УДК 621.318

NUMERICAL ANALYSIS OF MAGNETIC CIRCUITS IN THE FERROFLUID SEALS

J. Salwinski, W. Horak, M. Szczęch

AGH University of Science and Technology, Krakow, Poland

The article presents the results of numerical calculations of magnetic circuits using the finite element method. The modeling process of the seals with ferrofluid is described. The influence of the main parameters and geometry of the seal on the distribution of magnetic field is shown. The possibility of determining the distribution of the magnetic field in the working gap of seals, which plays a major role in determining the maximum pressure that is perceived by seal without losing density and is crucial in choosing the design dimensions of the seal.

Keywords: *magnetic fluids,* technical seals*, finite element method.*

Modern sealing with magnetic fluids are widely used in industry. This is due to their advantages: high durability, reliability, low point resistance movement and a wide range of settings in which they can work. These seals provide absolute density under static and dynamic loads. However, during construction they require professional knowledge and determine the distribution of the magnetic field that occurs in the seals, especially in the area of the sealing ridge also.

Ferromagnetic fluids are colloidal suspensions of magnetic particles with sizes of 5-10 nm. These particles are immersed in carrier fluid like water or synthetic oil. In addition to increase stability of the ferromagnetic liquids they are covered in surfactant. The main area of application of such substances is technical seals.

Magnetic fluid seals belong to the class of non-contact technical seals. By creating a liquid barrier they provide complete tightness in the vacuum, gas and liquid environments. These structures are also characterized by a small moment of resistance, which eliminates an amount of heat generated during operation. These seals can work over a wide range of operating parameters. The working temperature may vary in the range -100 to 200 ^{0}C, at a rotating speed 0 to 10000 rpm, at pressures of 0 to 1 MPa. The construction this type of seal consists of four basic elements. Typical construction is shown in (Fig. 1).

Rotating shaft *2* are located inside the fixed pole pieces *1*. Pole pieces and the shaft form a closed magnetic circuit. Magnetic fluid *4* is placed in a small gap (A-A view Fig. 1). The source of the magnetic field is a permanent magnet or an electromagnet *3* polarized in the axial direction. Ferrofluid *4* creates a liquid ring which is a barrier for sealing environment. The whole construction is placed in a non-magnetic housing *6*. The main advantages this type

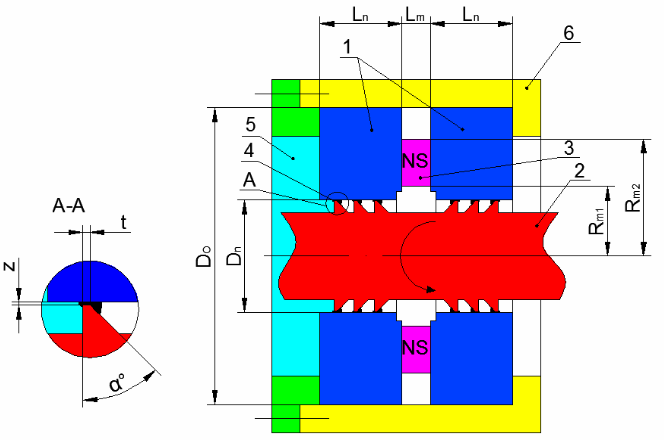

Fig 1. **Construction of multistage magnetic fluid seal:** *1*– pole pieces, *2*– shaft with sealing stages, *3*–source of magnetic field, *4* – magnetic fluid, *5*– sealing environment, *6*– non-magnetic housing, view *A–A* shows the region of the sealing stage. Geometrical parameters of magnetic fluid seals: *Dn*– nominal diameter of the seal, *Do*– the diameter of the pole pieces, *Ln*– length of the pole pieces, *Lm*– the length of the magnet source, R_{M1}, R_{M2}– the width of the magnet source, α – angle, *z* – size of the sealing gap, *t*– chamfer length

of seals are very low friction, high durability and the ability of self-regeneration, when the breakdown of liquid ring occurs. The mechanism of tightness loss for this type of seals is described in [1, 2]. Magnetic fluid seal works properly below its critical pressure value. For this value some magnetic fluid is displaced from the gap and after decrease, liquid O-ring will be rebuilt by magnetic field.

Objects and methods of investigation

Numerical simulations of magnetic field distribution in the seal.

In the design process for the proper selection of size, type, quantity of liquid, sealing stages, overall dimensions, a source of the magnetic field, magnetic field distribution in the structure must be taken into account, particularly in the region of the sealing gaps. The maximum and minimum flux density determines the value of critical pressure in the seal. Due to the nonlinear nature of this problem and sometimes complex geometries of the seal construction there is difficulty in estimating this distribution by empirical formulas.

Analyses of magnetic circuits in the magnetic fluid seals were made by using the finite element method. Program AnsysMultiphysic version 11th with Electromagnetic package was used for this purpose. In the numerical simulations an axially symmetric model was assumed. The size of the mesh was reduced in the gap area. Introduced the zero Dirichlet boundary conditions, i.e. it was assumed that the magnetic flux direction is parallel to the edges of a analyzed area, and the value of the magnetic stream at the border is zero. Numerical calculation were performed for the magnetic fluid seal with a nominal diameter D_n = 50 mm.

In order to obtain the correct numerical solution it was necessary to adopt appropriate magnetic induction curves for ferromagnetic materials, magnetic fluid and the source of the magnetic field. The steel elements were modeled by B-H curve for steels with carbon content up to 0,27 % [3] (Fig. 2*b*). Ferrofluid was modeled by B-H curve for magnetic fluid with saturation magnetization M_S = 40 kA/m by [4] (Fig. 2*a*).

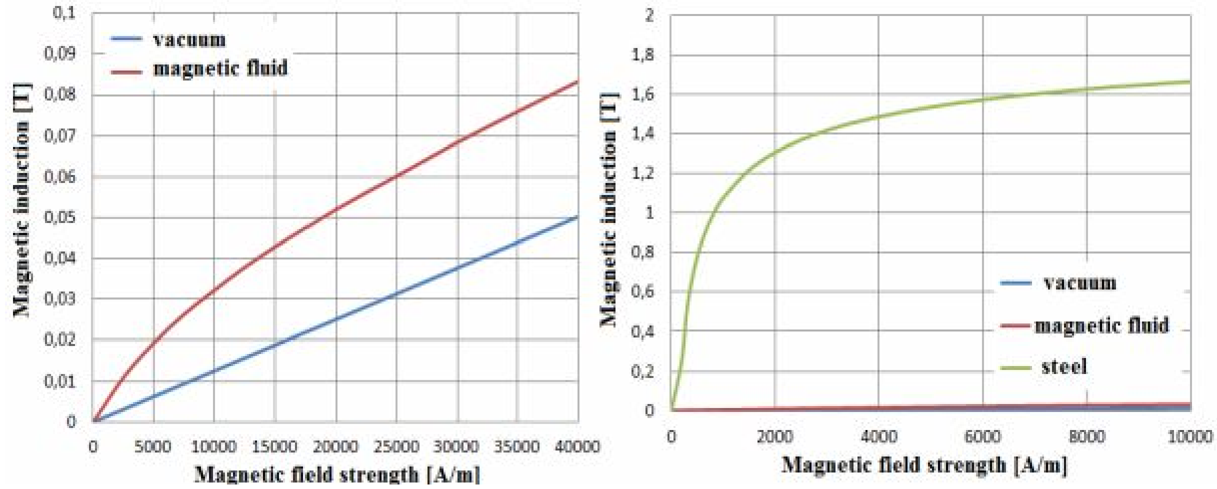

Fig. 2. **Curves of magnetic induction of magnetic circuit elements in the magnetic fluid seal:** *a)* magnetic fluid M_S = 40 kA / m, vacuum, *b)* steel with carbon content up to 0.27%, the magnetic fluid M_S = 40 kA / m, vacuum

Permanent magnet (trade name N38) was modeled as a ring with dimensions Ø80/Ø28/5. Coercivity for this element is Hc = 937,4 kA / m and remanent flux density Br = 1,241 *T*. An example of the contour plot of magnetic induction distribution in the seal for the geometry shown in (Fig. 1) is presented in (Fig. 3).

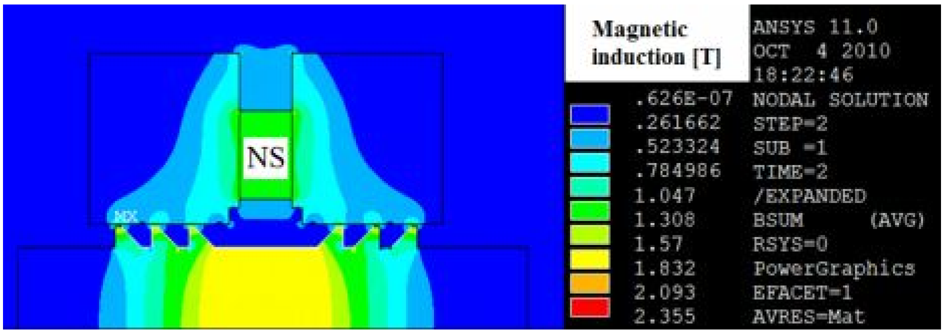

Fig. 3. **Contour plot of magnetic induction distribution in the magnetic fluid seal geometry**

The publication focuses on the distribution of magnetic induction in the region of the gap. Magnetic fluid was modeled assuming that the liquid boundary occurs in the region of constant magnetic induction. It was also adopted that the position of the liquid corresponds to the maximum operating pressure of the seal. Results of numerical calculation are presented for measurement line (Fig. 4). The distance of the line is ~0,02 mm away from the surface of pole pieces. This is the place for which magnetic induction has the smallest value and the magnetic fluid seal will break down.

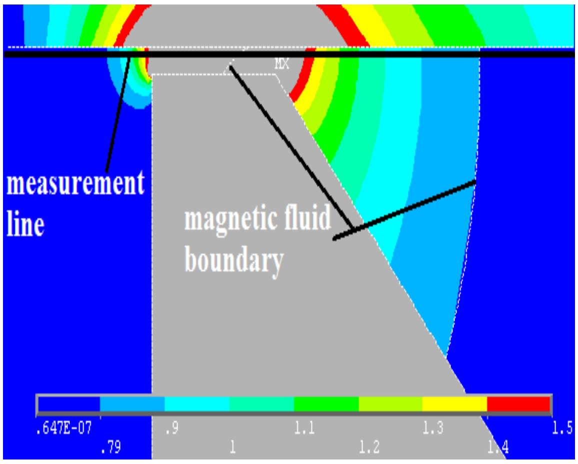

Fig. 4. **Contour plot of magnetic induction distribution in the magnetic fluid region**

The geometry of the sealing stage has a main influence on the magnetic induction in the gap. It affects the value of critical pressure. The results of simulations determined for different shapes of the sealing stages are shown in (Fig. 5). The most common geometry used in the magnetic fluid seals in industrial solutions is asymmetrical trapezoidal shape (Fig. 5*c*), and therefore, further numerical analysis will be conducted for the geometry of this type.

Results and discussion

A key operating parameter for the magnetic fluid seals is the critical pressure. It is the pressure value at which the break occurs in the liquid ring. It is possible to calculate the value of this parameter based on the knowledge of magnetic fluid properties. For these calculations it is necessary to obtain magnetic field distribution in the sealing gap [5]. In numerical calculations of the critical pressure for the ferrofluid seal, saturation magnetization Ms and the difference between magnetic induction B_{max}-B_{min} plays key role [6] (Fig. 6*a*).

$$\Delta p_{cp} = M_s \Delta B_{max-min} \tag{1}$$

Example of magnetic induction distribution along of the measurement line for the modeled geometry with and without magnetic fluid is shown in (Fig. 6*a*). In the case when the presence of the ferrofluid is taken into account, there is a drop of magnetic induction in the curve. The value depends mainly on the saturation magnetization Ms.

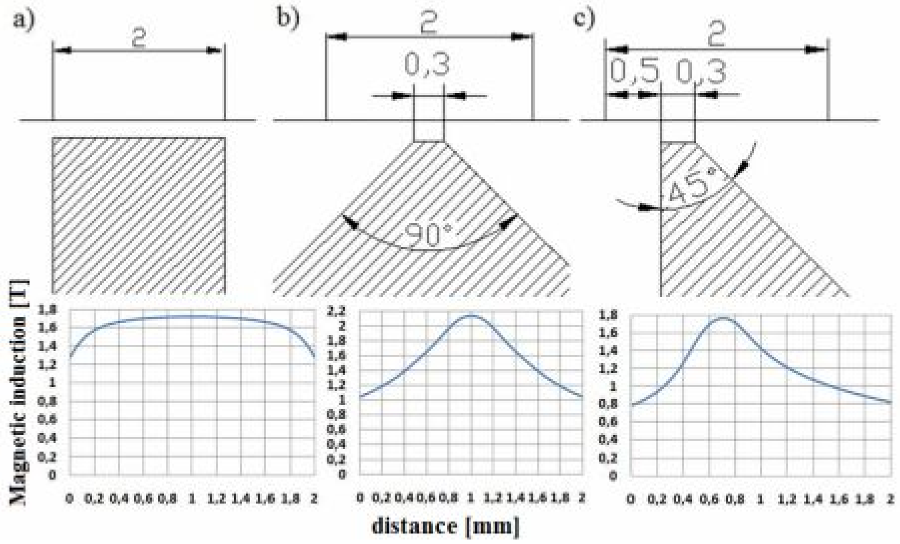

Fig. 5. **Distribution of magnetic induction in the magnetic fluid seal depending on the shape of the sealing stage, the size of the working gap «z» = 0.2 mm, *a*– rectangle *b*– symmetrical trapezium, *c*– asymmetric trapezium**

Conducted numerical calculation shows impact of the geometric parameters on the magnetic fluid seals. Fig. 7 shows influence of the gap height on maximum induction B$_{max}$. Curve on figure (Fig. 7*b*) defines the relationship between different lengths of parameter «t» (size of the chamfer) and B$_{max}$.

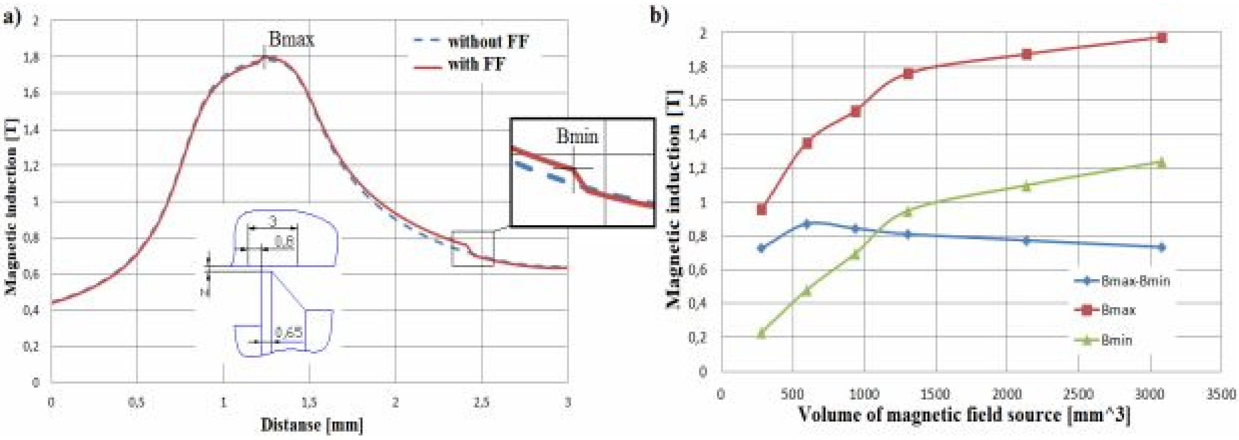

Fig. 6: *a* – **Distribution of magnetic induction on the length of the measurement line of the analyzed geometry with and without magnetic fluid, «z» the size of the working gap,** *b* – **Volume of magnetic field source and its influence on the magnetic induction: B_{max}, B_{min}, B_{max}–B_{min}**

The increase of the working gap size significantly reduces the value of B*max*, on the other hand, using too small gaps it leads to costs increase of the construction. In the presence of an axial throw of the sealing stage a blurring in the magnetic fluid seal may occur. Both parameters «z» and «t» also determine the magnetic fluid volume applied in the seal. Frequently it is between 50 to 200 μl. The diagram (Fig. 7*b*) shows that the most optimal values of the «t» parameter are in the range 0,6 ÷ 1,2 mm. Using too strong magnetic field source may reduce the value of the critical pressure due to decrease of difference B*max*–B*min*. The results of numerical analyzes that show the impact of the permanent magnets volume in the magnetic fluid seal in determining the critical pressure are presented in (Fig. 6*b*). This difference in strong fields decreases mainly due to the increase of B*min*.

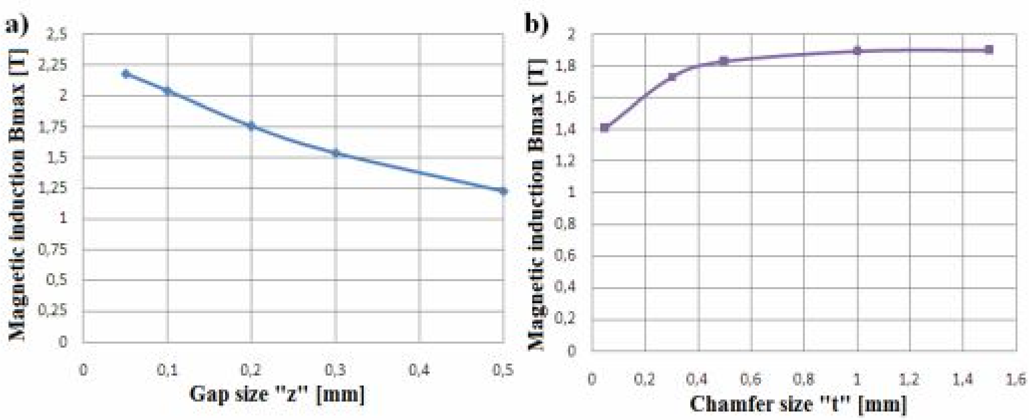

Fig. 7: *a* – **Influence of the working gap size «*z*» on the magnetic induction B_{max}, *b* – Influence of the chamfer length «*t*» on the magnetic induction B_{max}**

Conclusions

In the design process of the magnetic fluid seals several parameters must be taken into account, such as, source of the magnetic field, the magnetic properties of materials, magnetic and rheological properties of the ferrofluid. Analysis using finite element methods can be helpful in the design and to determine the value of magnetic induction in the seal. Conducted earlier considerations showed that the error between experiment and numerical analysis in determining the critical pressure from equation (1) for the magnetic fluid seals with one sealing stage may be less than 5%. The value of this error depends on the quality and the accuracy of structural elements and adopted B-H curves in the simulation.

REFERENCES

1. Proceeding of 8th International Conference on Magnetic Fluids, Timisoara, 1998. – [Edited by I. Anton, L. Vekas, and V. Sofonea] / Ochonski W. Some new designs of ferromagnetic seals / Ochonski W., Szydło Z., Zachara B. // Journal of Magnetism and Magnetic Materials. – 1999. – Vol. 201. – P. 1-497.
2. Ochonski W. Budowa uszczelnien z ciecza magnetyczna / W. Ochonski // Przeglad Mechaniczny. – № 8. – 1989.

3. Gieras J.F. Linear Synchronous Motors: Transportation and Automation Systems. – [2nd ed.] / J.F. Gieras, Z.J. Piech and B.Z. Tomczuk. – Boca Raton: Taylor & Francis – CRC Press, 2011. – 520 p.
4. Magnetic properties of polydisperseferrofluids: a critical comparison between experiment, theory, and computer simulation / [Ivanov A. O., Kantorovich S. S., Reznikov E. N. at all] // Phys. Rev. E. – Jun; 75, 2007. (6 Pt 1): 061405.
5. Szczech M. Calculation of static critical pressure in ferrofluid seals based on numerical simulation / M. Szczech, W. Horak // Mechanik. – 2011. – № 12.
6. Rosensweig R. E. Ferrohydrodynamics / R. E. Rosensweig. – Cambridge: Cambridge University Press, 1985. – 344 p.

Й. Салвінський, В. Горак, М. Шчеч

Числовий аналіз магнітних ланцюгів в ущільнювачах з феррорідин

У статті представлені результати числових розрахунків магнітних ланцюгів з використанням методу кінцевих елементів. Описано процес моделювання ущільнень з феррорідиною, показаний вплив основних параметрів і геометрії ущільнення на розподіл магнітного поля. Показано можливість визначення розподілу магнітного поля в робочому зазорі ущільнення, що відіграє основну роль при визначенні максимального тиску, який сприймається ущільненням без втрати щільності й має вирішальне значення при виборі габаритів конструкції ущільнення.

Ключові слова: *магнетичні рідини, технічні ущільнювачі, метод кінцевих елементів.*

Й. Салвинский, В. Горак, М. Шчеч

Численный анализ магнитных цепей в уплотнителях из феррожидкостей

В статье представлены результаты численных расчетов магнитных цепей с использованием метода конечных элементов. Описывается моделирование уплотнений из феррожикостей, показано влияние основных параметров и геометрии уплотнения на распределение магнитного поля. Показана возможность определения распределения магнитного поля в рабочем зазоре уплотнения, что играет основную роль при определении максимального давления, которое воспринимается уплотнением без потери плотности и имеет решающее значение при выборе габаритов конструкции уплотнения.

Ключевые слова: *магнетические жидкости, технические уплотнители, метод конечных элементов.*