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THE INFLUENCE OF TEMPERATURE ON COEFFICIENT OF MAGNETIC SUSCEPTIBILITY χ OF FERRO-OILS WITH DIFFERENT CONCENTRATIONS OF MAGNETIC PARTICLES

WPŁYW TEMPERATURY NA WSPÓŁCZYNNIK PODATNOŚCI MAGNETYCZNEJ χ FERRO-OLEJÓW O RÓŻNYM STĘŻENIU CZĄSTEK MAGNETYCZNYCH

Key words:

ferro-oil, magnetic susceptibility coefficient, magnetic particle’s concentration, slide journal bearings lubrication

Słowa kluczowe:

ferro-olej, współczynnik podatności magnetycznej, stężenie cząstek magnetycznych, smarowanie poprzecznych łożysk ślizgowych

Abstract

In this paper, the authors presented research concerning the determination of the relation between magnetic susceptibility coefficient χ of ferro-oil and temperature changes. The tests were conducted on the ferro-oil samples of various, chosen magnetic particles concentrations: 1%, 2%, 4%, 6%, and 8%. In accordance with the conclusions resulting from Curie-Weiss equation, the values of magnetic susceptibility χ depend on the physicochemical features of

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considered material, including the magnitude and amount (concentration) of magnetic particles and physical properties of its environment, i.e. the kind and direction of magnetic field and also on the operating temperature, which is the main subject of conducted tests in this paper.

This article presents the structure of the bench used for experimental designation of magnetic susceptibility coefficient in relation to temperature changes of tested ferro-oil. Moreover, the authors demonstrated a method enabling the determination of these values from obtained measurement data, conducted the analysis of obtained results and presented the conclusions.

INTRODUCTION

In author's previous research works, whose results are shown, inter alia, in **[L. 1, 2]**, the values of magnetic susceptibility coefficients of ferro-oil were designated in nominal, ambient conditions. In the actual, technical objects, the operating conditions of oils differ from nominal conditions. The aim of this paper was to determine the adjusted values of these coefficients for the thermal conditions similar to estimated ones in real, ferro-oil lubricated slide journal bearings. A. Miszczak's **[L. 3]** research leads to a conclusion that ferro-oil lubricating the journal bearing repeatedly reaches the operating temperature, depending on bearing load, exceeding the level 100ºC – 120ºC. Because of the constructional limitations of the test bench, the author conducted the tests on the magnetic susceptibility coefficient of ferro-oil at the 15ºC – 90ºC range. The area that exceeded this range was the field for extrapolation of the trend line.

It is important to draw attention to the physical impossibility of taking the actual, accurate measurement of the magnetic induction value of field B directly in a slot of operating journal bearing. This problem may be solved through the use of analytical and numerical methods, thus determining the components of magnetisation vector **N**, components of magnetic induction vector **B,** and components of magnetic field strength vector **H**. The efficiency of analytical and numerical methods significantly depends on the accuracy and correctness of physical parameter values implemented into the calculation model, especially including the precision in determining the values of magnetic susceptibility coefficients χ of ferro-oil. The smaller the differences between the determined and actual values, the more reliable are the results. The necessity to determine the actual values of magnetic susceptibility coefficients was the seedbed for this research work.

THE THEORETICAL FOUNDATIONS

All physical bodies that are influenced by the external magnetic field may be classified in terms of their magnetic properties as diamagnetic, paramagnetic, or ferromagnetic materials. The ferro-oil that is tested in this work belongs in these terms to the ferromagnetic class; however, its behaviour in the external magnetic field is influenced by a specific, distinctive physical structure. Ferro-oil is the colloidal combinations of magnetic particles drown in the base oil in the presence of the surfactant that prevents the coagulation. These particles form the single magnetic domains, which, in case of absence of an external magnetic field, present the random orientation of magnetization vectors. The appearance of external magnetic field results in reordering of a chaotic arrangement of particles-domains in accord with the lines of external field. If the magnitude of strength values of this field is large enough, all particles-domains are arranged in accordance with the direction of the lines and the sense of magnetic field strengths. In comparison to solid ferromagnetics, ferro-oil is magnetically saturated relatively quickly, because, contrary to them, it does not have to overcome the strengths resulting from a complicated domain structure. On the other hand, because of its specific structure, ferro-oil does not undergo permanent, constant magnetization, and when the external magnetic field declines, it returns to the state of magnetic neutrality, which is evinced by random orientation of magnetic moments of each particle-domain.

Anisotropic magnetic properties of ferro-oil are affirmed only for a relatively small portion of the external magnetic field strength. For appropriately large values of strength, the process of magnetic saturation occurs and the magnetization vector **N,** which is the direction of the resultant magnetic moment of the substance, in this state, coincides with the direction and sense of the effect of external magnetic field strengths **H**. In case of ferro-oil that was tested by the author in terms of this and earlier works **[L. 1, 2]**, the value of magnetic field strength **H** is approximately 45000A/m. For the larger values of field strength, it is reasonable to assume that the magnetic susceptibility of ferro-oil that results from vector equation binding the magnetization vectors **N** with magnetic field strength **H**,

$$\chi = \mathbf{N} / \mathbf{H}, \tag{1}$$

where:

$\mathbf{H}$ – external magnetic field strengths vector [A/m],
$\mathbf{N}$ – magnetization vector [A/m],
χ – magnetic susceptibility coefficient [-],
χ in the state of full magnetic saturation is a scalar **[L. 3, 4, 5, 6]**.

The values of magnetic susceptibility χ depend mainly on physiochemical properties of given, considered ferro-oil, including the magnitude and the amount of magnetic particles (concentration) and also the magnitude of magnetic moment, the kind and direction of magnetic field, or the temperature, i.e. magnitudes which the coefficients depend on in Curie-Weiss equation **[L. 4, 5]**:

$$\chi = C/(T - T_C), \tag{2}$$

where:

C – Curie constant [K],
T – temperature [K],
T_C – Curie temperature for considered ferromagnetic [K].

When using the Langevin equation for magnetization, it is possible to develop the constant Curie C as follows:

$$C = n\mu_0 m^2/3k_n, \tag{3}$$

where:

n – concertation of particles per unit volume [$1/m^3$],
μ_0 – vacuum magnetic permeability = $4\pi\ 10^{-7}$ [H/m].
m – magnetic dipole moment [$A\cdot m^2$],
k_n – constant [$H\cdot A^2/K$];

or including the concentration parameter ϕ after [L. 6]:

$$C = \pi\phi\mu_0 N_s^2 d^3/18k_n, \tag{4}$$

where:

N_s – value of magnetization at saturation level [A/m],
d – the average diameter of ferromagnetic particles in the ferro-oil [m],
ϕ – volume fraction of particles in the ferro-oil [%].

Based on, inter alia, **[L. 3, 4, 6]**, the correlation binding the vector of magnetic induction B, magnetic field strength H, and magnetization N for ferro-oil is expressed in the following form:

$$\mathbf{B} = \mu_o (\mathbf{H} + \mathbf{N}), \qquad \mathbf{N} = \mathbf{H} \cdot \chi; \tag{5}$$

hence,

$$\mathbf{B} = \mu_o \mathbf{H}(1 + \chi). \tag{6}$$

CHARACTERISTICS OF TESTED FERRO-OIL AND THE STRUCTURE OF THE TEST BENCH

The tests were conducted on the samples of ferro-oil produced by FerroTec Company from Unterensingen in Germany. This ferro-oil was made on the base of mineral oil LongLife Gold by Pennzoil Company, with viscosity grade SAE 15W-40. The manufacturer added to the base oil the magnetic particles of iron oxide Fe_3O_4, whose average diameter is 10nm, and approximately 15% volume fraction of a surfactant of unspecified name. The base oil and the additives create a homogenous colloidal mixture. Original (provided by the manufacturer) percentage concentrations of magnetic particles of tested ferro-oil were 6% and 8%. The other tested concentrations, i.e. 4%, 2% and 1%, were obtained by the author in the process of the dilution of the original samples with the previously mentioned base oil and substitutive surfactant which constituted 25% tetramethylammonium hydroxide solution $(CH_3)_4NOH$.

All measurements were taken on an authorial test bench whose structure is presented in **Fig. 1**.

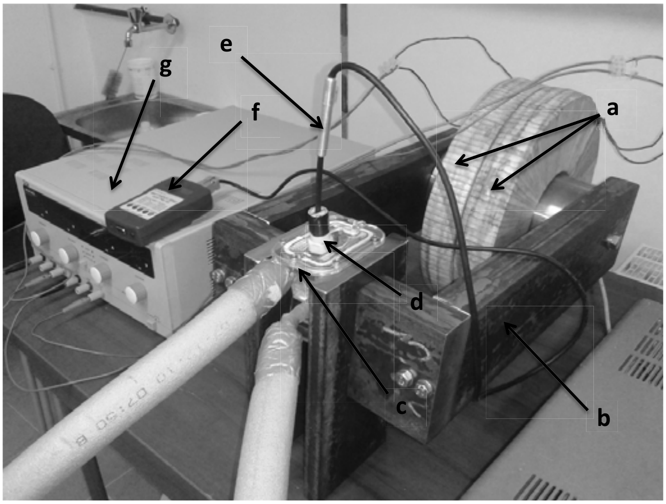

Fig. 1. Structure of the test bench for magnetic susceptibility coefficient χ of ferro-oils: a) – magnetic coils, b) – steel core, c) – thermostatic chamber cooperating with ultratermostat, d) – container with a ferro-oil, e) – effect Hall'a probe, f) – effect Hall'a measurement, and g) – amplifier

Rys. 1. Budowa stanowiska do badania podatności magnetycznej χ ferro-oleju: a) – dwie cewki magnetyczne, b) – rdzeń stalowy, c) – komora termostatująca skonfigurowana z ultratermostatem, d) – pojemnik z próbką ferro-oleju, e) – sonda hallotronomierza, f) – miernik hallotronomierza, g) – dwukanałowy zasilacz sieciowy

The test bench consists of a system of two magnetic coils with a steel core, whose diameter is 200mm, and which is the base for two steel arms closing the magnetic field in the way that the measurement volume between them creates a stable, homogenous, and "minefield" magnetic field. This volume is the place for the non-magnetic chamber stabilizing of the temperature of ferro-oil samples. The chamber was connected with ultra-thermostat by insulated conductors. The coils are powered by dual channel power supply of the MCP Company, type M10-DP-3020E, which enables taking measurements in the range to 60V and up to 40A, depending on used wiring configuration.

The measurement of the magnetic flux density was taken with Smart Magnetic Sensor of Asonik company meter, type SM102, that uses the Hall Effect. Especially for the purposes of this project, the manufacturer produced the dedicated measuring probe, whose construction facilitates taking measurements at elevated temperatures in the oil ambient. It is provided with Hall Effect sensors of a new production type, Toshiba THS119, of higher precision and measurement stability. During the test, the precision of measurement was 0.1mT.

The samples of tested ferro-oil were placed in a specially adapted container made of plastic whose construction prevented drawing the ferro-oil by an external magnetic field and enabled the stable and repeatable mounting of the measuring probe and temperature sensor Pt100.

EXPERIMENTAL TESTS AND THE ANALYSIS OF RESULTS

The proper experimental tests were preceded by the measurements that aimed to determine the change characteristics of magnetic susceptibility coefficients χ of ferro-oil depending on the changes of magnetic field strength H and to determine the parameters of test system at which the samples of ferro-oil reach full magnetic saturation. The measurements were taken under normal conditions, i.e. in the presence of atmospheric pressure and the medium temperature 20ºC. **Figure 2** presents the obtained results.

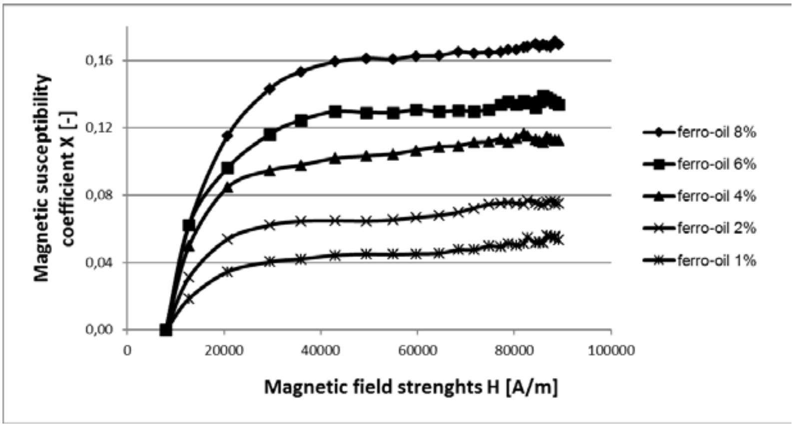

Fig. 2. The χ = f(H) characteristic for the tested ferro-oils
Rys. 2. Charakterystyki $\chi = f(H)_{\phi}$ dla badanych ferro-olejów

It is important to mention that, for the purpose of determining these characteristics, some crucial assumptions were made, namely, the magnetic field, in considered area, is solid, homogenous, and one-way oriented, perpendicularly to the frontal area of core arms. Moreover, the following simplification was made: Vectors of magnetic induction B and magnetic field strength H in the air are parallel to each other and have the same sense. Actually, the air belongs to the class of paramagnetics, but it is the weakest among the ones known in nature. Under normal conditions, its value of relative magnetic permeability is μ_r = 1.00000037.

In terms of analysis of obtained characteristics, it would be reasonable to assume that full saturation of ferro-oil samples appeared for magnetic field values higher than 45000A/m. In the literature cited above **[L. 6]**, the authors have shown that the state of saturation already occurs at the magnetic induction values of the field B = 25mT for ferro-oil with a concentration of 4%, which would apply to strength 22000A/m. These results correspond with the ones that were obtained in this work; however, attention should be paid to the fact that, for the higher concentrations of magnetic particles in ferro-oil, i.e. 6% and 8%, the state of saturation required higher values of external magnetic field strength. This fact appears to be related to significantly higher values of viscosity of these ferro-oils and the resistance of ferromagnetic particles mobility in the base oil or to such concentration of magnetic particles in volume unit of the tested substance, which makes each particle's domain prevent self-arranging of the direction of their magnetization vectors. In the second, crucial part of research, the changes of magnetic susceptibility coefficients χ for tested concentration of ferro-oil were measured in terms of temperature changes. The measurements were taken under conditions of the full magnetic saturation of the samples H = 85000A/m.

Obtained results are presented in **Fig. 3**.

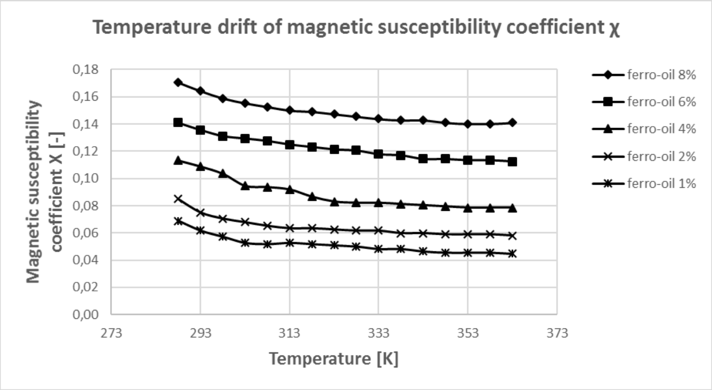

Fig. 3. The χ = f(T) characteristic for the tested ferro-oils
Rys. 3. Charakterystyka χ = f(T) dla badanych ferro-olejów

While analysing the obtained measurement results, it is possible to notice that, for each tested concentration of ferro-oil, along with temperature increase, the value of magnetic susceptibility coefficient χ at the tested temperature decreases. However, it is not a linear relation. The most significant decreases concern the temperature range of approximately 40–45°C, and according to concentration, they start from 12.56% at the highest concentration ϕ = 8% to 25.26% at the lowest ϕ = 1%. In the area that exceeds these values, the decrease of magnetic susceptibility coefficient value is already considerably lower and does not exceed the level of a further 10%. In absolute terms, total decreases of coefficients χ values at tested range of temperatures were 0.024–0.035 without the indication of a trend that is dependent on the magnetic particles' concentration in the ferro-oil sample.

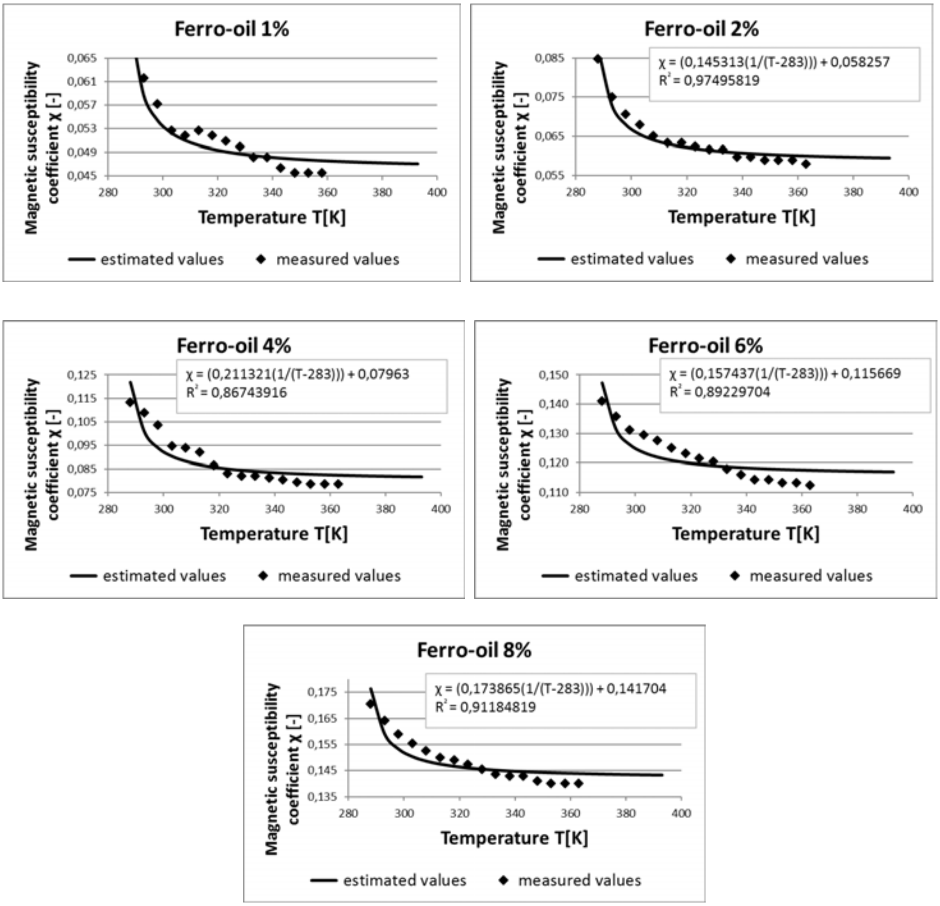

Fig. 4. The χ = f(T) characteristics together with fitted function models
Rys. 4. Charakterystyki χ = f(T) wraz z dopasowanymi modelami funkcji

The obtained measurement results were additionally analysed in terms of adjustment, expected based on theoretical considerations, of function model.

The adjustment was made using the software STATISTICA 9.1 of StatSoft Company for

$$\chi = (C/(T - T_C))+A, \tag{7}$$

where:

T_C – Curie temperature for ferro-oil T_C = 283K, from **[L. 3]**,
A – constant depended on ϕ [-].

The evaluation of parameters of this adjustment is presented in **Fig. 4**.

CONCLUSIONS

The aim of this work was to determine the characteristics of changes in the magnetic susceptibility values that are dependent on magnetic field strength for ferro-oil samples of different concentrations of magnetic particles χ = f(H) and the attributes of the temperature drift of these coefficients χ = f(T).

The obtained results of maximum values of magnetic susceptibility coefficients χ for the states of the full saturation of magnetic sample $\left(\chi_{\phi=1\%} = 0{,}06 \div \chi_{\phi=8\%} = 0{,}17\right)$, resemble the outcomes of similar, published works of various authors, e.g. **[L. 7, 8, 9]**, in which these coefficients were determined using the Langevin method.

The results of definite temperature drift are satisfactorily accurate in terms of expected changes based on the theoretical analysis, in the case of both the tendency towards changes and their values. The obtained values are going to be used by the author in further works targeted at the determination of the values of flow and operating parameters of slide bearings lubricated with ferro-oil especially the following: load carrying capacities, friction force, and friction coefficient. Ultimately, the knowledge of these parameters allows one to assess the appropriateness of the use of ferro-oil as a lubricant of slide journal bearings.

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Streszczenie

W niniejszym artykule zostały przedstawione badania dotyczące określenia zależności współczynnika podatności magnetycznej χ ferro-oleju od zmian temperatury. Badaniom poddane zostały próbki ferro-olejów o różnych, wybranych stężeniach cząstek magnetycznych: 1%, 2%, 4%, 6% i 8%. Zgodnie z wnioskami wynikającymi z równania Curie-Weissa wartości podatności magnetycznej χ zależą głównie od własnych cech fizykochemicznych rozpatrywanego materiału, w tym od wielkości i ilości (stężenia) cząstek magnetycznych oraz od fizycznych właściwości jego otoczenia, tj.: rodzaju i kierunku pola magnetycznego, jak również od temperatury pracy, która stanowi zasadniczy temat podjętych badań.

W artykule zaprezentowana została budowa stanowiska do eksperymentalnego wyznaczenia współczynnika podatności magnetycznej w kontekście zmian temperatury badanego ferro-oleju. Ponadto zaprezentowana została metoda umożliwiająca wyznaczenie tych wartości z pozyskanych danych pomiarowych oraz dokonano analizy uzyskanych wyników zakończonej wnioskami.