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EXPERIMENTS ON VISCOUS HEATING IN LEAKAGE-FREE ROTATING SEAL SYSTEMS WITH MAGNETIC NANOFLUID

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Two main aspects regarding to magnetic fluid rotating seals operation are discussed in this paper: the influence of the rotational speed and viscosity of magnetic nanofluids on seal temperature and the breakaway torque at start-up. Analytical methods for studying these technical issues and results obtained from experimental investigations are presented. Magnetic nanofluids with two types of carrier liquid (high vacuum oil and transformer oil) were tested having saturation magnetization in the range of 450-550 G. Temperature measurements were performed for three different rotational speeds: 600 rpm, 1000 rpm and 1450 rpm by using an experimental test bench.

Key words: magnetic nanofluid, rotating seal, viscous heating, breakaway torque

1. Introduction

Magnetic nanofluids are smart materials with a special feature, combining the behavior of a normal liquid with superparamagnetic properties. One of the most relevant applications of these fluids is the magnetic fluid rotating seal with a relative simple construction and high performance [1]. In such system the magnetic fluid is held in ring shapes by a permanent magnet which enables rotary motion while maintaining a hermetic sealing. Magnetic fluid seals are engineered for a wide range of applications including pressure and high vacuum sealing devices. Among the benefits are hermetic sealing, long lifetime, high reliability, non-contaminating, high-speed capability, optimum torque transmission, no set-leakage failures and smooth operation [2].

Many aspects are presented in different studies regarding to the magnetic fluid seal performance. Several papers discuss issues about the sealing capacity of the magnetic fluid seals [3, 4, 5]. The influencing factors such as magnetic field distribution [6, 7], centrifugal force [8] and centering effect [9] have also been investigated. The magnetic fluid behavior in high intensity nonuniform magnetic

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field is presented in [10]. The interface instability when sealing another liquid which can dramatically reduce the seal's lifetime was also studied in [11, 12]. Despite all these investigations only a very small amount of information can be found regarding to the effect of speed and viscosity of the magnetic fluid on the seal temperature [13].

Magnetic fluid sealing technology development is strongly related to the magnetic, thermo-physical and flow properties of magnetic nanofluids specially tailored for each application [5]. In seal systems with high viscosity magnetic nanofluids such as high magnetization fluids having high volume concentration of magnetic nanoparticles or magnetic fluids for vacuum applications care must be taken to the seal's heating. In contrary to the usual mechanical seals no mechanical friction exists. However, between the magnetic fluid and the rotating shaft appears viscous friction which can generate a relatively large amount of heat. Beside the adverse effect of the excessive heat on the seal component, it can lead to the evaporation of the magnetic nanofluid which cause seal failure. In order to avoid desorption of the surfactant and the accelerated evaporation of the carrier liquid the viscous heating of the magnetic nanofluid should not exceed about 100-120 ºC [5].

The breaking torque at the start of the rotary motion is another aspect that is discussed. From the moment when the shaft starts to rotate the necessary torque first start to decrease to the minimum value then rises to the maximum torque and it drops again. Therefore there is a need to know the starting torque to allow determining the capacity of the motor which can produce enough torque to drive the shaft.

2. Constructive details

Each particular combination of construction materials and design features has practical limits with respect to temperature, differential pressure, rotational speed and operating environment. A good magnetic fluid seal design involves careful selection of the materials and precise dimensioning.

Present investigations were carried out using one magnetic fluid seal system in which different types of magnetic fluid were injected (see Fig. 1.).

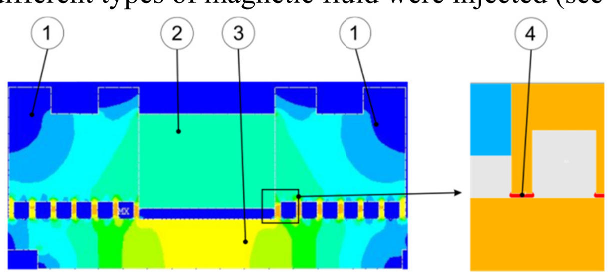

Fig. 1. Magnetic flux distribution in the magnetic fluid seal: 1 – pole pieces; 2 – permanent magnet; 3 – shaft; 4 – magnetic nanofluid.

According to [1, 5] the sealing capacity for a single sealing stage Δp is directly proportional to the saturation magnetization M_s and to the difference between the maximum and the minimum value of the magnetic flux density:

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

$$= M_s (B_{max} - B_{\min}) \quad (1)$$

$$\Delta p_{max} = \sum_{i=1}^{n} \Delta p_i = n \cdot \Delta p$$

Here μ_0 is the absolute permeability, M_s is the magnetic saturation, H_{max}, H_{min} represent the maximum respective the minimum magnetic field intensity measured between the pole pieces and the shaft, B_{max} is the maximum magnetic induction, B_{min} is the minimum magnetic induction, n is the number of stages and Δp_{max} is the sealing capacity of the magnetic fluid seal.

The material of the permanent magnet is anisotropic barium ferrite type FB 2.2. (Rofep, Romania) having a residual flux density equal to 0.37 T and a coercive force *Hc* of 175 kA/m.

The two pole pieces are made from soft magnetic materials with low carbon content (OLC 15). Each of them has seven teeth which guide the magnetic fluxes and thus helps magnetic fluid sealing rings formation.

Due to technological and functional reasons the use of rectangular teeth shape is recommended to get optimal values for the difference between the maximum and minimum values of the magnetic induction.

Three kind of magnetic fluids where tested during the present investigation. These are listed in table 1. The magnetic nanofluids were prepared at the Roseal Co. (Odorheiu Secuiesc, Romania).

Table 1

Magnetic nanofluids

Name	*Carrier liquid*	*Saturation magnetization [G]*
HVO-467G	High vacuum oil	467
HVO-520G	High vacuum oil	520
UTR-528G	Transformer oil	528

To close the magnetic circuit created by the permanent magnet, pole pieces and magnetic nanofluid, the rotating shaft should be made from soft magnetic material (OLC15). It can have solid cylindrical shape or tube shaped.

In order to avoid magnetic flux dissipation the housing is manufactured using nonmagnetic materials.

The high rotational accuracy is ensured by connecting two ball bearings to the pole pieces, inserting two spacer rings between them to reduce the flux dissipation.

3. Magnetic fluids

Magnetic fluids used in sealing technology must meet several requirements [7, 14]. In order to sustain high differential pressure they have to be tailored in such a way to ensure high saturation magnetization and low or very low vapor pressure. Usually, magnetic fluids in a sealing stage have to withstand an intense and strongly non-uniform magnetic field, Hmax ~ 10^6 A/m and |grad H| ~ 10^9 A/m^2 and thus they must ensure excellent colloidal stability in the intense and strongly non-uniform magnetic field [5, 10]. In special cases, chemical characterization is needed to avoid the destabilization of the magnetic fluid when aggressive gases are sealed.

To fulfill simultaneously all these requirements impose special conditions on the stabilization procedure of the preparation of the magnetic fluids, in order to avoid irreversible magnetic field induced structural processes.

In principle, the synthesis procedure of the magnetic nanofluids has two main phases. The first step of the preparation of the investigated magnetic nanofluids is to prepare magnetite nanoparticles through co-precipitation. The second phase contains the stabilization and dispersion of these particles in different carrier liquids in order to prevent irreversible aggregation of particles due to the attractive van der Waals and dipolar interactions [15, 16, 17]. Transformer oils are nonpolar carrier liquid, generally with low or medium viscosity and low tendency for evaporation. Vacuum oils are polar carrier liquids which need an additional stabilizing layer, physically absorbed on the surface of the first stabilizing layer [16, 18]. This vacuum oil has a relatively high viscosity with a tendency to non-newtonian flow behavior.

For HVO-467G and HVO-520G magnetic fluids Aneron high vacuum oil carrier liquid from the Merck Corporation (Germany) was used. The magnetic nanoparticles are magnetite particles with approx. 7 nm mean diameter.

The flow behavior of different types of magnetic fluids plays a significant role in the seal heating. Rheological measurements were elaborated using an Anton Paar Physica MCR-300 rheometer (Romanian Academy - Timisoara Branch, Romania) with plate - plate geometry and an attached thermostat.

While the magnetic nanofluid with high vacuum carrier liquid has a non-newtonian behavior (see Fig. 2.), the UTR-528G has newtonian behavior with a viscosity equal to 56 mPa·s at T = 20 °C in the absence of magnetic field.

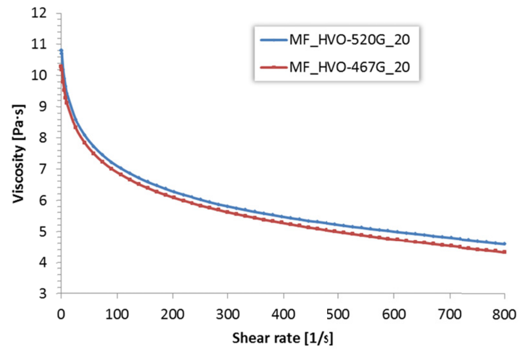

Fig. 2. Viscosity vs. shear rate at T = 20 °C.

The flow behavior of the investigated magnetic nanofluids was also determined in function of the temperature at different shear rates in presence of different magnetic field strengths (see Fig. 3, 4, 5).

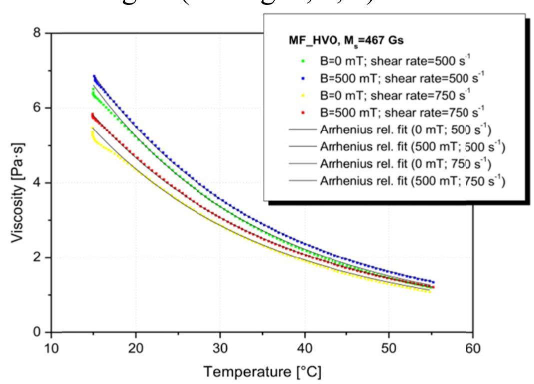

Fig. 3. Viscosity of the magnetic fluid HVO-467G in function of the temperature in magnetic field (B = 500 mT) and without magnetic field.

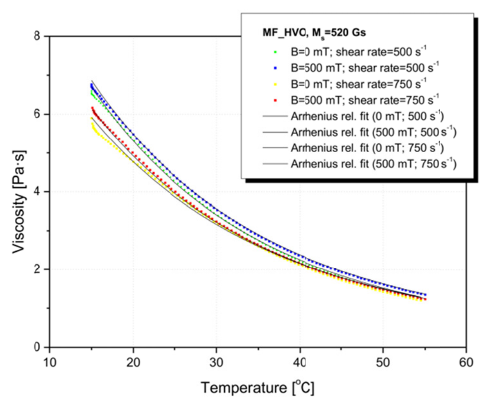

Fig. 4. Viscosity of the magnetic fluid HVO-520G in function of the temperature in magnetic field (B = 500 mT) and without magnetic field.

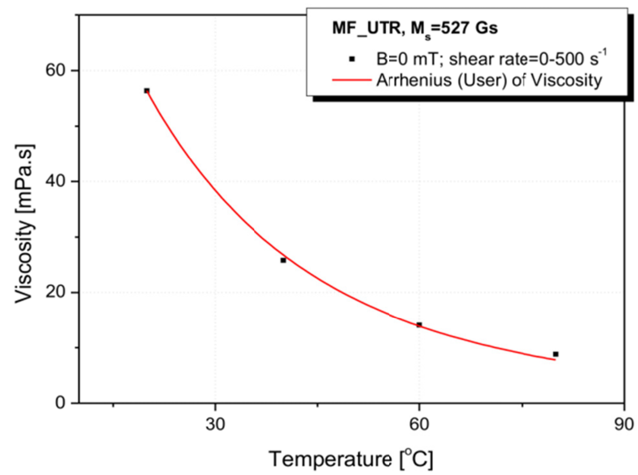

Fig. 5. Viscosity of the magnetic fluid UTR-528G in function of the temperature ($\dot{\gamma}$= 500 1/s).

The dependence of the viscosity of the suspensions on the temperature can be described by the Arrhenius type relation [15]:

$$\eta = A \cdot \exp\left(\frac{B}{T}\right) \tag{2}$$

where A represents a constant without physical meaning, $B = \frac{E_a}{k_B}$, E_a - activation energy, k_B - Boltzmann constant, T – absolute temperature. Thus, (1) can be expressed by the following formula:

$$\eta = A \cdot \exp\left(\frac{E_a}{k_B T}\right) \tag{3}$$

The fitting values of the Arrhenius type formula for the different magnetic nanofluids in absence and in presence of the magnetic field are listed in table 2.

Table 2

Fitting parameters

Sample name	*Magnetic field strength B [mT]*	*Shear rate $\dot{\gamma}$ [1/s]*	*Activation energy of viscous flow Ea [kJ/mol]*	*Reference viscosity (fit param. A) [Pa·s]*	*R^2*
HVO-467G	0	500	$(3.28\pm0.02)\cdot10^4$	5.24	0.99762
HVO-467G	500	500	$(3.19\pm0.005)\cdot10^4$	5.49	0.99977

Sample name	*Magnetic field strength B [mT]*	*Shear rate $\dot{\gamma}$ [1/s]*	*Activation energy of viscous flow Ea [kJ/mol]*	*Reference viscosity (fit param. A) [Pa·s]*	R^2
HVO-467G	0	750	$(3.11 \pm 0.02) \cdot 10^4$	4.36	0.99634
HVO-467G	500	750	$(3.08 \pm 0.004) \cdot 10^4$	4.66	0.99634
HVO-520G	0	500	$(3.27 \pm 0.01) \cdot 10^4$	5.31	0.99892
HVO-520G	500	500	$(3.18 \pm 0.01) \cdot 10^4$	5.48	0.99914
HVO-520G	0	750	$(3.03 \pm 0.02) \cdot 10^4$	4.77	0.99657
HVO-520G	500	750	$(3.13 \pm 0.01) \cdot 10^4$	4.92	0.99964
UTR-527G	0	500	$(3.13 \pm 0.07) \cdot 10^4$	0.06	0.9985

The “goodness’’ of the fit expressed by the coefficient of determination R^2 show that the temperature dependence of the viscosity can be very well fitted with the Arrhenius type relation.
Experiments show that the viscosity of such fluids may increase in magnetic field up to 10%. Due to the fact that the UTR-520G has a low viscosity and thus the influence of a small change induced by the magnetic field does not influence the results in a significant way, it was adopted a nominal increase of 10% of the viscosity of these fluids as experiments indicate.

4. Experimental setup

The block diagram of the experimental test bench of the magnetic fluid seals (see Fig. 6.) has been already presented in [14] with small changes. It has a modular structure containing five main modules.

The test module is composed of a rotating shaft driven by an electric motor of 0.55kW. An inverter ensures variable and controllable rotational speed of the shaft. During the experiments the rotational speed was varied up to 1450 rpm. The investigated magnetic fluid seals were mounted inside a test chamber which was connected to a pressure or a vacuum module.

The pressure module is composed by a compressed helium 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 magnetofluidic seals and also to allow investigation of the influence of the rotational speed on the sealing capacity and on the seal temperature.

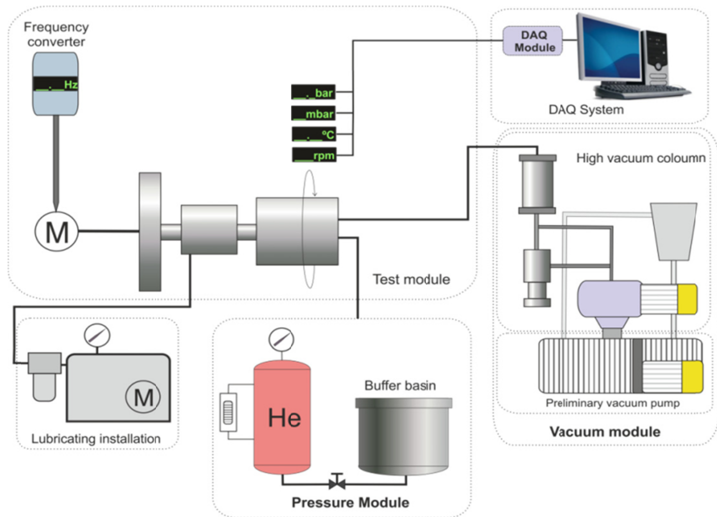

Fig. 6. Block diagram of the magnetic fluid seal test bench.

To investigate the influence of the rotational speed of the shaft and the viscosity of the magnetic fluids on seal temperature a pyrometer was used to measure the temperature relatively close to the magnetic fluid. In order to evaluate the characteristics of the magnetic fluid rotating seal devices, data are collected during testing, such as temperature of seal, pressure or vacuum in the test chamber and rotational speed of the shaft through a data acquisition system.
A software program was developed to ensure proper data collection and analysis.

5. Restults and discussion

Breakaway torque

The sealing gap in which the magnetic fluid is kept by magnetic field is relatively small and the resulted shearing stress in the magnetic fluid due to the rotation of the shaft is equal to the velocity gradient times the viscosity (see Fig. 7.):

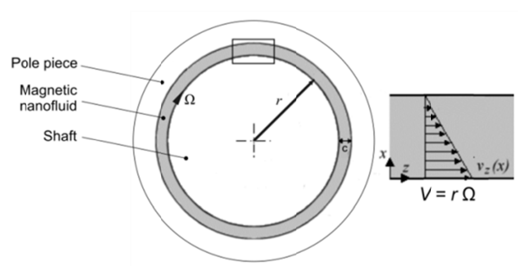

Fig. 7. Cross-sectional view of the seal device with magnetic sealing ring: r – radius of the shaft; c – sealing gap with magnetic nanofluid; Ω – angular velocity.

The force required to overcome the viscous friction is equal to the shear stress times the area of the sealing surface, while the torque is the viscous force times the lever arm:

$$T = (\tau A)r = \frac{4\pi^2 r^3 l \eta N}{c} \tag{4}$$

Where τ [Pa] is the shear stress, A [m^2] is the sealing surface area (contact surface between the magnetic fluid and the shaft), $r = 0.025$ m is the radius of the sealing surface, $l = 14 \times 5\cdot10^{-4}$ m is the length of the sealing surface, η [Pa·s] is the viscosity of the magnetic fluid in magnetic field, N [rot/s] is the number of rotations in a second and $c = 0.001$ m is the radial sealing gap.

Due to viscous heating the temperature of the magnetic fluid rises and thus the viscosity decreases which leads to a smaller viscous friction. Consequently the torque needed to start and stop the rotational motion become smaller. The data presented in figure 7 represents the additional torque needed to rotate the shaft at different temperatures. The reference torque was measured rotating the seal system without magnetic fluid. The necessary torque at a given temperature was also calculated according to (5) and is noted with letter C on the figure 8.

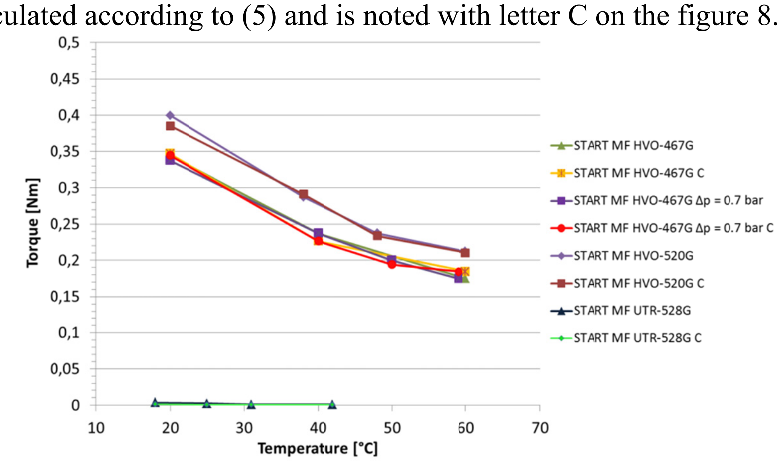

Fig. 8. Torque needed to rotate the shaft of the magnetic fluid seal.

Due to the non-newtonian behavior of the magnetic nanofluids with vacuum carrier liquid, the low peripheral speed at the beginning of the rotational motion and the presence of the magnetic field, the viscosity of such fluid increase the necessary torque to start the rotational motion in a significant way. Thus, at room temperature the starting torque increases approximately 43% in case of MF HVO-467G and with 50% in case of the MF HVO-520G, meanwhile when using magnetic nanofluid with similar saturation magnetization but with transformer oil carrier liquid this increase is reduced to approximately 0.5%. At high temperature (T = 60 °C) the raise of the breakaway torque reduces approximately to the half of the torque needed at room temperature. It can be observed that the experimental results are in good correlation with the calculations.

The starting torque of the mechanical seals is estimated at 3-4 times running torque and is directly proportional to the differential pressure [19]. In contrary, experimental results show no significant differences between the breaking torques of the magnetic fluid seals under pressure and without applying pressure. This can be explained by the fact that differential pressure can induce changes only by modifying the shape of the magnetic fluid ring and thus the contact surface area between the rotating shaft and the magnetic fluid which represents an insignificant change.

Viscous heat

The investigated magnetic nanofluids have a strongly temperature dependent viscosity (see Fig. 3, 4, 5). Due to the coupling between the energy and momentum equation the viscous heating plays an important role in the magnetic fluid seal operation. The viscous friction between the shaft and the magnetic nanofluid increases the temperature of the shaft and consequently decreases the viscosity of the magnetic fluid.
The heat generated by the viscous friction can be expressed by the following formula [13] (see Fig. 9, 10):

$$Q = \frac{8\pi^3 \eta r^3 l N^2}{c} \tag{5}$$

where *Q[W]* is the generated viscous heat.

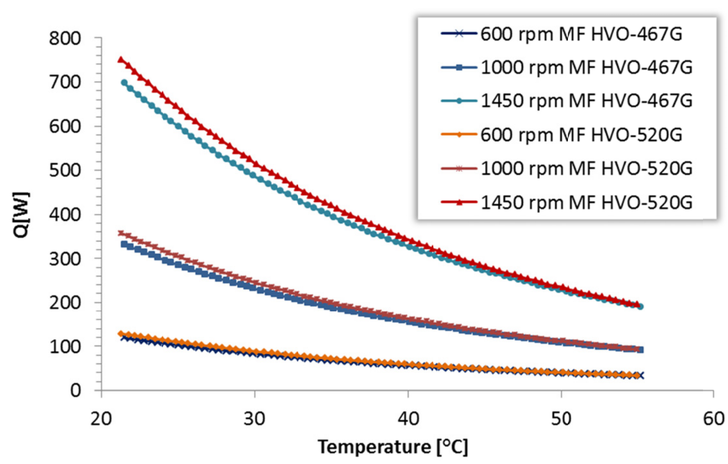

Fig. 9. Heat generated by the viscous friction for three different rotational speed: 600 rpm, 1000 rpm and 1450 rpm in case of HVO-467G and HVO-520G.

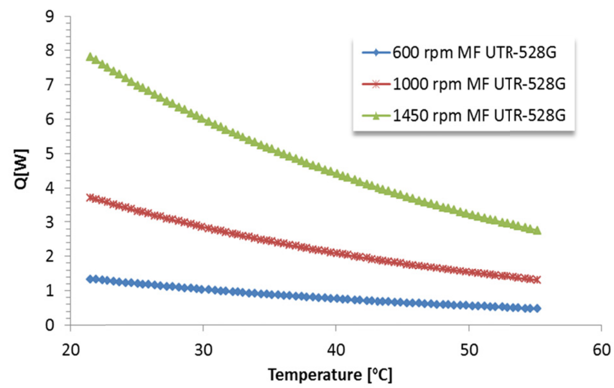

Fig. 10. Heat generated by the viscous friction for three different rotational speed: 600 rpm, 1000 rpm and 1450 rpm in case of UTR-528G.

The heat produced by the viscous friction is dissipated mainly through the pole pieces. The heat transfer is characterized by the Brinkman number [15] (see Fig. 11):

$$Br = \frac{\eta \cdot v^2}{\lambda \cdot T} \tag{6}$$

where λ [W·m^{-1}·K^{-1}] is the thermal conductivity of the magnetic nanofluid, v[m/s] is the peripheral speed of the shaft, T [K] is the absolute temperature.

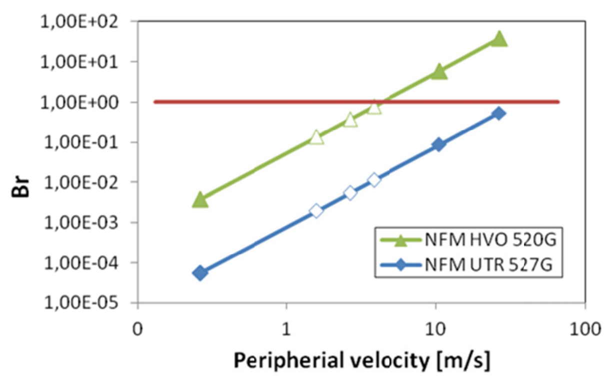

Fig. 11. Brinkman number vs. peripheral velocity in case of UTR-528G and HVO-520G (empty dots correspond to the Brinkman number values for the three different rotational speed: 600 rpm, 1000 rpm and 1450 rpm)

The Brinkman number gives information about the need of an additional cooling system. In case of Br > 1, the heat transfer is insufficient and the pole pieces require forced cooling.

The thermal conductivity of the magnetic fluids were measured using LFA 447 NanoFlash® Light Flash System (NETZSCH-Gerätebau GmbH, Germany) at the National Institute for R&D in Electrical Engineering ICPE-CA Bucharest.

The temperature of the seal was measured relatively close to the magnetic nanofluid sealing rings until the equilibrium state has been reached and the seal has gained its maximum temperature.

Figure 12 presents the temperature increase due to the viscous friction. The reference temperature was measured by rotating the seal system without magnetic nanofluids.

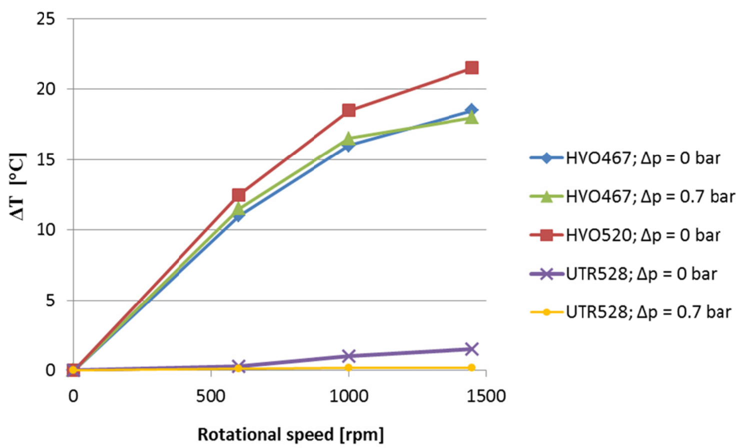

Fig. 12. Effect of speed and viscosity on seal temperature.

It can be observed that the rise of temperature due to viscous friction in case of using magnetic fluid with transformer oil carrier liquid with almost the same saturation magnetization is negligible. Meanwhile the vacuum oil based magnetic nanofluid at high rotational speed increase the temperature of the seal even up to 20 °C. The rotational speed has a strong influence on the heat generated by the viscous friction. Since the temperature of the seal has a negative influence on the magnetization of the magnetic nanofluids the generated heat can reduce the seal capacity, as well.

6. Conclusion

The results summarized in the paper evidence the influence of the composition and saturation magnetization of the magnetic fluids on the operating conditions of MF seals at high rotation speed values.

From technological point of view the results give an insight to the influence of different types of magnetic nanofluids on the seal temperature and the breakaway torque. Magnetic nanofluids with transformer oil carrier liquid and moderate saturation magnetization have a negligible influence on the seal heating and on the starting torque.

The Brinkman numbers obtained for the two different types of fluids up to a rotational speed equal to 1450 rpm, are below 1. It shows that the pole pieces don't need additional cooling system. This also has been confirmed by experiments, the sealing system being able to provide a stable long-term sealing capacity for the tested parameters. Note, that for higher rotational speed (over 1600 rpm) the sealing system with magnetic fluids with high vacuum carrier liquid (HVO-467G and HVO-520G) will need forced cooling.

However, for the non-newtonian vacuum oil based magnetic nanofluid, the low rotational speed at start-up in the presence of strong magnetic field, the breakaway torque is increased in a significant way. Taking into account that the investigated fluids (HVO-467G and HVO-520G) increased the torque at start-up up to 50% and the seal temperature with 20 °C, magnetic nanofluids with higher saturation magnetization definitely would lead to more significant effects on the operating conditions.

Similar effects will arise for transformer oil based magnetic nanofluids having high saturation magnetization. The viscosity of such a magnetic fluid having a saturation magnetization Ms = 1000 G reaches 4 Pa·s, while a fluid with Ms = 1300 G has about 15 Pa·s viscosity. For these values significant start-up torque and heating-up effects are expected.

Maintaining an adequate temperature is necessary due to the fact that the high temperature decreases the magnetization of the magnetic fluids and increases the rate of evaporation and thus has a negative influence on the seal performance.

Further experiments could be performed to obtain information about the exact temperature not only of the seal but of the magnetic fluid itself. For this, it is required to change the position of the pyrometer in order to be able to measure exactly the temperature of the magnetic fluid sealing ring at the last sealing stage. These measurements could give more precise information about the heat generated by viscous friction for different magnetic fluids and also about the amount of heat dissipation.

8. Acknowledgement

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REFERENCES

[1] *K. Raj*, Magnetic fluids and devices: a commercial survey, in: B. Berkovsky, V. Bashtovoi (Eds.), Magnetic fluids and applications handbook, Begell House, New York, 1996, pp. 657-751.

[2] *R. Flitney, M.* Seals and sealing handbook (Fifth Edition), Elsevier Publisher, 2007 pp. 268-271

[3] *Z. Meng, Z. Jibin, H. Jianhui*, An analysis on the magnetic fluid seal capacity, Journal of Magnetism and Magnetic Materials, **vol. 303**, 2006, pp. 428–431

[4] *J. Qian, Z. Yang*, Characteristics of a magnetic fluid seal and its motion in an axial variable seal gap, J. China Univ. Mining & Technology, **vol. 18**, 2008, pp. 0634–0636

[5] *I. Borbáth, Z. Kacsó, L. Dávid, I. Potencz, Doina Bica, Oana Marinică, L. Vėkás*, Applications of magnetic nanofluids in rotating seals, Convergence of micro- and nanoengineering, Bucharest; Romanian Academy Publ. House, 2006, pp. 200-210

[6] *D. Li, X. He, Z. Zhang*, A study of static magnetic fluid seal of large flange diameter, Magnetohydrodynamics, **vol. 44**, no. 1, 2008, pp. 75–82

[7] *Tünde Borbáth, V. Panaitescu, I. Potencz, I. Borbáth, L. Vékás,* Analiza câmpurilor magnetice în etanşări rotitoare cu nanofluide magnetice, A XI-a Conferinţă Naţională multidisciplinară – cu participare international "Profesorul Dorin PAVEL – fondatorul hidroenergeticii româneşti", Sebeş, **vol 19**, 2011, pp. 337-344

[8] *J. Zoua, X. Lib,Y. Lua, J. Hua,* Numerical analysis on the action of centrifuge force in magnetic fluid rotating shaft seals, Journal of Magnetism and Magnetic Materials, **vol. 252**, 2002, pp. 321–323

[9] *R. Ravaud, G. Lemarquand*, V.Lemarquand Mechanical properties of ferrofluid applications: Centering effect and capacity of a seal, Tribology International **vol. 43**, 2010, pp. 76–82

[10] *L. Vékás, I. Potencz, Doina Bica, R.Minea*, The behaviour of magnetic fluids under strong nonuniform magnetic field in rotating seals, Journal of Magnetism and Magnetic Materials, **vol. 65**, 1987, pp. 223-226.

[11] *T. Liu, Y. Cheng, Z. Yang*, Design optimization of seal structure for sealing liquid by magnetic fluids, Journal of Magnetism and Magnetic Materials, **vol. 289**, 2005, pp. 411-414.

[12] *Y. Mitamura, S. Arioka, D. Sakota, K. Sekine, M. Azegami,* Application of a magnetic fluid seal to rotary blood pumps, J. Phys.: Condens Matter, **vol. 20**, 204145, 2008, 5 pp.

[13] *Z. Li,* Magnetic fluid seals for DWDM filter manufacturing, Journal of Magnetism and Magnetic Materials, **vol. 252**, 2002, pp. 327-329.

[14] *Tünde Borbáth, Doina Bica, I. Potencz, I. Borbáth, T. Boros, L. Vékás*, Leakage-free rotating seal systems with magnetic nanofluids and magnetic composite fluids designed for various applications, international journal of fluid machinery and systems, **vol. 4**, no. 1, January-March 2011, pp.67-75

[15] *L. Vékás*, Nanofluide magnetice: sinteză, structură, proprietăţi, aplicaţii, Editura Academiei Române, 2012 (to be published)

[16] *Doina Bica*, Preparation of magnetic fluids for various applications, Romanian Reports in Physics, **vol. 47**, no. 3- 5, 1995, pp. 265-272.

[17] *L. Vékás, Doina Bica, Oana Marinica*, Magnetic nanofluids stabilized with various chain length surfactants, Romanian Reports in Physics, **vol. 58**, no. 3, 2006, pp. 257–267

[18] *Doina Bica, I. Potencz, L. Vekas, G. Giula, Florica Potra*, Romanian Patent RO 115533 B1, 2000

[19] *A. Arnold,C. Fone*, Mechanical seal performance and related calculations, Proceeding of the twenty-sixth international pump users symposium, 2010