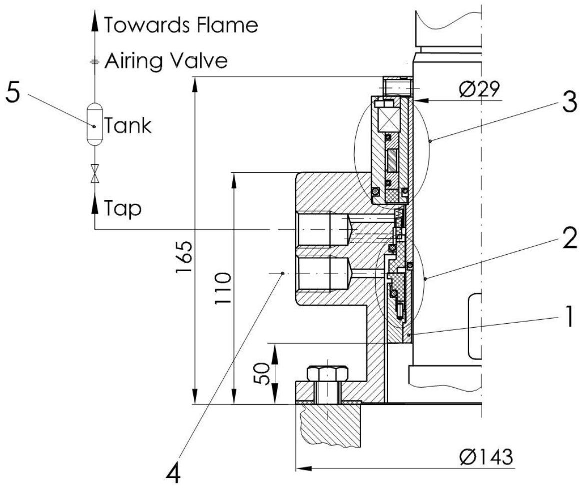
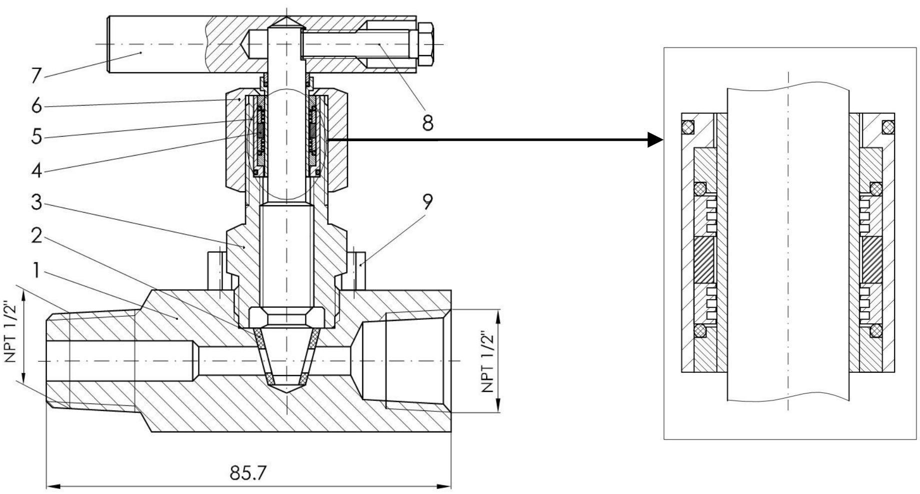


Fig. 7a. Sketch of a mechanical- magnetic fluid combined seal for liquefied gas pump
1 - shaft; 2 - mechanical seal; 3 - magnetic fluid seal; 4 - inlet for cooling and lubrication fluid;
5 - system for escaped process fluid evacuation
Fig. 7b. Mechanical- magnetic fluid combined seal for liquefied gas pump

Other application of the magnetic fluid seal:

- *Gas valves up to **40 bar** equipped by a sealing system using high magnetization magnetic nanofluids or magnetic composite fluids (see Fig. 8a, b.)*

Practically the sealing capacity of such gas valves is independent of the number of open-close cycle, assuring hermetic sealing for o long time.



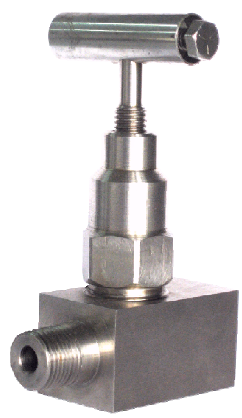


Fig. 8a. (left side) Sketch of gas valves equipped by magnetic fluid seal; 1 - Body; 2 - Valve seat;
3 – Guide; 4 - Magnetic liquid seal; 5 - Bar (Valve stem); 6 - Stuffing box; 7 - Valve Handle;
8 – Screw; 9 - Spiral elastic suspension pin;
Fig. 8b. (right side) Gas valves equipped by magnetic fluid seal

5. Testing procedures of magnetofluidic rotating seals

In order to determine the functioning parameters of the magnetic fluid seals, the test stand represented in Fig. 9 was built. It can test magnetic fluid seals with diameters up to 240 mm in a large pressure domain: [10^{-7}bar – 50bar] at a rotational speed up to 3000 rot/min.

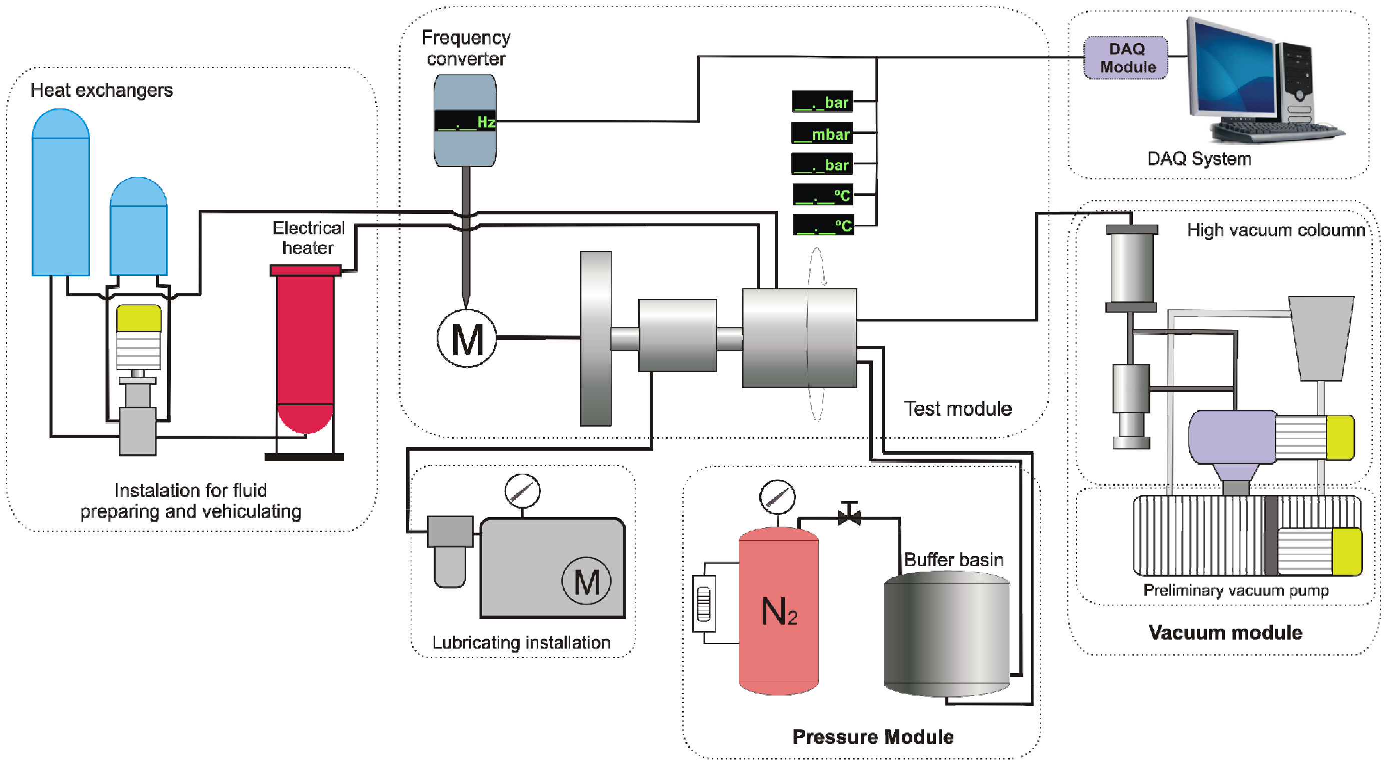


Fig. 9. Main components of the magnetic fluid seal test stand

The experimental *test module* is composed of a rotating shaft driven by an electric motor, while an inverter ensures the variable rotational speed of it. The shaft suspension is ensured by a ball bearing whose lubrication and cooling is done by the lubrication unit. The magnetic fluid seal to be experimented is mounted inside the test chamber, which is connected to the pressure module or the vacuum module, depending on the type of the seal.

In case of fluid sealing an additional installation is added to ensure the prescribed temperature and circulation of the fluid, required in the test chamber, an *installation for fluid preparing and circulation* with two heat exchangers and an electrical cooler.

The *vacuum module* has two main components, a preliminary vacuum pump and a high vacuum column, capable to ensure 10^{-5} Torr.

The *pressure module* is composed by a compressed nitrogen cylinder supplied with a pressure adjuster connected to the buffer basin through an adequate flexible pipe.

In order to evaluate the characteristics of the magnetic fluid rotating seal devices, data are collected during testing, such as temperature of seal, outlet pressure in the buffer basin, temperature and pressure or vacuum in the test chamber and rotational speed of the shaft.

A software program was developed to ensure proper data collection and analysis (see Fig. 10.).

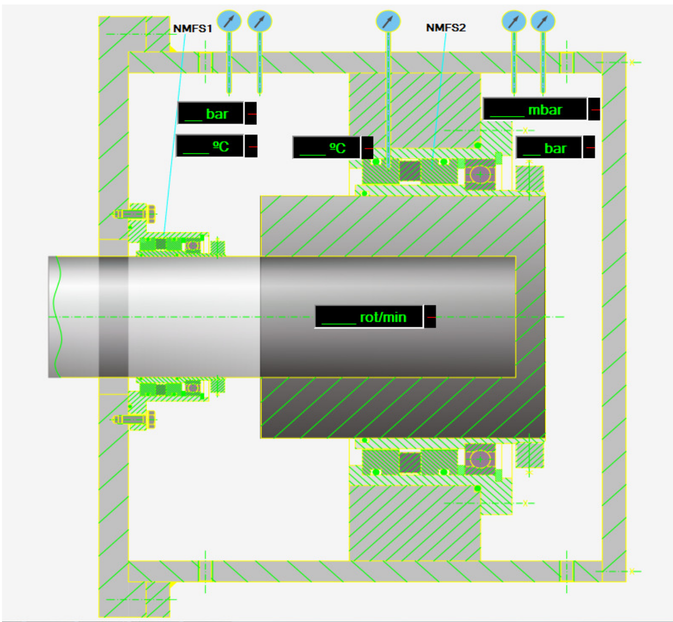


Fig. 10. Test chamber with measured parameters.

6. Sealing capabilities of different types of magnetizable fluids

From all of the investigated magnetizable fluids, the composite fluids give the highest values for the maximum sustainable/burst pressure for a single sealing stage (Fig. 11).

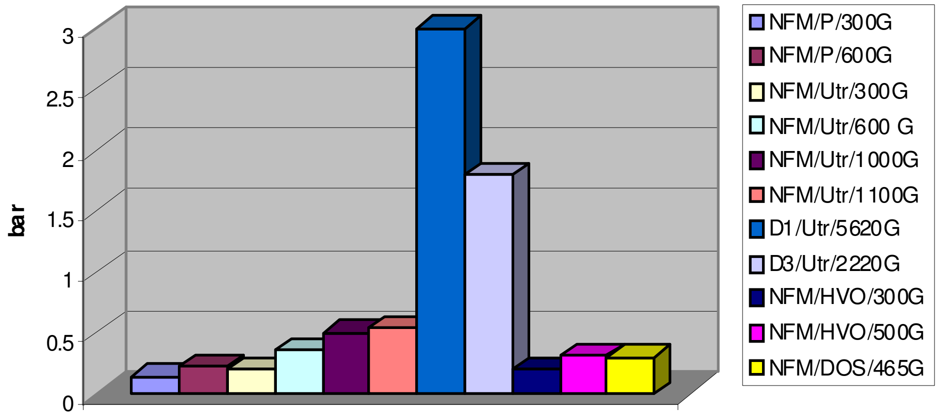


Fig. 11. Comparison of the burst pressure of a single sealing stage with magnetic nanofluids and magnetic composite fluids D1 = 5620G, D3 = 2220G

At temperatures below 0ºC there are recommended magnetic nanofluids on light hydrocarbon carrier.

7. Conclusions

Leakage-free magnetic fluid feedthroughs and mechanical-magnetic fluid tandem seals were developed for several tens of bars sealing capacity, using high magnetization magnetic nanofluids and composite magnetic fluids. A sealing capacity of seals rising up to 50 bars were tested using a custom designed experimental stand. The tandem seals and composite magnetic fluids are envisaged for hydraulic equipments, as well as for semi-active brakes and vibration dampers for hydraulic turbine units.

Acknowledgements

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