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APPLICATIONS OF MAGNETIC NANOFLUIDS IN ROTATING SEALS

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Abstract

Magnetic nanofluids specially tailored for seals and various type of leak-proof rotating seals are presented. The build-up and main characteristics of magnetic fluid feedthroughs and magnetic fluid-mechanical seal arrangements are described, for high power electric switches, vacuum deposition systems and liquefied gas pumps applications.

1. Introduction

Leakage-free rotating seals are among the most important applications of magnetic fluids developed up to now [1]. Magnetic fluid seal (MFS) uses extend from high vacuum systems and computer hard disk drives to environment protecting combined seals for refineries and chemical plants. Recent advances in the field include high speed, large diameter, tight tolerance MFS for high precision optical component manufacturing [2] and for liquid sealing [3, 4]. Magnetic fluid sealing technology development is strongly related to the magnetic, thermo physical and flow properties of magnetic nanofluids specially tailored for each application.

In this work we report on several types of rotating MF seals designed and manufactured using magnetic fluids prepared for this purpose. The paper reviews some previous results obtained in the framework of the long-term cooperation between LMF-CFATR (Romanian Academy, Timisoara Division), NCESCF-UP Timisoara and ROSEAL Co. and presents newly developed sealing magnetic fluids and mechanical – magnetic fluid tandem rotating sealing devices.

2. Magnetic nanofluids in rotating seals. Specific requirements

The main components and build-up (fig.1), calculus and design of multi-staged MF seals, as well as the physical conditions to be fulfilled by magnetic fluids in a seal are thoroughly discussed in [1, 5, 6, 7, 8, 9].

Usually, a magnetic fluid in a sealing stage have to withstand an intense and strongly non-uniform magnetic field, $H_{max} \sim 10^6$ A/m and $|\mathrm{grad}\, H| \sim 10^9$ A/m^2, consequently its magnetization attains the saturation value M_s. The volume density of the magnetic force $|\mu_0 M \mathrm{grad} H|$ is about 10^4 times greater than the volume density of gravitational force ρg. Under these conditions the sealing capacity of a single stage is [6, 8]

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

E. g., for a magnetic fluid with $M_s = 60$ kA/m and $B_{max} - B_{min} = 1$ T the sealing capacity of a single stage is $\Delta p = 0.6 \times 10^5$ Pa.
As it was shown in [6], the maximum sealed pressure per unit length of a seal, Δp^*, is the relevant quantity for MF seal design:

(2) $\Delta p^* = M_s B_{max} F (k, \delta, \Delta, H_1, H_2)$,

where F is a function of $k = H_1/H_s$ (H_1 – magnetic field strength at the minimum gap δ of the sealing stage (H_{max}); H_s – magnetic field strength at magnetic fluid saturation magnetization), Δ – distance between sealing stages, H_2 – magnetic field strength at the smaller pressure side of the magnetic fluid "O" ring of the sealing stage.

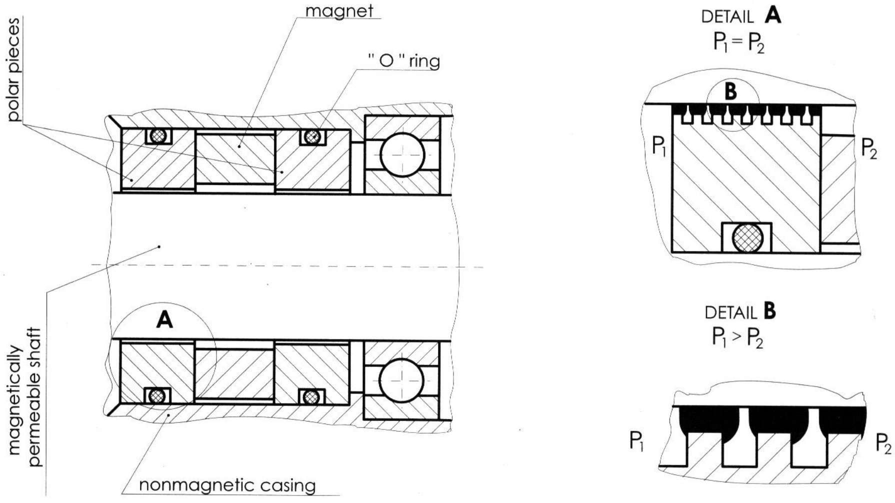

Fig.1. Main components of a magnetic fluid rotary seal (magnetic fluid "O" rings evidenced in detail B)

The optimal width b of the bottom of the pole of a sealing stage is $b \approx 4\delta$ [6]. Usually, H_2 is the smallest value of the intensity of the magnetic field in the seal gap (H_{min}), if the quantity of magnetic fluid is exceeding the optimum volume. For magnetic fluid volume less than the optimum, H_2 has a greater value and consequently, the magnetic fluid "O" ring sealed pressure decreases (Eq. (1)). From Eqs. (1,2) it follows that magnetic fluids in sealing applications have to withstand the long-term action (~ years) of intense and strongly non-uniform magnetic fields ($H_{max} \sim 10^6$ A/m; $|\text{grad} H| \sim 10^9$ A/m^2), with significant influence on their colloidal stability [10]. Usual operating conditions, in particular rotation of sealed shaft, are related to viscous dissipation P_v at a sealing stage [11]:

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

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 100-120 ºC, 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 [11]:

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

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.

3. Synthesis and characterization of magnetic nanofluids for rotating seals

Long-term colloidal stability of magnetic nanofluids, 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 [12, 13]. 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. Magnetic fluids for sealing applications have to be tailored in such a way to ensure high magnetization, low viscosity, low or very low vapour pressure and excellent colloidal stability in intense and strongly non-uniform magnetic field. These requirements are sometimes difficult to fulfil simultaneously and impose special conditions on the stabilization procedure applied in MF preparation, to avoid irreversible magnetic field induced structural processes [13].

According to the synthesis procedures described in [12], developed at the Lab. Magnetic Fluids from Timisoara, transformer oil (TR30), diester (DOA = dioctyl adipate (bis(2-ethylhexyl)adipate), $C_{22}H_{42}O_4$; DOF = dioctyl phtalate (bis(ethylhexyl)phtalate), $C_{24}H_{38}O_4$ and DOS = dioctyl sebacate (bis(2-ethylhexyl)sebacate), $C_{26}H_{50}O_4$) and high vacuum oil (HVO (KW, Merck)) based magnetic fluids were prepared for various type of magnetic fluid seals (MFSs). The high boiling point (over 200 ºC) carriers, especially DOS, DOF and HVO, were selected for high vacuum and/or for very long duty seals, while TR30 for pressure seals. The sealing MF synthesis procedures developed [12, 14] were applied taking into account the non-polar or polar character of the carriers: TR30- non-polar; DOA, DOF and DOS – weakly polar; HVO – non-polar with some polar additives. The stabilization/dispersion of magnetite nanoparticles in TR30 required monolayer sterical stabilization with chemisorbed oleic acid (OA), while in the case of polar diester carriers double layer sterical stabilization with oleic acid (chemisorbed primary surfactant) + dodecylbenzene-sulphonic acid (DBS; physically adsorbed secondary surfactant) proved to be efficient. In the case of HVO carrier a polymeric secondary surfactant was used to achieve long-term colloidal stability of the resulted magnetic fluid. This type of magnetic fluid with very low vapour pressure, below 10^{-7} mbar at 20ºC, was developed specially for vacuum MF seals. The surfactant OA in the composition of sealing MFs was technical grade (approx. 70% oleic acid and the rest shorter chain length saturated acids), except the MF/TR30 samples stabilized with chemically pure OA. The structural, magnetic and flow properties of various magnetic fluids, including sealing MFs are presented in [15-17], while their long-term (5-10 years) behaviour was investigated in industrial and prototype MF seals, as will be presented in the next section.

The magnetization curves of the selected types of sealing MFs, determined with a vibrating sample magnetometer (VSM 880, ADE Techn., USA), are given in Figs. 1, 2.

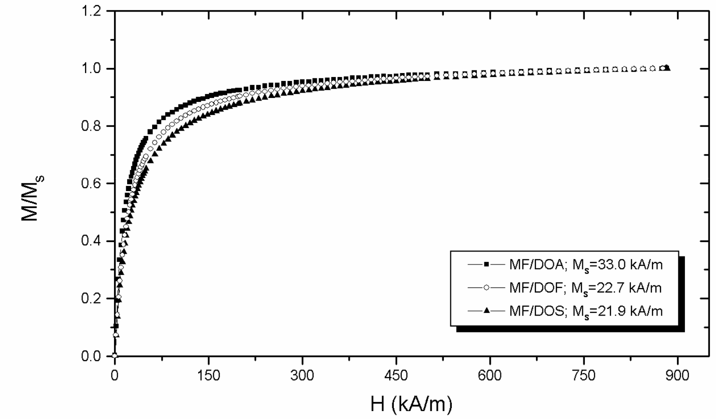

Fig.2. Non-dimensional full magnetization curves for diester based magnetic fluids: MF/DOA, MF/DOF and MF/DOS

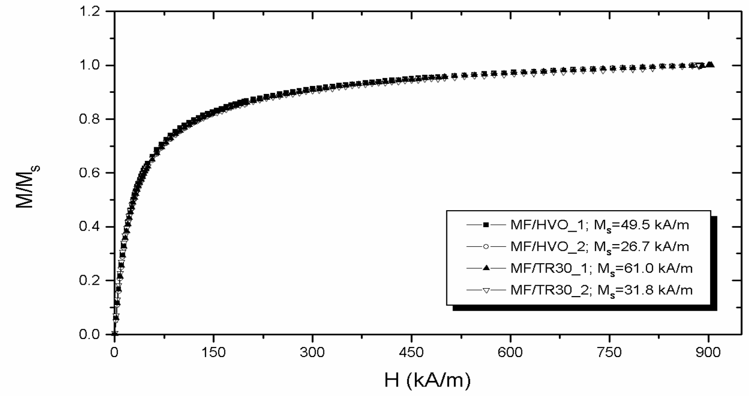

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Fig.3. Non-dimensional full magnetization curves for high vacuum oil (HVO) and transformer oil based magnetic fluids: MF/HVO_1,2 and MF/TR30_1,2.

The initial susceptivity χ_i and saturation magnetization M_s of MF samples, as well as the mean magnetic diameter $<D_m>$ and the standard deviation σ of the log-normal size distribution of magnetic nanoparticles, were obtained using the relationships derived in [15], which take into account the dependence of magnetic moments on magnetic diameters. The results are summarized in Table 1.

Nr. crt.	**Indicative**	**Carrier liquid**	**M_s (kA/m)**	**χ_i**	**$<D_m>$ (nm)**	**σ (nm)**
1.	MF/HVO_1	high vacuum oil (KW; Merck)	49.5	1.0	6.9	2.0
2.	MF/HVO_2	high vacuum oil (KW; Merck)	26.7	0.6	6.4	2.1
3.	MF/DOA	dioctyl adipate (technical grade)	33.0	1.2	8.3	2.4
4.	MF/DOF	dioctyl phtalate (technical grade)	22.7	0.6	7.5	2.2
5.	MF/DOS	dioctyl sebacate (technical grade)	21.9	0.5	6.8	2.1
6.	MF/TR30_1	transformer oil	61.0	1.3	6.5	4.4
7.	MF/TR30_2	transformer oil	31.8	0.7	6.1	4.6

Table 1. Magnetic properties and magnetic size distribution parameters of sealing MFs

The magnetic fluids 1-7 developed for leakage-free rotating seal applications have medium and high saturation magnetization and varies between 20 and 60 kA/m in order to meet the requirement of various type of rotating MF seals. The mean magnetic size of magnetic nanoparticles is in the range 6.0-8.5 nm. It was found that this dimensional range is adequate to satisfy both the requirements of colloidal stability and magnetization of magnetic nanofluids to be used in MF rotating seals. For 6.0 nm or less particle size high colloidal stability of magnetic fluids is easier to achieve, however the relative significance of the non-magnetic surface layer of about 1 nm increases and the saturation magnetization M_s will be lower at the same solid volume fraction. When the particle sizes exceed 9-10 nm, the magnetic dipolar interactions between them increase the interaction parameter over unity, $\lambda > 1$, favoring agglomerate formation and reducing long-term colloidal stability of the sealing MF, especially at low operational temperature values.

3. Design and manufacturing of magnetic fluid rotating seal devices

Some previous results

The design of MF seals for various applications was performed using a graphic-analytical method developed taking into account the magnetic characteristics of permanent magnet and soft magnetic components (pole pieces, shaft), as well as the seal gap and run-out values specified for practical cases. Two types of MF feedthroughs were designed and manufactured for two different kind of applications.

Magnetic fluid feed-through for high power electric switches

High power electric switches use SF_6 gas to impede the formation of electric arc at switching-off, therefore 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. The magnetic fluid feedthrough developed for this application is presented in fig. 3 a, b.

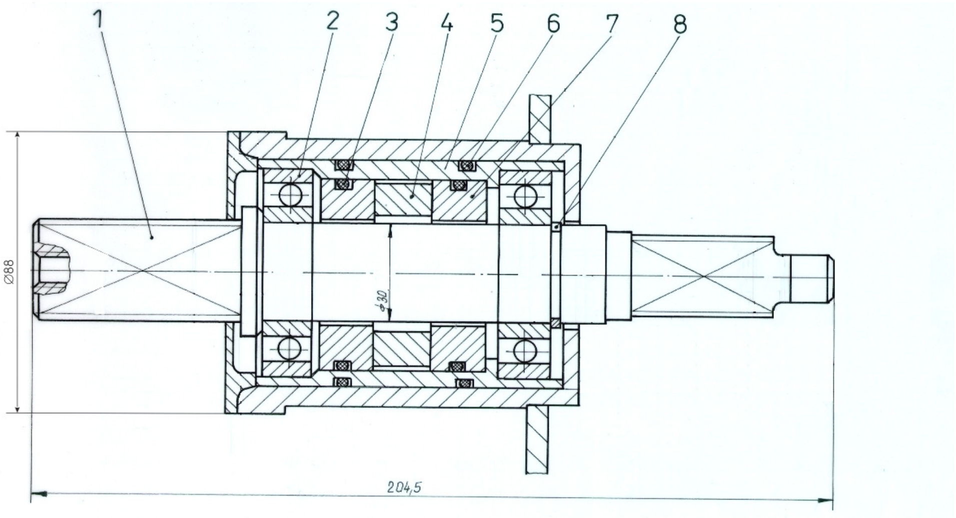

Fig.4a. Sketch of magnetic fluid feedthrough for high power electric switches with SF_6. Components: 1- shaft; 2- ball bearing; 3,6- “O” ring; 4- permanent magnet; 5- non-magnetic casing; 7- polar piece; 8- safety ring.

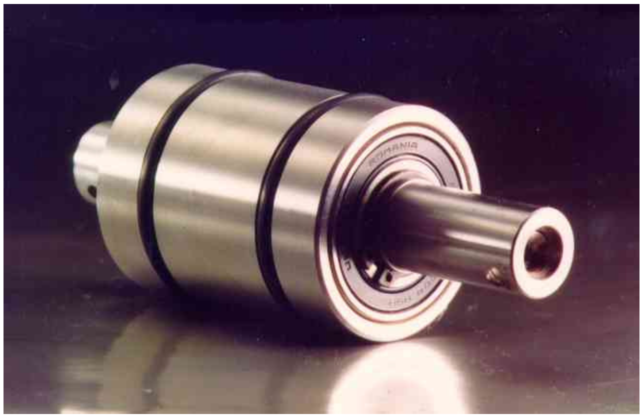

Fig. 4b. Magnetic fluid feedthrough for high power electric switches

The MF feedthroughs for very low rotational speed and 7 bars pressure difference were manufactured at ROSEAL S.A. and conferred high reliability and years long operational life for high power electric switches produced by “Electroputere” S.A. Craiova.

MF vacuum feedthrough for crystal growth equipment

The feedthrough presented in fig. 4 was designed for vacuum sealing applications, up to 10^{-6} torr, in particular for crystal growth equipments. It has the same components as the seal of fig.3a, but for a shaft of diameter $\Phi = 9$ mm. This type of MF seals was experimented several years with very good results, its maintenance free operational life being up to 5 years.

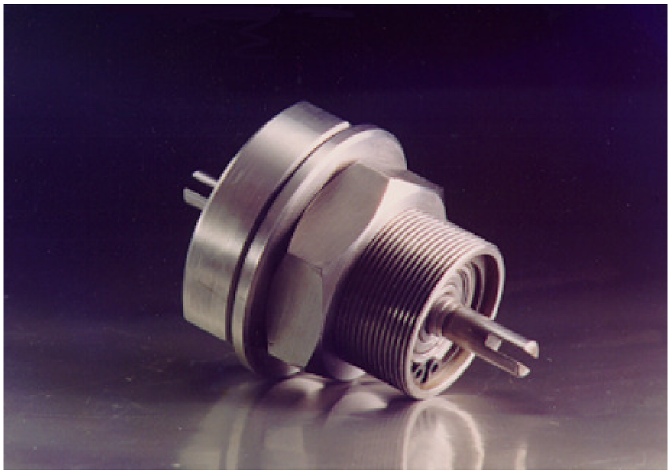

Fig. 5. MF vacuum feedthrough

New tandem magnetic fluid seal – mechanical seal arrangements

Rotating seals with magnetic nanofluids are particularly efficient when solutions are needed for preserving the environment or for ensuring safety operating conditions for various equipments. E.g., while technologies are available to ensure valves and fittings to be leakage-free, it is very difficult to seal without leakage the rotating shaft of a pump. Indeed, even the most performing mechanical seals used for this purpose leak with time because of friction wear. For this reason usually two mechanical seals are employed on the pump, one primary seal to tightly seal the process fluid and a secondary seal for safety reasons. In the space between the two seals a safety fluid is continuously circulated to eliminate the escaped volatile compounds and hazardous materials. The circulating fluid is a lubricating and cooling liquid in most of the cases to ensure proper operating conditions for the mechanical seals.

Combinations of magnetic fluid and mechanical seals (tandem seals) offer several advantages over usual multiple mechanical seal arrangements. Such a dual MF + mechanical seal was proposed in already in [18] for agitators of chemical reactors.

Recently, we developed tandem seals for liquefied gas pumps and compressors, as well as for vacuum deposition equipments.

Mechanical – magnetic fluid tandem seal for liquefied gas pump

The primary mechanical seal retains the high-pressure process fluid, but since the seal is not hermetic some liquefied gas actually escape through the mechanical seal and gas fill up the low pressure chamber between the mechanical and magnetic fluid seal, being evacuated by a circulatory system. This sealing arrangement is capable to reduce the emission of volatile pollutants virtually to zero.

In fig.5 a,b a tandem seal is presented, designed for a vertical axis pump for liquefied gas. The mechanical seal retains up to 25 (40) bars, for up to 3000 rot/min rotation speed of the shaft, while the leakage-free magnetic fluid seal prevent any escape of gases from the chamber between the two seals up to 3 bars. The gas accumulated in the chamber is evacuated to an external recovery system or flame (fig. 5 b.)

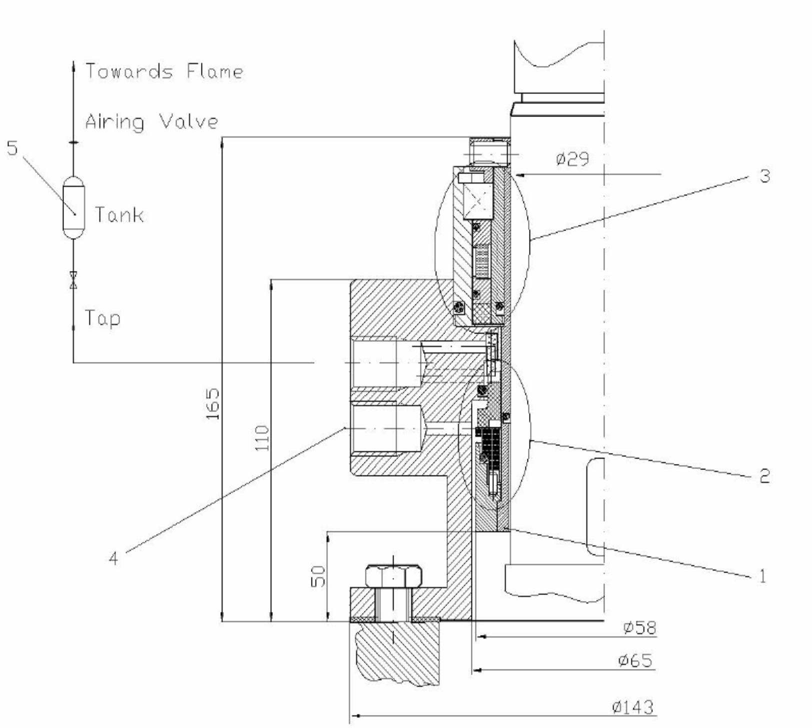

Fig.6a. Sketch of a mechanical- magnetic fluid combined seal for liquefied gas pump

1- shaft; 2- mechanical seal; 3- magnetic fluid seal; 4- inlet for cooling and lubrication fluid; 5- system for escaped process fluid evacuation

Fig.6b. Mechanical- magnetic fluid combined seal for liquefied gas pump

Mechanical – magnetic fluid tandem seal for high vacuum deposition systems

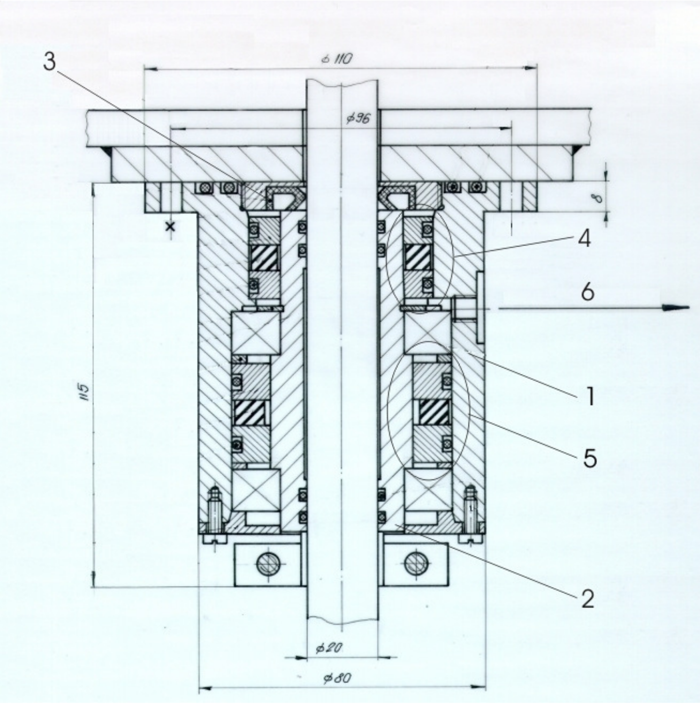

Fig.7. Magnetic fluid – mechanical seal for high vacuum deposition system: 1- non-magnetic shaft; 2- magnetically soft sleeve; 3-friction seal; 4- primary magnetic fluid seal; 5- secondary magnetic fluid seal; 6- to preliminary vacuum pump.

The combined seal from fig. 6 was designed for high vacuum (up to $5x10^{-7}$ torr) deposition system. The mechanical seal at the high vacuum side prevent metal vapors to reach the primary magnetic fluid seal. The chamber between the two magnetic fluid seals is connected to a preliminary vacuum pump, this way keeping a very small pressure difference on the primary MF seal. Practically a single sealing stage is exposed to high vacuum and this way the multi-stage primary MF seal has prolonged operational life. The secondary MF seal is air tight and allows no contamination; any vacuum leak during deposition would compromise the quality of thin layer covering of components.

Conclusions

The 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. Combinations of mechanical and magnetic (tandem) seals conducted to reliable solutions for leak-proof sealing of liquefied gas pumps and high vacuum deposition systems. These dual seal arrangements keep the advantages of both types of rotary seals, such as relatively high sealed pressure difference and long-term leakage-free operating regime.

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