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INFLUENCE OF PAD GEOMETRY MODIFICATION ON THE PERFORMANCE OF THRUST BEARINGS LUBRICATED WITH MAGNETORHEOLOGICAL FLUID

WPŁYW MODYFIKACJI POWIERZCHNI OPOROWEJ NA PARAMETRY PRACY WZDŁUŻNEGO ŁOŻYSKA ŚLIZGOWEGO SMAROWANEGO CIECZĄ MAGNETOREOLOGICZNĄ

Key words: magnetic fluids, thrust bearing, geometry modification, magnetic field distribution, thrust bearing.

Abstract Magnetic fluids belong to the class of controllable materials. The influence of magnetic fields on this type of substance results in a change in its internal structure and an almost immediate change in its rheological properties. The ability to control the rheological characteristics in a very wide range, in combination with the ease of generating and controlling the magnetic field, creates the possibility of using this type of substance in systems with controlled operating parameters. The use of magnetic fluids in bearings may allow the design of some types of bearings to be simplified and enable efficient, fast, and precise control of the system operation, with a much shorter response time and higher stiffness than is the case with conventional sliding friction bearings.

The paper presents the results of experimental tests carried out on a laboratory stand designed for thrust bearings lubricated with magnetic fluids. The analyses carried out concerned the determination of how the pad surface modification of the slide bearing, lubricated with magnetorheological fluids, influences the system performance parameters.

Słowa kluczowe: ciecze magnetyczne, geometria równoległych płytek, rozkład pola magnetycznego, łożysko wzdłużne.

Streszczenie Ciecze magnetyczne należą do klasy materiałów sterowalnych. Oddziaływanie polem magnetycznym na tego typu substancje skutkuje zmianą ich struktury wewnętrznej i w efekcie niemal natychmiastową zmianą właściwości reologicznych. Możliwość zmiany ich charakterystyk reologicznych w bardzo szerokim zakresie, co w połączeniu z łatwością generowania i sterowania polem magnetycznym stwarza możliwości zastosowania tego typu substancji w układach o kontrolowanych parametrach pracy. Zastosowanie cieczy magnetycznych w układach łożyskowych, może pozwolić na uproszczenie konstrukcji niektórych typów łożysk, umożliwić efektywne, szybkie i precyzyjne sterowanie pracą układu przy znacznie krótszym czasie odpowiedzi i wyższej sztywności, niż ma to miejsce w konwencjonalnych rozwiązaniach ślizgowych węzłów tarcia.

W pracy przedstawiono wyniki badań eksperymentalnych przeprowadzonych na stanowisku laboratoryjnym przeznaczonym do badania wzdłużnych łożysk ślizgowych smarowanych cieczami magnetycznymi. Przeprowadzone analizy dotyczyły określenia wpływu modyfikacji powierzchni oporowej wzdłużnego łożyska ślizgowego, smarowanego cieczą magnetoreologiczną, na parametry pracy układu.

INTRODUCTION

Magnetic fluids are complex materials composed of suspended ferromagnetic particles and a carrier fluid that does not exhibit magnetic properties. Changes in the properties of magnetic fluids are the result of the suspension microstructure change. In a macroscopic scale, this occurs as a fluid stress state change [**L. 1–4**]. The two main types of magnetic fluids can be distinguished. Ferrofluids (FF) are prepared based on particles with a diameter of the order of several nanometres, whereas magnetorheological fluids (MR) contain particles of the order of several micrometres [**L. 1, 5, 6**]. Due to the particle size, each of these

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substances has a different range of rheological property change. In MR fluids, a much wider range of variability is observed as a function of magnetic field strength; however, these types of magnetic fluids do not exhibit such high stability (no sedimentation), as is the case of ferrofluids. Due to significant differences in the behaviour of both substances, they are used in different technical applications. FF are mainly used in seals [**L. 7**], while MR fluids are mainly used in vibration dampers, brakes, and clutches [**L. 8**]. There are also works on the development of slide bearings working with this type of fluid [**L. 9–12**]. There are several factors that indicate the potential use of magnetic fluids as a lubricant in sliding friction bearings. It is possible to control the viscosity of the lubricant by interacting with a variable magnetic field. Another property is the ability to keep the fluid in a certain position by means of magnetic field forces. This may be important, for example, in the absence of gravity. In addition, magnetic pressure is created in the magnetic fluid under the action of a magnetic field that can be used to separate cooperating bearing surfaces. Bearings with a magnetic fluid as a lubricant can be characterized by a relatively simple construction, smaller requirements regarding manufacturing tolerances and, above all, the possibility of active control of working parameters.

Research presented in the work [**L. 13**] indicates the possibility of using MR fluids as a lubricant, which allows high stiffness to be obtained regardless of the working height gap of the thrust bearing. In the work [**L. 14**], the design of a thrust bearing operating without the circulation of a lubricant is discussed. The load bearing capacity has been achieved because of the so-called "self-sealing" effect. By using a suitable shape of the bearing surface, it is possible to keep the magnetic fluid in a specific position using a magnetic field. This allows the flow of lubricant from the bearing working gap to be limited. Thrust bearings lubricated with magnetic fluids gain an additional source of capacity resulting from the normal stress formation. However, the issue of pressure generation is complex and work related to this topic is still being carried out [**L. 4, 13, 15, 16**].

The subject of the work is to discuss the influence of the thrust bearing slide pad surface modification on the friction torque and axial force. Numerical simulation studies verified by measurements of the magnetic field distribution were carried out. Experimental tests were performed on a measuring stand using two MR fluids with different properties.

DESIGN OF THE TEST STAND AND TEST METHOD

The scheme of the test stand is presented in **Fig. 1**. A detailed description of the test device is presented in the work [**L. 17**].

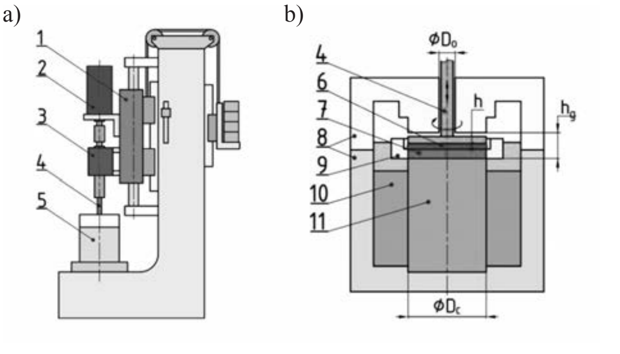

Fig. 1. a) The scheme of the test stand, b) The scheme of the measuring cell

Rys. 1. a) Schemat konstrukcji stanowiska, b) schemat komory badawczej

The main part of the test stand is the support frame, onto which the drive and the measuring systems as well as the test cell are affixed. Two independent systems can be distinguished in the drive system that positions the movable plate (Pos. 4) in the axial direction (Pos. 1) and enforces rotary motion (Pos. 2). The system (Pos. 1) is a linear servo motor that also acts as an axial load setting system. The movement of the linear motor causes the displacement of the rotary motion drive system mounted on it. The main measurement unit is a rotary force and torque transducer (Pos. 3). The test cell (Pos. 5) is divided into two parts (Pos. 8). In the lower part, there is an electromagnet consisting of windings (Pos. 10) and core (Pos. 11). The magnetic fluid (Pos. 6) is placed between two parallel surfaces: a movable plate (Pos. 4) and a properly shaped fixed plate (pad bearing plate) (Pos. 7) mounted in the holder (Pos. 9).

Figure 2 shows the geometries of the tested pad bearing plates. Each plate has a diameter of 45 mm and a thickness of 5 mm. All plates were made of a ferromagnetic material (steel 41Cr4). Apart from the flat plate (FP) (**Fig. 2a**), the test was performed using three types of geometries: plates with grooves of various configurations (GS – groove on a smaller diameter, GL – groove on a larger diameter, GSL – grooves on a smaller and larger diameter), see **Figs. 2b**, **c**, and **d**, plates with projections (PS – projection on a smaller diameter, PL – projection on a larger diameter, PSL – projections on a smaller and larger diameter), see **Figs. 2 e**, **f**, and **g**, and a plate with spiral projections (SP), see **Fig. 2h**.

The tests were carried out using two MR fluids: Basonetic 5030 (manufactured by BASF) and MRF-140CG (manufactured by LORD Co.). Both of the tested fluids are characterized by a relatively high saturation magnetization and high density, which indicates a high content of ferromagnetic particles. Moreover, the high saturation magnetization should allow the observation of differences between the influences of the magnetic field distribution in the examined pad bearing geometries. The tested fluids differ primarily in off state dynamic viscosity. Selected properties of the tested MR fluids are summarized in **Table 1**.

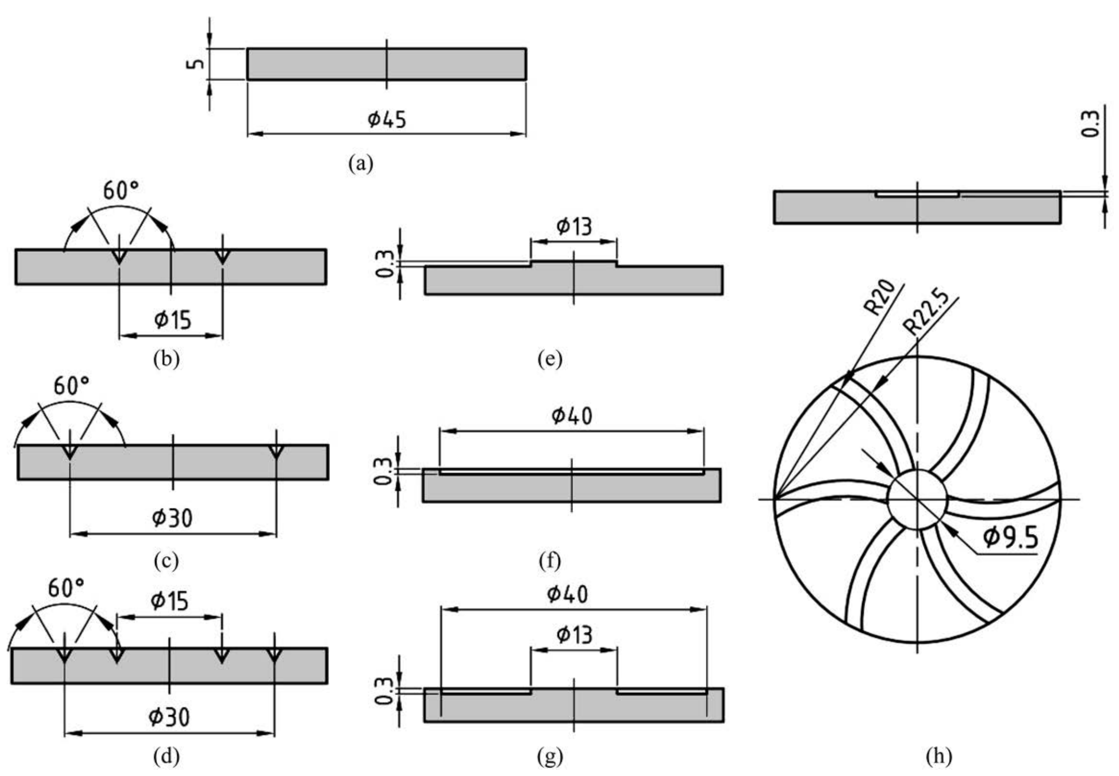

Fig. 2. Tested geometries: a) flat plate (FP), b) grooved plate on a small diameter (GS), c) grooved plate on a large diameter (GL), d) grooved plate on a small and large diameter (GSL), e) plate with a projection on a small diameter (PS), f) plate with a projection on a large diameter (PL), g) plate with projections on a small and large diameter (PSL), h) geometry with spiral projections (SP)

Rys. 2. Badane geometrie płytek oporowych: a) płytka płaska (FP), b) płytka z rowkiem na małej średnicy (GS), c) płytka z rowkiem na dużej średnicy (GL), d) płytka z rowkiem na małej i dużej średnicy (GSL), e) płytka z wypustem na małej średnicy (PS), f) płytka z wypustem na dużej średnicy (PL), g) płytka z wypustem na małej dużej średnicy (PSL), h) geometria z zakrzywionymi wypustami (SP)

Table 1. Physical properties of the examined MR fluids

Tabela 1. Właściwości fizyczne badanych cieczy MR

No.	Name	Density	Dynamic viscosity (B = 0 T, $\gamma = 100\ s^{-1}$)	Saturation magnetization (H = 800 kA/m)
		g/cm^3	mPa·s	kA/m
1	MRF-140CG	3.54	1569.1	698
2	Basonetic 5030	4.12	582.9	791

The paper presents the results of two test types. The first stage of the research was focused on determining the spatial distribution of the magnetic field in the bearing working gap. For this purpose, numerical simulations were carried out using the finite element method, and test stand measurements of the magnetic field induction distribution were made in the working gap of the analysed geometries. Numerical analyses were carried out using the ANSYS 14.5 software. The problem was modelled as an axial-symmetric one. The mesh size in the area of the measuring gap has an average size of about 0.05 mm. Dirichlet's zero boundary conditions were adopted, i.e. the magnetic flux direction was assumed to be parallel to the edges of the analysed geometry, and the flux value at the boundaries was assumed as 0. In the case of measuring cell components with ferromagnetic properties, such as the core and housing, the B-H curve characteristic for steels with a carbon content of up to 0.27% was adopted. In the case of the remaining elements, the value of relative magnetic permeability was equal to 1. The coil with the number of coils N = 1175 was modelled as the source of the magnetic field, through which the current of a defined value was applied.

The second part of the research was concerned with determining the axial force and friction torque for each of the examined geometries. The tests were carried out for the working gap height h = 0.5 mm. The temperature in the test cell was constant, T = 20°C. The volume of the applied MR fluid was V = 0.4 ml. The tests were carried out at a constant value of the electromagnet current I = 2 A (corresponding to the average value of magnetic field induction at B = 0.3 T). The diameter of the movable plate was 60 mm. Its rotational speed was changed in the range n = 0–140 min^{-1}. In addition, in the case of "CP" geometry, two directions of plate rotation were taken into account. The right rotation (CP-rev.R) should be understood as the case in which, as a result of the projection shape, the MR fluid moves in the direction of the bearing axis. The left turns (CP-rev.L) have the opposite direction.

Each test was conducted at least three times to check if the results are repeatable. The paper presents the result of one of the repeated measurements.

RESULTS

Figure 3 presents the results of numerical simulations and measurements of the magnetic induction distribution. The test stand measurements (using a Teslameter) were performed only for the FP, GS, GL, and GSL geometry to determine if the simulation results are reliable. In the case of the PS, PL, and PSL pads, only simulation tests were carried out. For the CP geometry, the simulation of the magnetic field distribution was omitted. This is not an axially-symmetric problem, so its numerical solution would require 3D analysis and the obtained results could not be directly compared with the results for other geometries.

Comparison of the measurement results (**Figs. 3 a–d**) shows a good convergence with the results of the numerical simulation. The largest differences occur in the case of the magnetic induction peak occurring over a diameter of about 52.5 mm. This is noticeable for all geometries and is caused by the occurrence of a hole in the side wall of the upper part of the test chamber, through which the measuring probe was introduced. This opening reduces the magnetic induction in this region.

The results of the numerical simulation presented in Fig. 3e indicate that, in the case of the pad plates with projections (PS, PL and PSL), the peak of magnetic induction occurring on the edge of the plate is smaller by about 0.1–0.15 T compared to the FP plate. Furthermore, it can be seen that, in the case of an additional projection in the plate axis (PSL geometry), there is no difference in the magnetic induction peak values at the edge of the plate compared to WD. There is only an additional induction jump at the length of 25 and 35 mm due to a change in geometry.

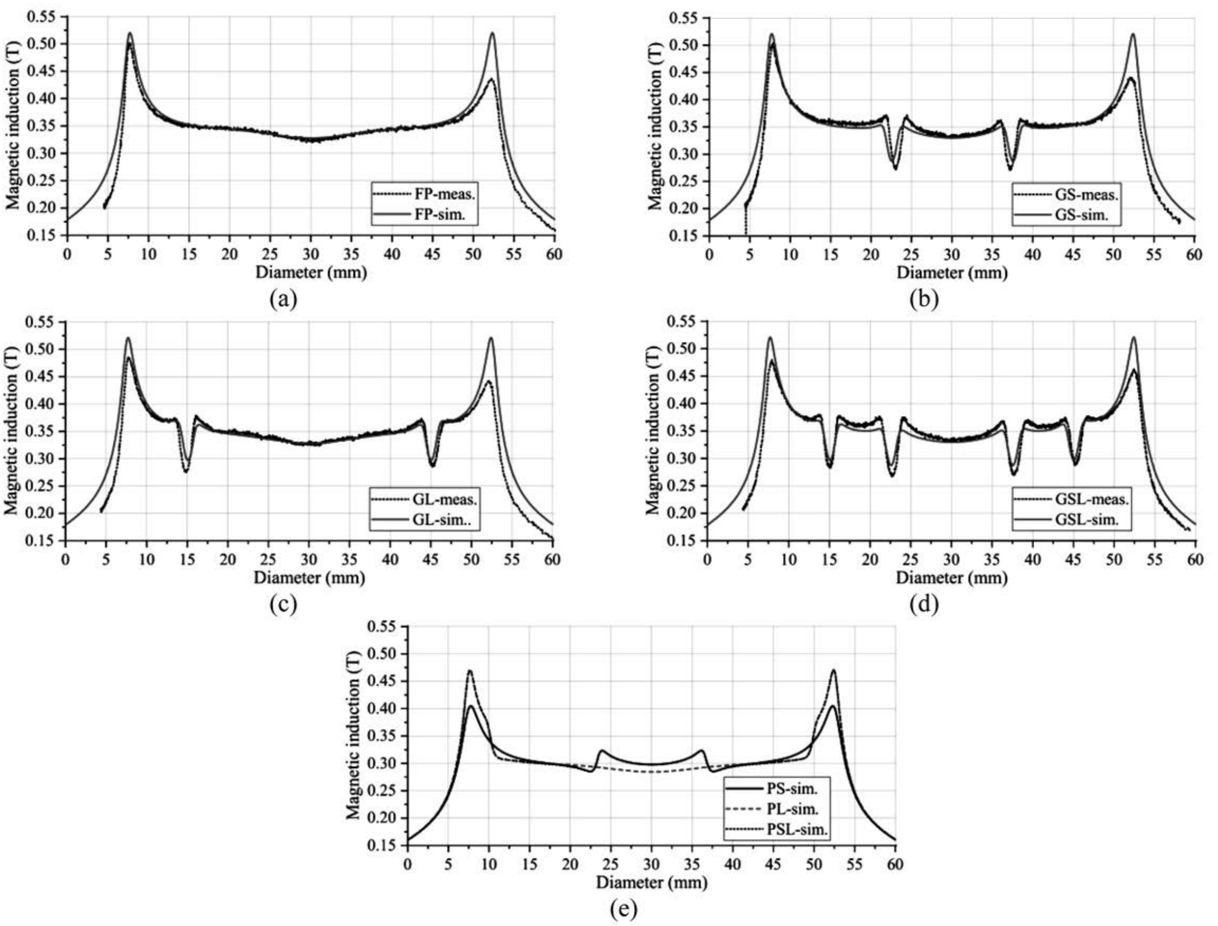

Fig. 3. Magnetic induction distribution for tested geometries obtained by measurements (meas.) or simulation (sim.) for I = 2 A

Rys. 3. Rozkłady indukcji magnetycznej dla badanych geometrii uzyskanych na drodze pomiarów (meas.) lub symulacji (sim.) dla I = 2 A

Figure 4 shows the results of torque measurements. With a rotational speed below 40 min^{-1}, no significant difference between pad geometry was recorded. At higher rotational speeds, the increase in torque friction for the PSL and PL geometry is observed, which is mainly due to the fact that the geometry modification causes a magnetic induction increase near the outer diameter of the measuring plate (see **Fig. 3e**).

For plates with grooves (GS, GL, and GSL) there are no significant differences with respect to the flat plate in the whole speed range.

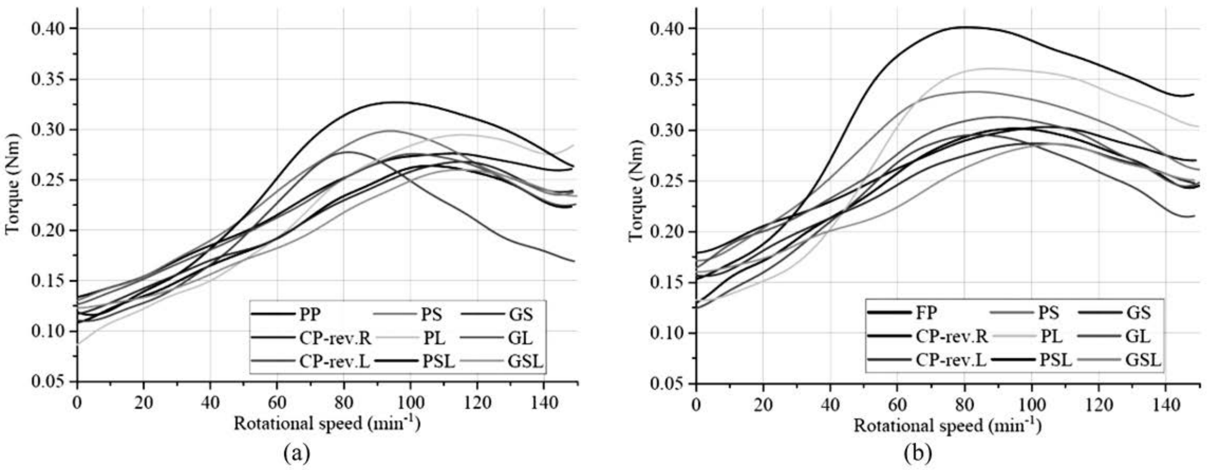

Fig. 4. Results of friction torque measurement for the fluids; a) MRF-140CG, b) Basonetic 5030
Rys. 4. Wyniki pomiaru momentu tarcia dla cieczy; a) MRF-140CG, b) Basonetic 5030

For each measurement, it is possible to indicate the value of the rotational speed (critical speed) above which the torque decreases. This phenomenon is associated with the ejection of MR fluid from the measuring gap due to the centrifugal force. In the case of magnetic fluids, this process is particularly important due to the relatively high density of this type of substance in relation to typical fluid lubricants.

In **Fig. 5**, the values of the rotational speed for which the maximum torque value was obtained are summarized. An increase in the critical speed in relation to the flat plate for the CP- rev.R, GS and GSL geometries is observed; whereas, for the CP- rev.L, PS and PSL plates, there was a significant decrease in the critical speed.

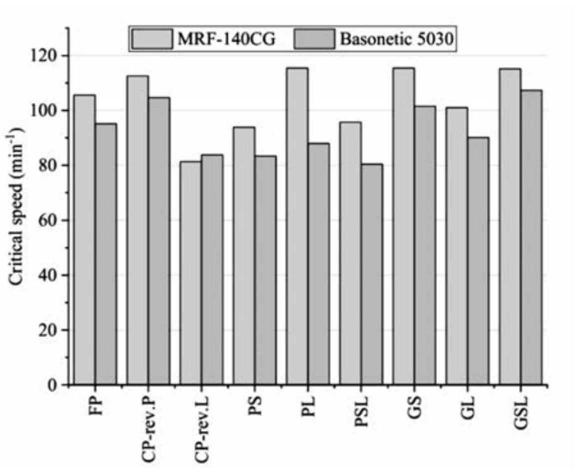

Fig. 5. Critical speed of the studied geometries
Rys. 5. Prędkość krytyczna dla badanych geometrii

Figure 6 presents the results of axial force measurement. In most cases, the value of the measured force drops in the range of 0–60 min^{-1}, and then slightly increases to give a local maximum in the range of 65–80 min^{-1}. At higher rotational speeds, a further reduction in the force value is observed. The shape of the curves is probably due to the change in the internal structure of the MR fluids.

In a certain range of rotational speed, deformation promotes the formation of ferromagnetic particle structures, which results in an increase in normal force. However, above a certain rotational speed, only the destruction of the particle structure takes place.

The most similar results to the PP geometry were obtained for GS, GL, and GSL. This indicates that this type of geometry modification does not have a significant impact on the force value.

In the case of Basonetic 5030, larger differences in the force values between geometries are observed than for MRF-140CG.

In the case of Basonetic 5030 and MRF-140CG, the highest forces were recorded for CP-rev.R, and for PS and PL it was in the range of 50–150 min^{-1}.

In each of the fluids, significant differences were observed for the CP geometry, when the plate direction of rotation was changed. This indicates the possibility

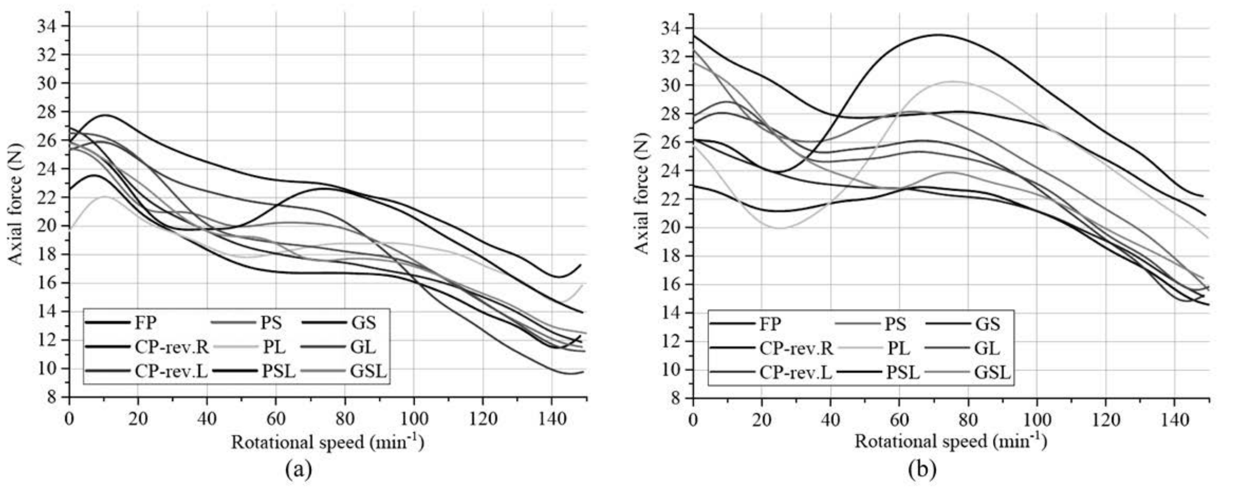

Fig. 6. Axial force results for the fluids; a) MRF-140CG, b) Basonetic 5030
Rys. 6. Wyniki pomiaru siły osiowej dla cieczy; a) MRF-140CG, b) Basonetic 5030

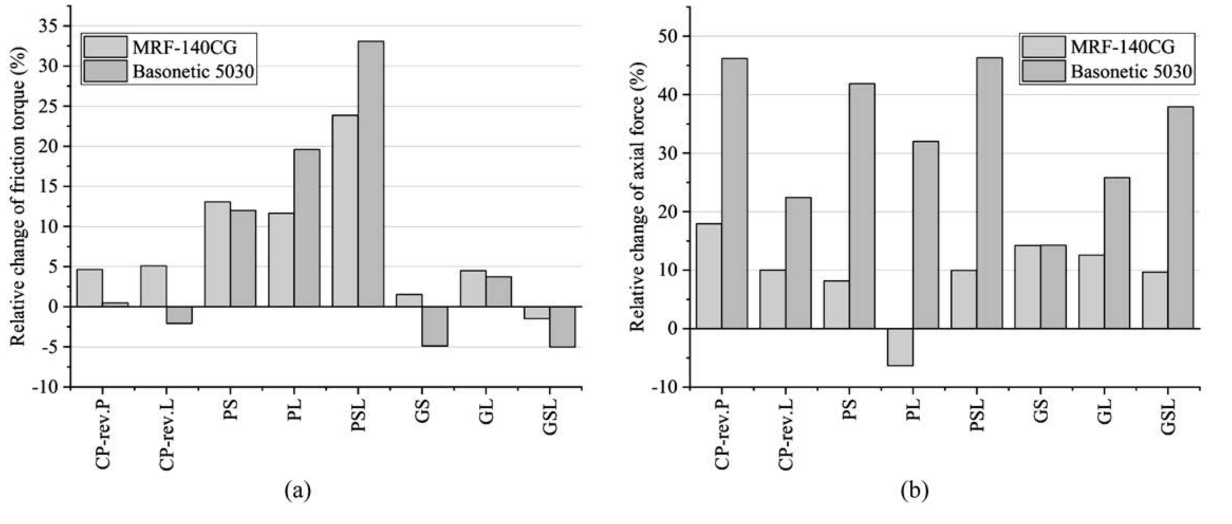

Fig. 7. Relative changes in: a) frictional torque, b) axial force
Rys. 7. Względne zmiany: a) momentu tarcia, b) siły osiowej

of the hydrodynamic lubrication effect occurring in this type of geometry.

Figure 7 shows the differences in the maximum values of torque and axial force between FP and other geometries.

In the case of torque friction, the impact of the pad surface shaping is visible for the geometry with the projections (PS, PL, and PSL). In these cases, an increase in torque from 12% to nearly 33% is observed. For GS, GSL, and CP-rev.L geometry, a slight reduction in the friction torque was obtained.

In the case of axial force, almost every modification of the plate positively influenced the value of the measured parameter. The difference in relation to the flat plate (FP) was even 45%. As expected, due to the higher saturation magnetization, larger differences were observed for the Basonetic 5030 fluid.

CONCLUSIONS

The modification of the pad plate surface geometry of the thrust bearing lubricated with magnetic fluid is an effective method of shaping the spatial magnetic field distribution. As a result, it is possible to modify the system operation parameters. The main conclusions from the conducted research are as follows:

- For the GS and GSL geometries, no significant change in the torque was observed, while a slight increase in the critical speed was obtained.

- Geometries with projections (PS, PL, and PSL) have an unfavourable effect on the system operation parameters. Although they allow one to achieve an increase in axial forces, they cause a significant increase in torque (from 10 to 33% in relation to a flat plate).
- In the case of critical speed, the plate geometry change allowed this parameter to be changed by approximately ±20% in relation to the results obtained for a flat plate. An increase in the critical speed was obtained for the geometries at which the highest magnetic induction value occurred in the plate edge region. In addition, there were regions causing a local decrease in magnetic field for plates (in this case, grooves). These changes can be explained by the occurrence of the self-sealing effect, resulting from the presence of a magnetic induction gradient.

The differences in results obtained when changing the direction of rotation for CP geometry indicate the possibility of hydrodynamic phenomena occurring.

The greater impact of pad plate geometry modification is visible for fluids characterized by a higher saturation magnetization.

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