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Experimental and numerical determination of the static critical pressure in ferrofluid seals

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Abstract. Ferrofluids have various engineering applications; one of them are magnetic fluid seals for rotating shafts. There are various constructions of this type of seals, but the main difference is the number of sealing stages. The development of this construction is a complex process which requires knowledge of ferrofluid physical and rheological properties and the magnetic field distribution inside the sealing gap. One of the most important parameters of ferrofluid seals is the critical (burst) pressure. It is the pressure value at which a leak will occur. This study presents results of numerical simulation of magnetic field distribution inside the seal gap and calculations of the critical pressure value. The obtained pressure values were verified by experiments.

1. Introduction

Rotating shaft seals with magnetic fluid belong to the class of contactless technical seals. The principle of operation of such seals is a formation of a tight barrier by means of a magnetic fluid ring, which is kept in the gap by the magnetic field. This type of design is characterized by a small resisting moment, high reliability and durability. Such seals can operate, in a wide range of work parameters under static and dynamic conditions, maintaining an absolute tightness.

Ferrofluids are colloidal suspensions of magnetic particles of dimensions: 5-10 nm. Usually oil or water is applied as a carrying fluid, and in order to improve their stability ferrofluids contain additions of surface active substances. In contrast to magnetorheological fluids ferrofluids are highly stable.

Constructions of magnetic fluid seals consist of some basic components. An example of the design used in numerical calculations and in the presented hereby investigations is shown in Figure 1. A magnetic field source constitutes either the permanent magnet or an electromagnet (pos.3) polarized in the axial direction. The rotating shaft (pos.2) and pole pieces (pos.1) constitute the main part of the magnetic circuit. The whole is placed in a non-magnetic housing. The magnetic fluid (pos.4) is kept by the magnetic field in the sealing stage (pos.7). For research reasons this is an asymmetrical seal with stages situated on one side only.

2. Critical pressure

The crucial parameter characterising each sealing is the pressure value of the sealing factor, at which an abrupt leak will occur (critical pressure). The seal burst is of a point character and occurs in the weakest place in the circuit of the magnetic fluid ring. The fluid is displaced and thrown out from the sealing in the axial direction.

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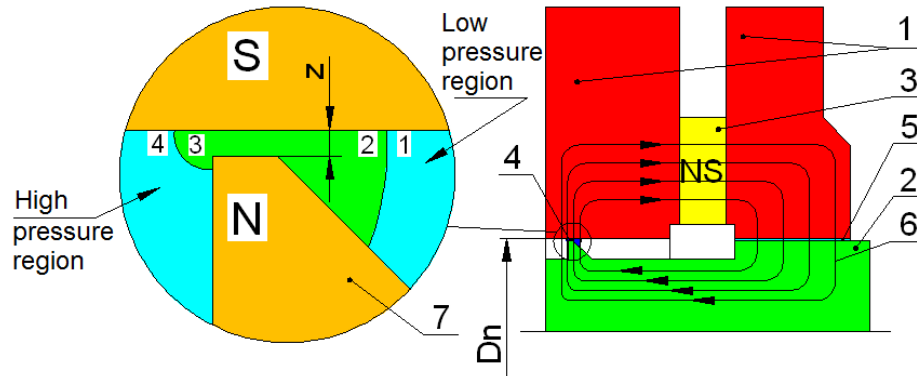


Figure 1. Geometry of the magnetic fluid seal; 1– Pole pieces, 2– Sealing bush, 3– Permanent magnet, 4– Ferrofluid, 5– Air gap, 6– Magnetic field, 7- Sealing stage, z - Gap size, D_n –Nominal diameter.

In case of an excessive pressure increase and a leak, the magnetic fluid sealing can restore itself when the pressure will decrease below its critical value. This effect is known as ‘Reseal’. The critical pressure value can be calculated on the bases of the Bernoulli’s theorem [1]:

$$P + \frac{1}{2}\rho v^2 + \rho gh - \mu_0 MH = \text{const.} \quad (1)$$

where P is total pressure in a magnetic fluid (Pa s), ρ is density of a magnetic fluid (kg/m^3), g is gravitation constant (m/s^2), M is magnetisation (A/m), μ_0 is vacuum magnetic permeability ($\text{V}\cdot\text{s/A}\cdot\text{m}$), H is magnetic intensity (A/m), and h is reference height (m).

When the influences of gravitation and centrifugal forces are omitted the following equation is obtained [1]:

$$\Delta P_{kr} = \mu_0(M_s H_3 - M_s H_2) = \mu_0 M_s \Delta H = M_s \Delta B_{3-2} \quad (2)$$

where M_s is magnetic saturation in A/m, ΔB_{3-2} is difference of the magnetic induction value in points 3 and 2 (Figure 1).

Magnetic saturation M_s is a constant value at the assumption that the magnetic fluid is of an intensity higher than 800 kA/m. This condition is fulfilled in the discussed cases. Typical M_s values of magnetic fluids are within the range: 20-60 kA/m. In order to assess the critical pressure value the knowledge of the magnetic field distribution in the sealing is necessary. In the majority of seals due to a small height of the gap z , in which the magnetic fluid is placed, there is no possibility of an accurate, direct measurement of the magnetic field distribution. The smallest thickness of probes in the equipment for measuring the magnetic field are of the order of 1-1.5 mm, while the heights of working gaps are within the range: 0.1-0.5 mm. Due to a non-linear character of the problem and sometimes complicated sealing geometry it is difficult to assess this distribution by means of mathematical formulae.

3. Numerical simulations of the magnetic field distribution

Analyses of magnetic circuits in seals with the magnetic fluid were performed by the finite element method. Due to the circular symmetry of the analysed geometry in numerical simulations two-dimensional, axisymmetric model was assumed. The grid size was compacted in the gap zone. Dirichlet’s zeroing boundary conditions were introduced, which means that it was assumed that the

magnetic flux was parallel to the boundaries of the analysed area and that the flux value at the boundary would be zero. Simulations were performed for the magnetic fluid sealing of a nominal diameter: $D_n = 50$ mm. Simulations as well as experiments were carried out for three values of a gap height: 0.1, 0.2, 0.3 mm and three volumes of ferrofluid: 0.05, 0.1, 0.2 mL applied for sealing with one stage. For sealing of two or three stages the gap of 0.2 mm and the fluid amount of 0.1 mL were selected. As the magnetic field source the permanent magnet was used. This was the magnet of a trade name N38 and a coercive force $H_c = 937.4$ kA/m and $B_r = 1.241$ T. For the ferromagnetic elements (shaft, pole pieces) the curve B-H, characteristic for structural steel of a carbon content up to 0.27% [2], was assumed. The magnetic fluid BM-30 Batch 257 [4], for which the saturation magnetisation equals $M_S = 37.5 \pm 0.5$ kA/m was used in investigations. On the grounds of the references the magnetisation curve B-H for this type of fluid was assumed according to [5].

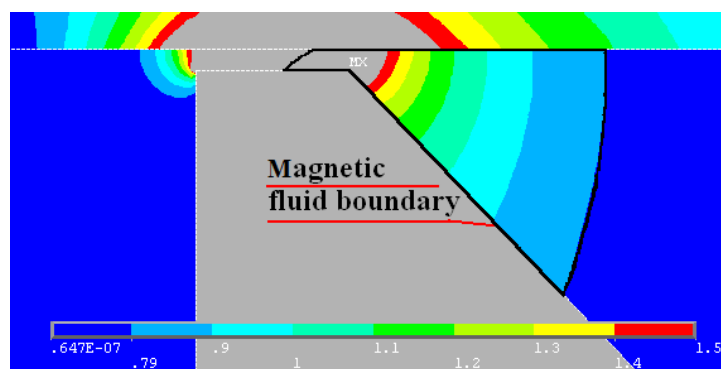


Figure 2. Contour distribution of the magnetic induction T with the modelled fluid-0.1 mL.

The shape of the investigated geometry was modelled according to the real dimensions of the structure. The position and shape of the magnetic fluid in the seal were modelled with maintaining the constant fluid volume rule and the fluid boundary occurrence along the constant magnetic induction rule [6]. The typical contour distribution of the magnetic induction in the analysed seal and the assumed ferrofluid shape is presented in Figure 2. For the needs of the simulation the fluid was placed in the position in which it would have been if the critical pressure had occurred.

On the bases of the numerical analysis the curves of the magnetic induction distribution in the gap - were determined. An example of the diagram for the geometry applied in investigations is presented in Figure 3.

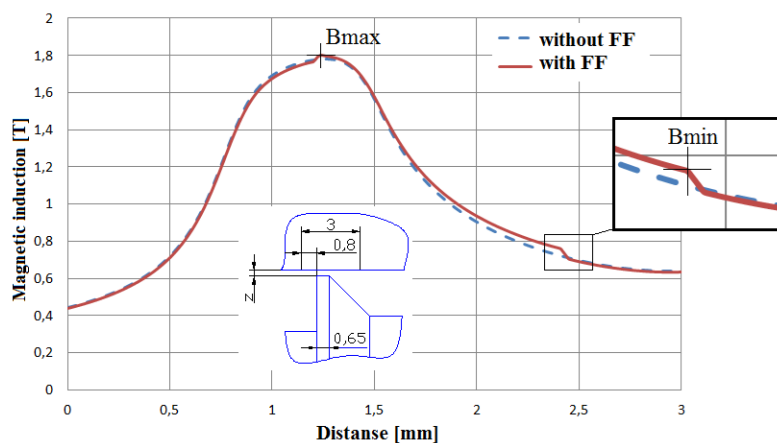


Figure 3. Magnetic induction distribution in the analysed geometry of the cases with and without the magnetic fluid [3].

The characteristic stage, which appears in the magnetic fluid presence and is not seen when there is a lack of this fluid, is emphasised in this figure. The stage appears at the interface boundary. Its value depends on magnetic fluid properties and on the magnetic field intensity in the gap.

The critical pressure value was calculated on the basis of equation (2), as a product of the ferrofluid saturation magnetisation and the difference of the magnetic induction $B_{\max}-B_{\min}$.

Accuracy of the simulation method was verified with use additional templet with gap width 1.5 mm and constant magnetic induction. This has provided the possibility of direct measurement magnetic induction inside gap by the Hall Effect sensor. Measurement results were compared with numerical simulation results. On this basis it has been shown that the difference between the simulation and the measured value of the magnetic induction does not exceed 2% of the measured value.

4. Experimental determination of the critical pressure value

Experimental investigations verifying the correctness of the calculated critical pressure value were performed on the research stand for testing seals with the magnetic fluid MAST1 [7]. This stand allows for the precise measurements of the pressure, speed, torque and temperature. Investigations were performed for the same geometry of seals as in the case of numerical simulations. Measurements were carried out under static conditions (system rotational speed = 0 rpm). The measurement consists in introducing the linearly increasing pressure and observing the moment of its abrupt drop.

In seals with magnetic fluids the static critical pressure is a time function. With the stabilisation time increasing obtains higher and higher values - up to a maximum. In order to eliminate this effect influence the special measuring procedure was applied. Each measurement was preceded by 5 minutes of the stabilising period after adding the fluid, followed by successive 5 minutes when the tested seal operated at the peripheral speed equal 1 m/s, after which the right measurement was performed. An example of the critical pressure diagram is presented in Figure 4.

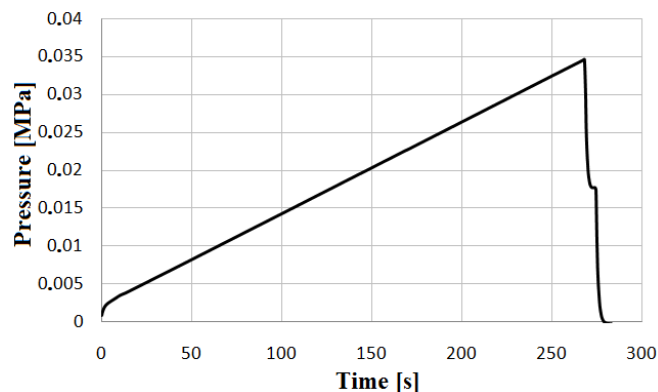


Figure 4. Burst pressure curve for BM-30 Batch 257 fluid; working gap: 0.1 mm, rotational speed: 0 rpm, critical pressure: 0.0346 MPa [3].

The critical pressure results obtained by means of the simulation and their comparison with experimentally obtained values are presented in Fig. 5. They concern seals with one sealing stage. The largest error was obtained for the smaller volume of the applied fluid (0.05 mL) and the largest gap $z = 0.3$ mm. The pressure obtained on the simulation basis was by 34.3 % higher than the measured one. The smallest error was obtained for the largest gap $z = 0.3$ mm and the largest volume of the magnetic fluid (0.2 mL) -1.4 %. Positive values of the relative error, it means that the measured critical pressure was higher than the one numerically obtained, appeared only for the smallest working gap size (0.1 mm).

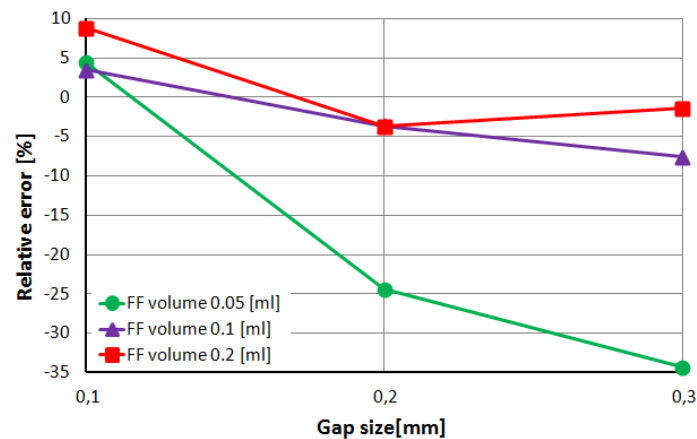


Figure 5. Relative error (%) of the critical pressure between measurement and simulation results, for various working gap sizes and various fluid volumes applied for one sealing stage.

The relative error results and critical pressure values for seals with various sealing stages are presented in Figure 6 (a,b). The highest critical pressure value equal 0.097 MPa was obtained in tests for three sealing stages. The relative error for one and two sealing stages does not exceed -4%. On the other hand for the three sealing stages this error has been already -26.3%. In each case simulations overstated the critical pressure value.

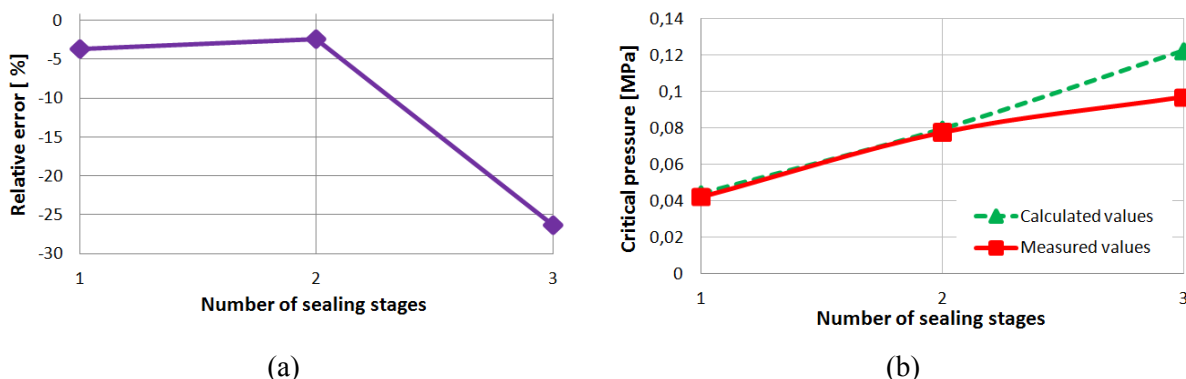


Figure 6. (a) Relative error (%) of the critical pressure between the measured values and calculated on the basis of simulations for various sealing stages, working gap $z = 0.2$ mm, fluid volume applied for one sealing stage 0.2 mL, (b) Critical pressure values.

5. Conclusions

The determination method of the critical pressure of the sealing with the ferrofluid with the application of the numerical simulation of the magnetic field distribution and on the basis of experiments, was presented in the hereby research.

On the bases of the performed considerations, it can be stated that the proposed method allowed to determine the static critical pressure of the sealing with the magnetic fluid on the bases of analytical equations and simulation calculations.

The relative error of the determined pressure value depended on the ferrofluid volume modelled in numerical simulation, in addition to which the modelling of small fluid volumes leads to under-assessing the critical pressure value, first of all for seals with a larger gap size. In case of multistage seals the simulation results should be corrected, since for more than 3 stages the error was above 25%.

Differences between the critical pressure calculated values and values assumed as the real ones are caused by an inaccuracy in producing and assembling elements of the research stand, surface

roughness, misalignment of sealing bushes and pole pieces and others. Divergences of the obtained results were also influenced by the ferrofluid surface shape assumed in simulations as well as the selection of curves describing magnetic properties of the numerically modelled geometry.

References

- [1] Rosensweig R E 1985 *Ferrohydrodynamics* (Cambridge University Press)
- [2] Gieras J F, Piech Z J and Tomczuk B 1999 *Linear synchronous motors: Transportation and automation systems*
- [3] Horak W and Szczęch M 2011 Wyznaczanie statycznego ciśnienia krytycznego w uszczelnieniach z cieczą ferromagnetyczną na podstawie obliczeń numerycznych *Mechanik* **12** 988
- [4] Salwiński J, Szydło Z, Horak W and Szczęch M 2011 Badanie zmian lepkości cieczy ferromagnetycznych poddanych działaniu stałego pola magnetycznego *Tribologia* **2** 143
- [5] Ivanov A O, Kantorovich S S, Reznikov E N, Holm Ch, Pshenichnikov A F, Lebedev A V, Chremos A and Camp P J 2007 Magnetic properties of polydisperse ferrofluids: A critical comparison between experiment, theory, and computer simulation *Phys. Rev. E* **75** 6
- [6] Balac S and Caloz G 2002 Magnetostatic field computations based on the coupling of finite element and integral representation methods *IEEE Transactions on Magnetics* **38** 2
- [7] Salwiński J, Szydło Z, and Szczęch M 2010 Experiments on magnetic fluid seals operating in water condition *17th Int. Colloquium Tribology* Technische Akademie Esslingen 93