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Original Paper (Invited)

Leakage-free Rotating Seal Systems with Magnetic Nanofluids and Magnetic Composite Fluids Designed for Various Applications

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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.

Design concepts and some constructive details of the magnetofluidic seals are discussed in order to obtain high sealing capacity. Different types of magnetofluidic sealing systems and applications are reviewed. Testing procedures and equipment are presented, as well as the sealing capabilities of different types of magnetizable 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, involving nanosized magnetite and several micron sized iron particles [3], with strongly bidisperse size distribution, develop higher yield stress [4] and better stability against sedimentation [5] as conventional magnetorheological (MR) fluids. Such type of nano-micro structured magnetizable fluids are envisaged beside high pressure magnetofluidic seals, also for MR clutches and brakes [6] 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 [7].

In this paper there are presented the main steps of synthesis, as well as the magnetic properties of high magnetization nanofluids and nano-microstructured composite magnetic fluids, developed for various types of magnetofluidic seals. Rotating magnetofluidic feedthroughs and mechanical-magnetofluidic combined seals designed for leakage-free sealing of high vacuum and several tens of bar gas pressure applications, are briefly described.

2. Synthesis of magnetic fluids

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

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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, 9] 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 main steps [8] : 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) [11]; 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 are synthesized at micropilot scale by ROSEAL Co., applying the following procedures [13]:

(a) organic non-polar carriers: dispersion of OA monolayer coated magnetite nanoparticles in various low vapor pressure non-polar carriers (transformer oil and various mineral oils at $t \approx 120$-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.

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 [14] 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 of magnetofluidic seals

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

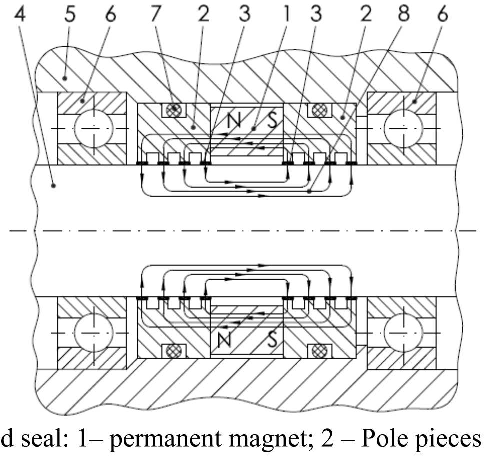

Fig. 1 Magnetic fluid seal: 1– permanent magnet; 2 – Pole pieces (soft magnetic materials); 3 – Magnetic nanofluid; 4 – Shaft (ferromagnetic material); 5 – Housing (nonmagnetic material); 6 – Bearings; 7 – “O” ring; 8 – Magnetic flux

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.

The role of the bearings is to keep distance between the shaft and the housing and to ensure high rotational accuracy, keeping the precision of the coaxiality in the range of hundredth of millimeters.

The sealing capacity depends on the volume of the magnetic fluid which influences the magnetic field intensity in the sealing gap. Consequently there is an optimum value of the magnetic fluid volume and below this value, the sealing capacity of the magnetic fluid sealing ring, decreases.

When the volume of the magnetic fluid is kept constant, the magnetic field intensity on the magnetic fluid surface decreases with the increasing of the sealing gap, causing capacity loss. For given ring permanent magnet dimensions, the magnetic fluid sealing ring thickness must be as thin as possible.

From technological and functional reasons the use of rectangular teeth shape is recommended to get optimal values for $\Delta B = B_{max} - B_{min}$. Experimental researches show that the following proportional values give the best results (see Fig. 2.):

- Teeth width: $b = (3 \sim 5) \cdot d$
- Groove width: $c = (7 \sim 10) \cdot d$
- Groove depth: $h = (8 \sim 15) \cdot d$, d - air gap

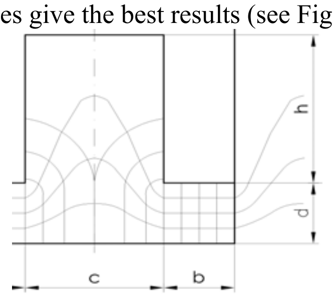

Fig. 2 Sealing stage

To avoid magnetic flux dissipation the housing should be manufactured from nonmagnetic materials. To obtain high magnetic flux density in the seal gap the dissipated magnetic flux (see Fig.3) through the housing (Φd_1), through the air between the pole pieces (Φd_3) and due to the bearings and pole pieces (Φd_2) must be minimized by keeping the ratio of useful magnetic flux to dissipated flux much less than 1.

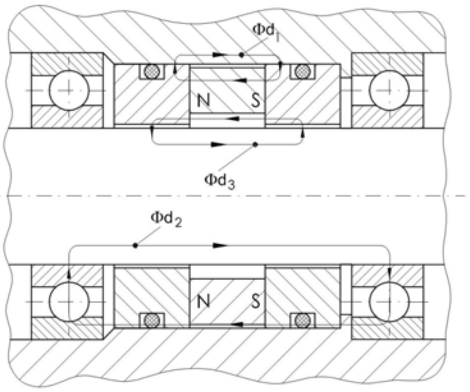

Fig. 3 Magnetic flux dissipation in magnetic fluid seals

Φd_1 - magnetic flux through the housing**;** Φd_2 - magnetic flux due to the bearings and pole pieces**;**

Φd_3 - magnetic flux through the air between the pole pieces**;**

Since the field intensity is usually high in a magnetofluidic seal and, therefore, the magnetization of the fluid attains the saturation value, the maximum sustainable pressure difference Δp of a single sealing stage filled with the magnetic fluid can be determined with the following formula [12, 9]:

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

the sealing capacity being directly proportional to the saturation magnetization M_s.

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:

$$\Delta p_{max\_total} = n \cdot \Delta p \qquad (2)$$

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

$$P_v = 2\pi R^3 \omega^2 \eta \, f(\delta, t, b) \qquad (3)$$

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]:

$$\Delta p(v) = \Delta p(0) - (1/2) \rho v^2 d/R \qquad (4)$$

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.

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, covering applications from high vacuum systems and computer hard disks to solutions for environment protection, used in chemical, biochemical, pharmaceutical and also in refining industry [2].

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 (1)-(4), the geometrical and magnetic characteristics of the magnetic circuit, as well as other material properties.

Some examples 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. 4.) 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.

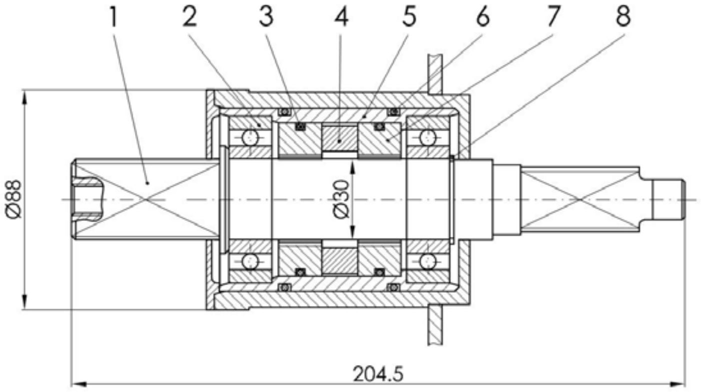

Fig. 4 Sketch of magnetic fluid feedthrough for high power electric switches with SF_6. Components: 1- shaft; 2- ball bearing; 3,6- "O" ring; 4- permanent magnet; 5- non-magnetic casing; 7- polar piece; 8- safety ring.

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.

4.1.3 MF feedthrough for mixers

This type of 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.).

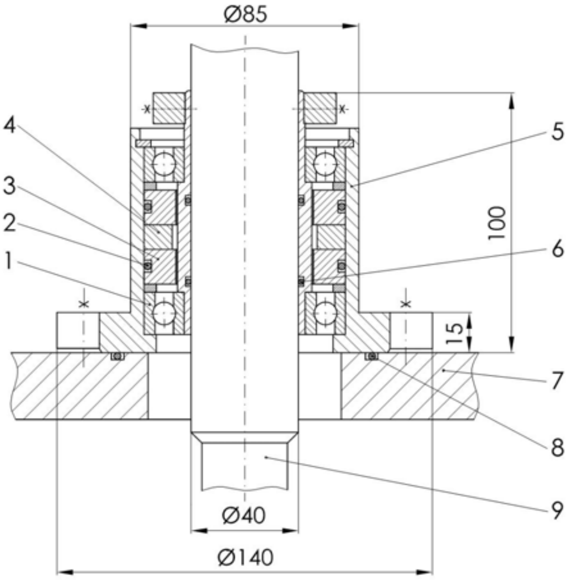

Fig. 5 Sketch of MF feedthrough; Components: 1 – bearings; 2, 6, 8 - "O" ring; 3 – pole pieces; 4 – permanent magnet; 5 – seal casing; 7 – mixer casing; 9 - shaft

4.2 Tandem magnetic fluid seal – mechanical seal arrangements

To ensure leak-proof sealing of liquefied gases in a secure way tandem seals were designed consisting in mechanical seal and 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.

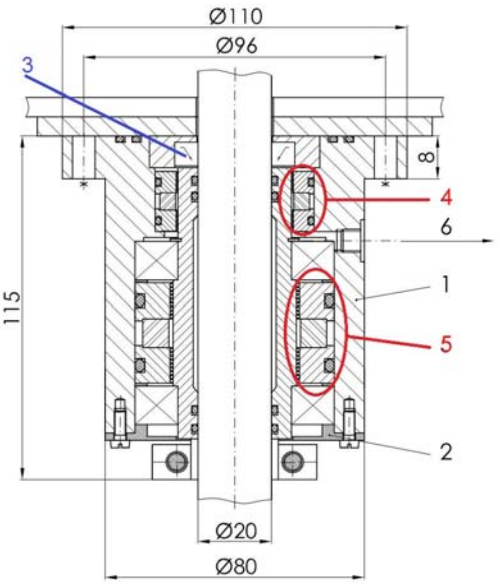

Fig. 6 Sketch of magnetic fluid – mechanical seal for high vacuum deposition system;
Components: 1– non-magnetic shaft; 2 – magnetically soft sleeve; 3-friction seal;
4 – primary magnetic fluid seal; 5 – secondary magnetic fluid seal; 6 – to preliminary vacuum pump.

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. 7.).

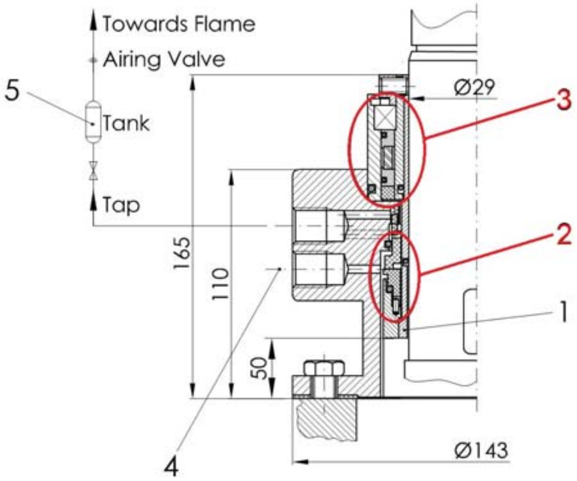

Fig. 7 Sketch of a mechanical–magnetic fluid combined seal for liquefied gas pump;
Components: 1 – shaft; 2 – mechanical seal; 3 - magnetic fluid seal;
4 – inlet for cooling and lubrication fluid; 5 – system for escaped process fluid evacuation

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. 8,9,10.)*

These gas valves are equipped by a sealing system based on magnetic fluids with important advantages compared to the well-known mechanical seals, making the seal leakage-free, with an exceptional long working life without maintanance (~ 5 years). Practically the sealing capacity of such gas valves is independent of the number of open-close cycle, assuring hermetic sealing for a long time.

Several types of closing and regulating gas valves with MFS were designed: gate valve flanged, needle valve, ball valve (see Fig. 8,9,10.). These valves have a relatively simple construction and low producing cost.

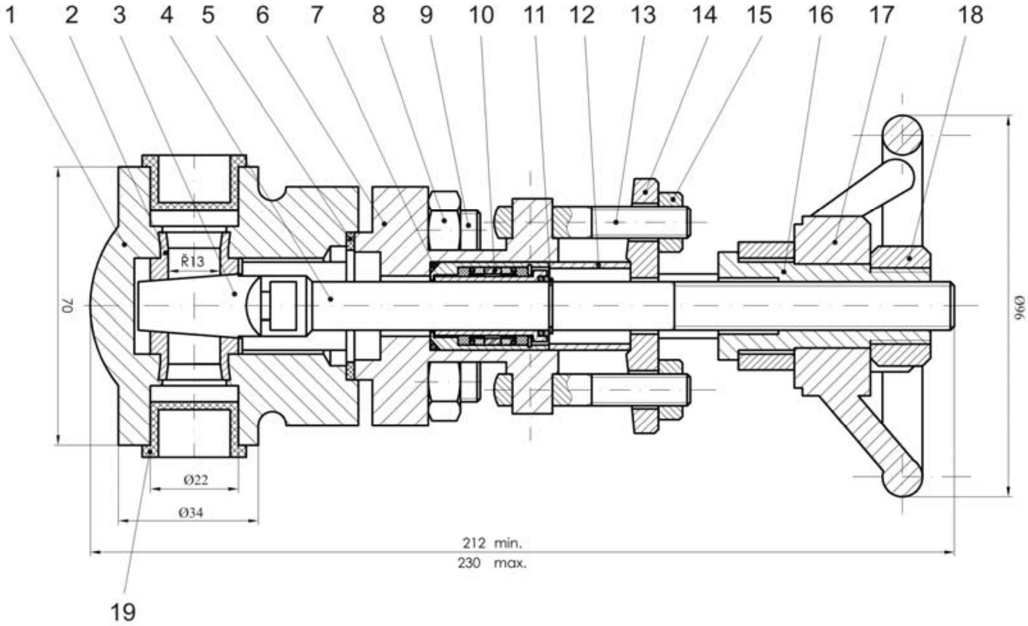

Fig. 8 Sketch of isolating valve equipped by magnetic fluid seal; Components: 1 – Body; 2 – Reducer; 3 – Conical disc; 4 – Valve spindle; 5 – Gasket; 6 – Valve guide; 7 – "O" ring; 8 – Screw Nut M10; 9 – Joint pin; 10 – Magnetic liquid seal; 11 – Elastomeric ring; 12 – Sealing gland; 13 – Screw hoop; 14 – Flange; 15 – Screw Nut M8; 16 – Threaded sleeve; 17 – Handwheel; 18 – Screw Nut M18x1.5; 19 – Protection cap;

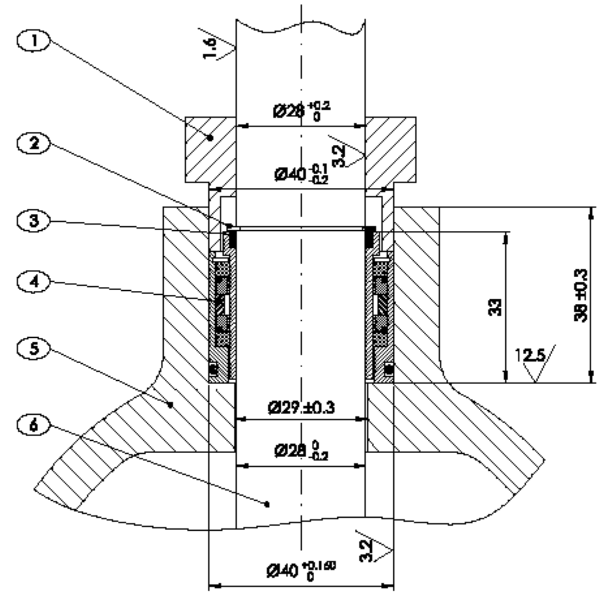

Fig. 9 Sketch of needle valve equipped by MF seal; Components: 1 – Gland; 2 – Elastomeric ring; 3 – Push ring; 4 – Magnetic fluid seal; 5 – Bonnet; 6 – Steam;

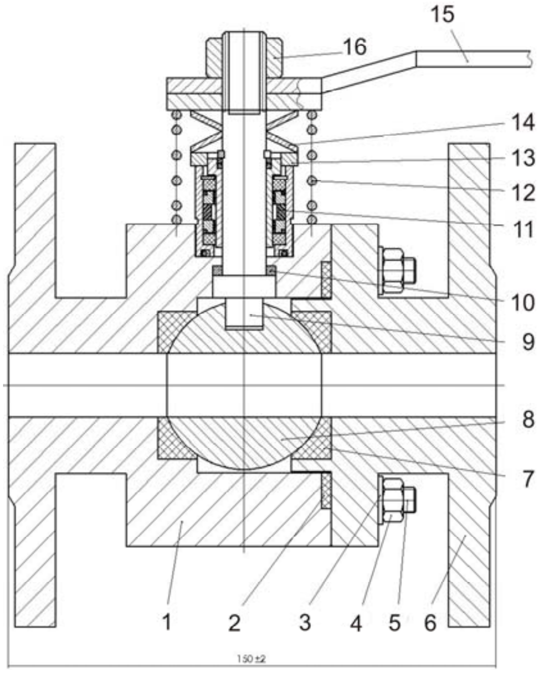

Fig. 10 Sketch of ball valve with MF seal; Components: 1 – Body; 2 – Gasket; 3 – Grower washer N6; 4 – Screw Nut; 5 – Joint pin; 6 – Flange; 7 – Spherical Gasket; 8 – Ball; 9 – Shaft; 10 – Bearing; 11 – MF seal; 12 – Cylindrical spring; 13 – Distance piece; 14 – Disc spring; 15 – Handle; 16 – Screw nut M14;

Since the rotational speed of the shaft of a valve is low and so the relative velocity between the solid wall and the magnetic fluid is reduced, no special conditions referring to the viscosity of the magnetic fluid are required. Magnetic composite fluids (D-fluids in

Fig. 13.) with very high saturation magnetization (up to 400 kA/m) are used to ensure high sustainable pressure difference (Fig. 13.).

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. 11. was built. It allows testing magnetic fluid seals with diameters up to 240mm in a large pressure domain: [10^{-7}bar – 50bar] at a rotational speed up to 3000 rot/min.

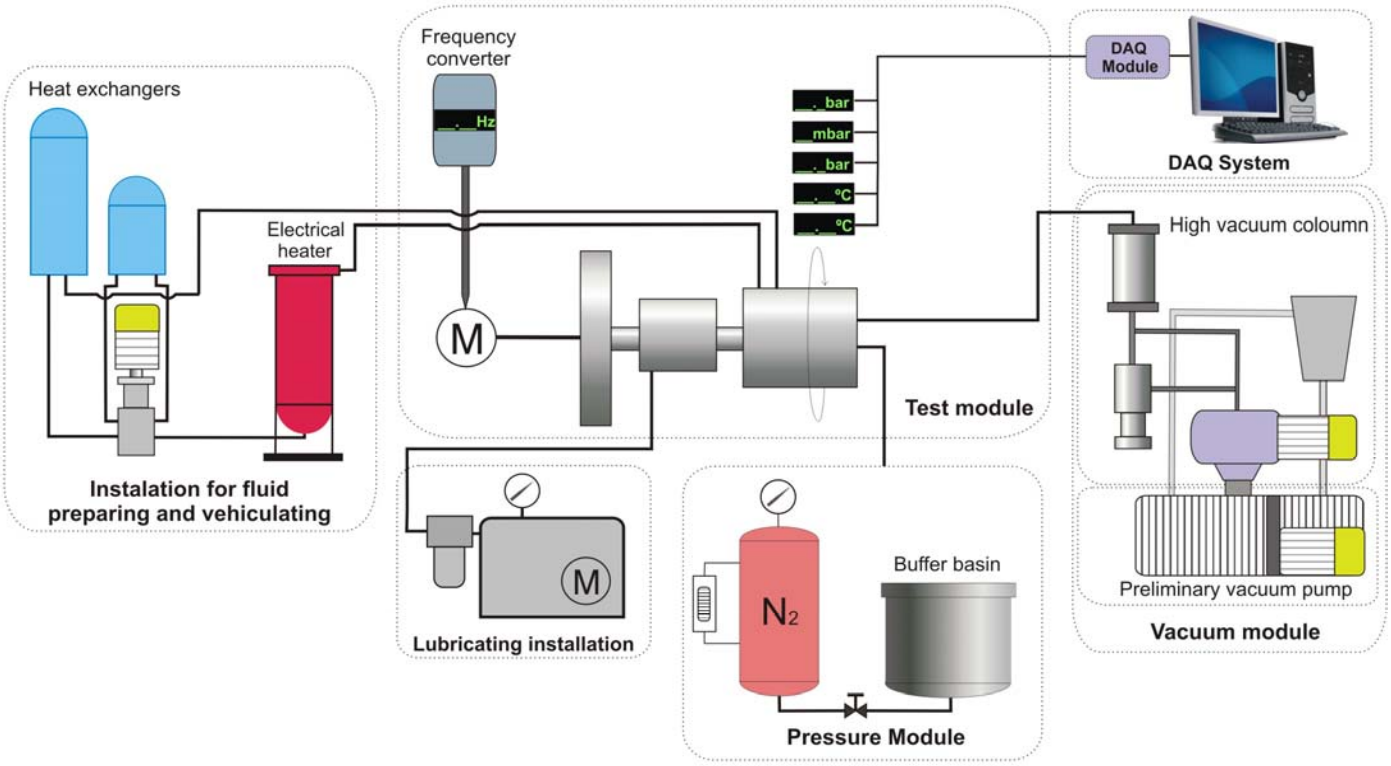

Fig. 11 Main components of the magnetic fluid seal test stand

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.

The test stand was designed in order to determine the sustainable pressure difference of the MFS and also to allow investigations over the influence of the rotational speed of the shaft on the sealing capacity. The main concept is to generate pressure or vacuum in Chamber 1 (see Fig.12) and through monitoring the change of the pressure in both chambers (Chamber 1 and 2) it can be determined the sustainable pressure or vacuum difference of the MFS. Two magnetic fluid seals are mounted in the test chamber: the NFMS1 (see Fig. 12), which have to sustain only a low differential pressure and ensure leak-proof operating regime of the entire test chamber and the tested MFS (NFMS2, see Fig. 12). In order to investigate the influence of the rotational speed of the shaft and the surface roughness of the polar pieces and the shaft on the heating of the magnetic fluid through viscous dissipation, temperature is measured relatively close to the magnetic fluid using a pyrometer and the ambient temperature using a thermocouple. 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.

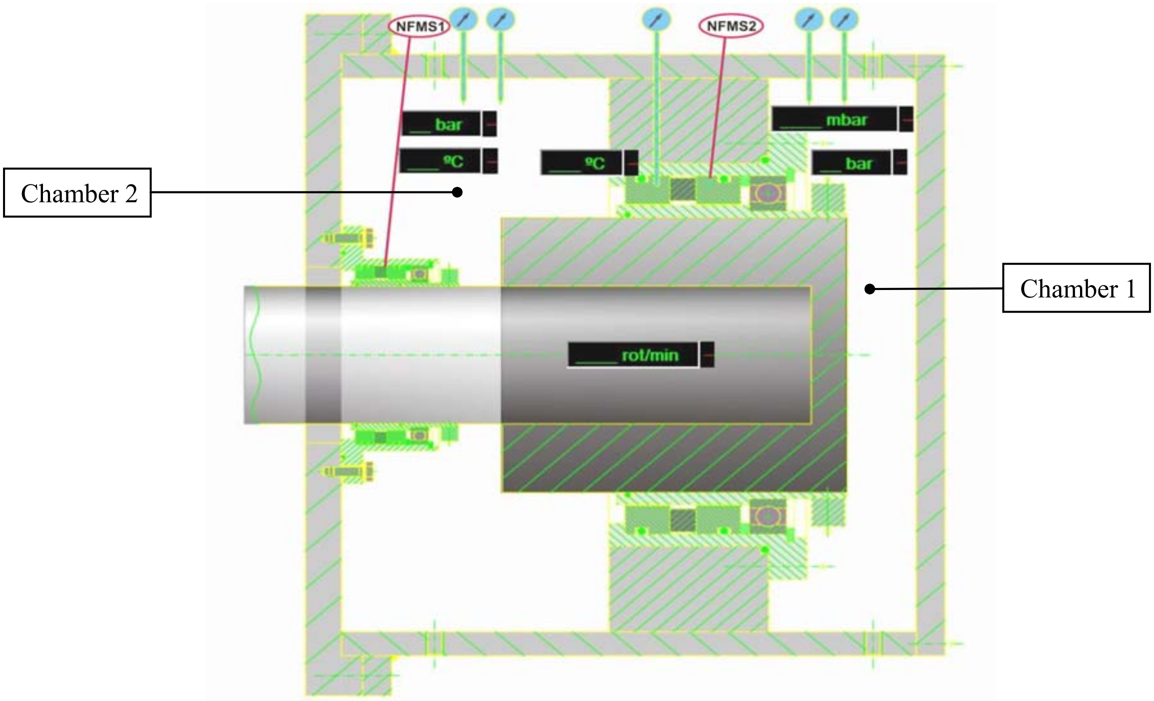

Fig. 12 Test chamber with measured parameters.

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 (see Fig. 13). The approximatively linear dependence of burst pressure vs. saturation magnetization is in agreement with eq. (1).

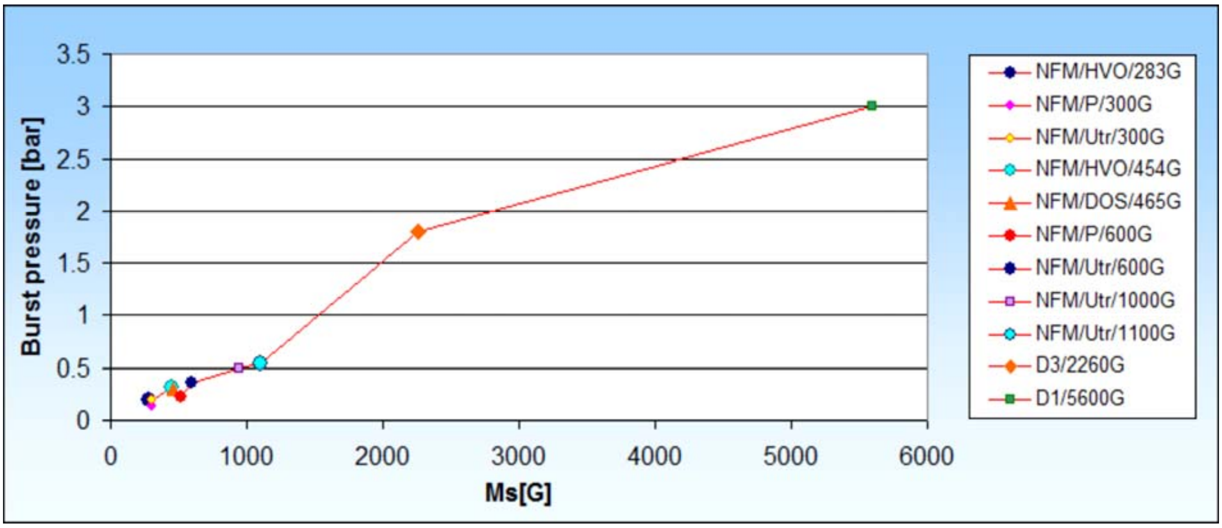

Fig. 13 Comparison of the burst pressure of a single sealing stage
with magnetic nanofluids and magnetic composite fluids

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

7. Conclusions

Magnetic nanofluids specially developed for MF rotary seals proved long-term stability in the specific conditions of these seals, i.e. intense and highly non-uniform magnetic field, as well as high vacuum. 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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Nomenclature

b	Teeth width [m]
B_{max}	Maximum magnetic induction [T]
B_{min}	Minimum magnetic induction [T]
c	Groove width [m]
CMF	Composite magnetizable fluid
d	Air gap / Thickness of the magnetic fluid ring[m]
h	Groove depth [m]
H_{max}	Maximum magnetic field intensity measured between the pole pieces and the shaft [A/m]
H_{min}	Minimum magnetic field intensity measured on the surface of the magnetic fluid [A/m]
MF	Magnetic fluid
MFS	Magnetic fluid seal
MR	Magnetorheolgical fluid
M_s	Saturation magnetization [A/m]
n	Number of magnetic fluid sealing stages [-]
P_v	Viscous dissipation[W/m³]
R	Radius of the shaft [m]
t	Width of a sealing stage at the tip [m]
Δp_{max_total}	Maximum sustainable differential pressure of the MFS [bar]
Δp	Maximum sustainable differential pressure of one MF sealing stage [bar]
η	Viscosity of the magnetic fluid [Pa·s]
μ_0	Absolute permeability [Wb/(A·m)]
ρ	Fluid Density [kg/m³]
Φd_1	Magnetic flux through the housing [Wb]
Φd_2	Magnetic flux due to the bearings and pole pieces [Wb]
Φd_3	Magnetic flux through the air between the pole pieces [Wb]
ω	Angular velocity of the shaft [1/s]

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