Journal of KONES Powertrain and Transport, Vol. 21, No. 4 2014

ISSN: 1231-4005
e-ISSN: 2354-0133
ICID: 1130456
DOI: 10.5604/12314005.1130456

MODELS OF VISCOSITY CHARACTERISTICS η=η(B) OF FERRO-OIL WITH DIFFERENT CONCENTRATION OF MAGNETIC PARTICLES IN THE PRESENCE OF EXTERNAL MAGNETIC FIELD

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Abstract

The purpose of this article is to determine, identify and describe the viscosity characteristics of the ferro-oil with different concentrations of magnetic particles in the presence of an external magnetic field interaction. These characteristics are defined in the context of magnetic induction changes.

These rheological tests were performed on a Physica MCR 301 rheometer. It was used a measuring system 'plate to plate' type which was armed with magneto-rheological research system MRD 180/1T. The tests were performed for the selected temperature of the medium i.e. 90°C, the shear rate Θ changes were carried from 0 to 1000 1/s. Changes of the magnetic field intensity value were ranged from 0 to 500 mT.

The selected concentrations of magnetic particles in a ferro-oil were 1%, 2%, 4%, 6% and 8% and the tested ferro-oil was product of FerroTec of Unterensingen (Germany), which is a mixture of colloidal mineral motor oil Penzzoil's LongLife Gold's SAE 15W-40 with Fe_3O_4 magnetic particles and the surfactant.

Analyses of the results, identify and matching characteristic were calculated using STATISTICA software.

It has been proposed three categories of functions mapping the waveforms of the results obtained experimentally: the exponential function, logarithmic with basis of the normal and the polynomial function.

Keywords: *ferro-oil, dynamic viscosity, magnetic particles concentration, external magnetic field*

1. Introduction

The contemporary technically advanced constructions of the friction nodes, in particular the structures of sliding bearings, often require to use of non-standard lubricants with specific, selected properties. One of these, such perspective, special lubricants is ferro-oil, which is characterized by, among others, susceptibility to the ability to control its physical properties, with particular attention to viscosity advancement. Consequently, the application of ferro-oil in the system of the friction pairs, allows for shaping and controlling tribological properties of those systems, and eventually utility properties of the entire device. The above-mentioned features of ferro-oil directly derived from their physico-chemical structure and in particular from the content of additive of magnetically active particles in the base oil. This addition, however, makes the ferro-oil belongs to the class of lubricants of the non-Newtonian characteristics, and its viscosity exhibits dependence on pressure and temperature, as well as non-classical shear rate and direction of operation, the type and intensity of the external magnetic field [7, 8]. Such an extended arrangement of the dependence gives rise to additional difficulties in the modelling process and the description of the behaviour of the slide journal bearings lubricated with ferro-oil. These difficulties have been affirmed already at the time of the adequate constitutive models selection and consistently evolving along with the subsequent stages of numerical-analytical modelling. In this context, identification of mathematical relationships involving basic physical quantities of ferro-oil or fitting functions which describing them is therefore becoming crucial. The scheduled, in the next stage of research study, construction of test stand to a hydrodynamic lubrication of slide journal bearings with ferro-oils, will also require verification of the experimental results based on previously developed physical and mathematical models of viscosity.

2. The theoretical foundations

Probably the most important of the physico-chemical properties of lubricating oils, including ferro-oils is their viscosity. Generally, the viscosity is defined as the internal friction of the fluid, and is most often expressed as the dynamic viscosity. It is a fundamental quantity used in describing and comparing the performance of lubricating oils, allows estimating the potential behaviour of the oils in the nodes of friction and possible consequences arising from their use. Widely considered, it is expressed in the form of a whole group of rheological characteristics which binding it with the basic operating parameters such as temperature, pressure or shear rate, but also in the context of the specific operating conditions. In the case of ferro-oils considered in this work, it is the additional presence of an external magnetic field.

The study of ferro-viscosity oils with different concentrations of magnetic particles in the presence of a constant external magnetic field of variable intensity so far conducted by the authors, the results of which can be found, inter alia, in [1, 2], leads to certain conclusions. First of all:

- with increasing the concentration of magnetic particles in the ferro-oil also increases the value of the dynamic viscosity; it has been observed [1] than 7-fold increase between the extreme concentrations, i.e. under consideration: 1% and 8% for a dependence on constant temperature,
- viscosity increases are not proportional to increases in the magnetic particles concentrations [1], which may indicate that the viscosity is not merely a derivative of the increased molecular weight of the mixture, but also results from the other properties of its internal structure, such as magnetic particles coagulation in the oil especially at higher concentrations,
- the presence of a constant external magnetic field affects additional increases the dynamic viscosity of ferro-oil [2],
- observed increases range from several percent at low concentrations to nearly 50% at the highest [2],
- the largest increase in viscosity is accompanied by switching the magnetic fields, i.e., the change between 0 and 50 mT, and regardless of the concentration is approximately 10-15% of the initial value [2],
- the further increasing the value of magnetic induction of external magnetic field results in minor increments the viscosity values up to stabilize at around 200 mT [2].

Also, research conducted this year by the authors [3] indicate that the values of the magnetic induction of 150-200 mT follows to overall directional arrangement of magnetic particles in ferro-oil (full magnetic saturation), responsible for the increase in its viscosity.

With the increase in the concentration of magnetic particles in the ferro-oil, and a higher intensity of the magnetic field, are affirmation strong non-Newtonian, viscoelastic properties of the tested ferro-oils.

The above observations and results obtained on, so qualitatively and quantitatively, however, do not indicate clearly on mathematical and physical dependence on relationship between the values, which have been tested. This work is a proposal for the selection of the appropriate function and matching for a particular relationship between the dynamic viscosity of the tested ferro-oil with the chosen concentrations of magnetic particles with the value of the magnetic induction of the applied external magnetic field $\mu=\mu_o(B)$.

The review of the literature on selected issues does not give a satisfactory answer how to illustrate the characteristics of $\mu=\mu_o(B)$.

In a series of works, among others, in [4] it can be found the proposal of linear model of above-mentioned relationship for the incompressible ferro-fluid:

$$\mu = \mu_m (1+\boldsymbol{\delta}\mathbf{B}), \tag{1}$$

where:

$\mathbf{B}$ – magnetic induction vector [T=N/Am],

$\boldsymbol{\delta}$ – coefficient of magnetic field viscosity vector [T^{-1}],

μ – dynamic viscosity of ferro-fluid under magnetic activity [Pa·s],
μ_1 – dynamic viscosity of ferro-fluid without magnetic activity [Pa·s].

For bi-directional magnetic field $\mathbf{B}_{(x,z)}$ and the assumptions of isotropic of ferro-fluid $\delta_x=\delta_z=\delta$ it can be assumed that:

$$\mu_x = \mu_1\,(1+\delta B_x), \tag{2}$$

$$\mu_z = \mu_1\,(1+\delta B_z), \tag{3}$$

where:
μ_x – dynamic viscosity at a longitudinal magnetic field [Pa·s],
μ_z – dynamic viscosity at a traverse magnetic field [Pa·s],
B_x – magnetic induction in the direction of the longitudinal [T],
B_z – magnetic induction in the direction of the transverse [T].

It seems that this proposal few closely mirrors the obtained results. The nature of the experimentally obtained functions far removed from linearity in particular in the intermediate area, where there is incomplete ferro-magnetic saturation of ferro-oil. Only in the areas of the beginning of rise of magnetic field and the opposite diametrically - the full magnetic saturation, linear zooming could give satisfactory results.

In some works, including the [6] it's proposed a relationship modelled by the exponential function on following form:

$$\eta_{1B}(\phi,z) = \exp(\delta_B B_0 B_1) =\exp(\delta_{B1} B_1), \tag{4}$$

where:
$\eta_{1B}\,(\phi,z)$ – dimensionless dynamic viscosity depends on the magnetic induction,
δ_B – dimensional coefficient taking into account the impact of the magnetic induction B changes to the dynamic viscosity [T^{-1}],
δ_{B1} – dimensionless coefficient taking into account the impact of the magnetic induction B changes to the dynamic viscosity,
B_0 – magnetic induction [T],
B_1 – dimensionless magnetic induction.

While the use of an exponential function to describe the changes in viscosity of the pressure or temperature, appears to be well founded, so use it for modelling separate changes in viscosity of the external magnetic field can't be considered directly correct. This function fairly well describes the scope of the changes corresponding to the accumulation of magnetic saturation, but at the moment of the full magnetic saturation achievements by ferro-oil, completely deviates from the actual course.

A completely different approach to modelling the magnetic viscosity increment function can be found in [5]. The authors, in the first step, propose to describe the function of the dynamic viscosity depending on pressure and temperature by means of a generalized form of Roelands' equation:

$$\eta_c(p,T) = \eta_{co}\exp\{(\ln\eta_{co}+9.67)[(1+5.1 \times 10^{-9}p)^{z} \times (T\text{-}138/T_0\text{-}138)^{-So}\text{-}1]\}, \tag{5}$$

where:
η_c – the dynamic viscosity of ferro-fluid [Pa·s],
η_{co} – the initial dynamic viscosity at standard conditions of air pressure and ambient temperature [Pa·s],
p – pressure in the oil film [Pa],
T – temperature in the oil film [^{o}C],
T_0 – ambient temperature T_0=293.15 K,
s_o – temperature-viscosity coefficient s_o=1.1,
z – temperature-pressure coefficient z=0.68

and only so determined the function of the viscosity they propose to correct of the unit taking into account the change in viscosity under the influence of a magnetic field H.

$$\eta_f(p,T,H) = \eta_{f0} + k_1 \times \Delta\eta(H), \tag{6}$$

where:

η_f – viscosity of ferro-fluids in magnetic fields [Pa·s],
η_{f0} – viscosity of ferro-fluids without magnetic fields [Pa·s],
k_1 – experimentally obtained proportionality coefficient,
$\Delta\eta$ – viscosity increment in magnetic field [Pa·s].

Such an approach allows the use of the exponential function as a basis for modelling the overall change in viscosity ferro-oil from the cumulative impact of all external performance. There is not still resolved the problem of modelling these increases of viscosity $\Delta\eta(H)$. In above-mentioned paper, authors propose for that the combined use of a polynomial function of 6-th degree and hyperbolic function. However, the combined action carries a risk of problems with finding mathematical solutions.

3. Results of modelling

In the present study, has been measured the value of dynamic viscosity in samples of ferro-oil mixture constituting colloidal mineral engine oil LongLife Gold of Penzzoil Company, which viscosity grade SAE 15W-40 with Fe_3O_4 magnetic particles and a surfactant. Studied ferro-oil is manufactured by FerroTec in Unterensingen (Germany). The percentage of the magnetic particles (by volume) in the tested samples of ferro-oil was 8%, 6%, 4%, 2% and 1%, and their average diameter was 10 nm. Surfactant content by volume accounted for approximately 15% Vol. Surfactant name has not been specified by the manufacturer, as this is his trade secret.

Rheological studies were carried out on Physica MCR 301 rheometer in the “plate-plate” measurement system with an adapter to magneto-rheological studies MRD 180/1T. The applied adapter enables to obtain almost homogeneous distribution of magnetic field strength. Thermal stabilization was carried out by a water jacket in a closed chamber and controlling the nature of the magnetic field was conducted by current’s changes. Tests were performed in the constant 90ºC temperature for shear rate’s changes from 0 to 1000 s^{-1} as regards changes an external magnetic field intensity 0 - 500 mT.

Analyses of the results identify and matching characteristic was calculated using StatSoft STATISTICA 9.1 software.

Three models of functions have been proposed for fitting the experimentally obtained results. The first is the exponential form:

$$\eta_B = \eta_0 \exp(\delta_{B1} B), \tag{7}$$

where:

η_B – dynamic viscosity depends on the magnetic induction [Pa·s],
η_0 – initial dynamic viscosity depends without magnetic field [Pa·s],
δ_{B1} – coefficient taking into account the impact of the magnetic induction B changes to the dynamic viscosity for exponential model [T^{-1}],
B – magnetic induction [T].

This model was adapted only for the range of changes corresponding to the build-up magnetic saturation of the ferro-oil.

In the whole range of studied changes of ferro-oil’s viscosity have been proposed two models of matching function. The logarithmic model and polynomial model. Logarithmic model is described in the following relationship:

$$\eta_B = z_2 \ln(\delta_{B2} B), \qquad \text{for } B>0,$$
$$z_2 = \eta_0, \text{ for } B=0, \tag{8}$$

where:

η_B – dynamic viscosity depends on the magnetic induction [Pa·s],
η_0 – initial dynamic viscosity depends without magnetic field [Pa·s],

δ_{B2} – coefficient taking into account the impact of the magnetic induction B changes to the dynamic viscosity for logarithmic model [T^{-1}],

B – magnetic induction [T],

Z – coefficient of the proportionality [Pa·s].

There has been adopted the second-degree polynomial function model:

$$\eta_B = \delta_{B3}B^2 + z_3B + c, \tag{9}$$

where:

η_B – dynamic viscosity depends on the magnetic induction [Pa·s],

δ_{B3} – major coefficient taking into account the impact of the magnetic induction B changes to the dynamic viscosity for polynomial model [Pa·s /T^2],

z_3 – minor coefficient taking into account the impact of the magnetic induction B changes to the dynamic viscosity for polynomial model [Pa·s /T],

c – coefficient of displacement [Pa·s],

B – magnetic induction [T].

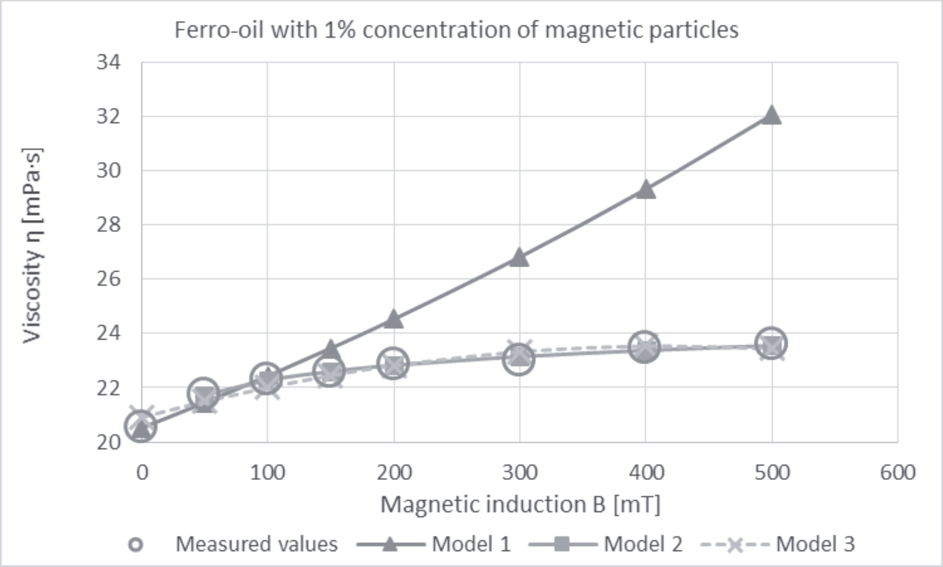

Fig. 1. Models of functions fitted for the results of changes in the viscosity due to magnetic induction for 1% ferro-oil

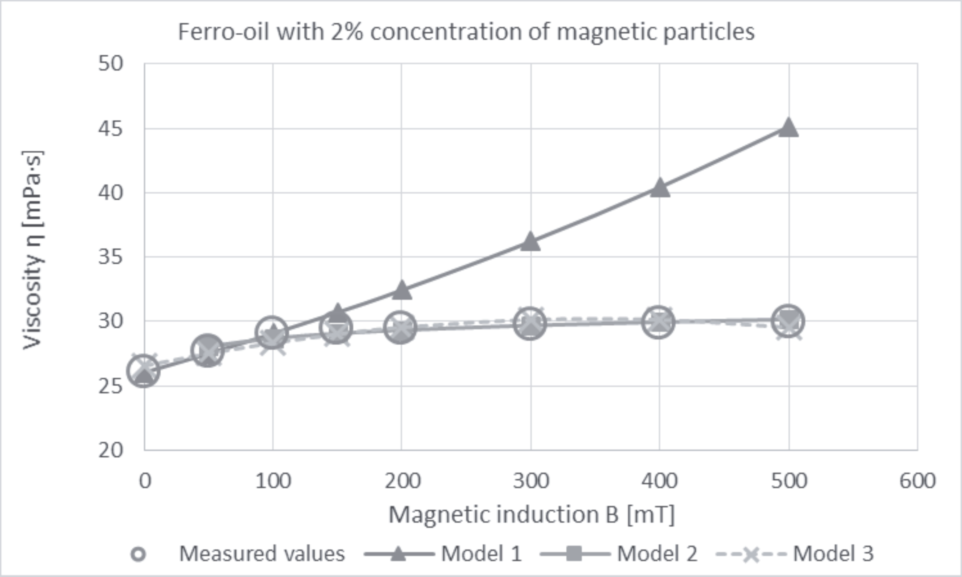

Fig. 2. Models of functions fitted for the results of changes in the viscosity due to magnetic induction for 2% ferro-oil

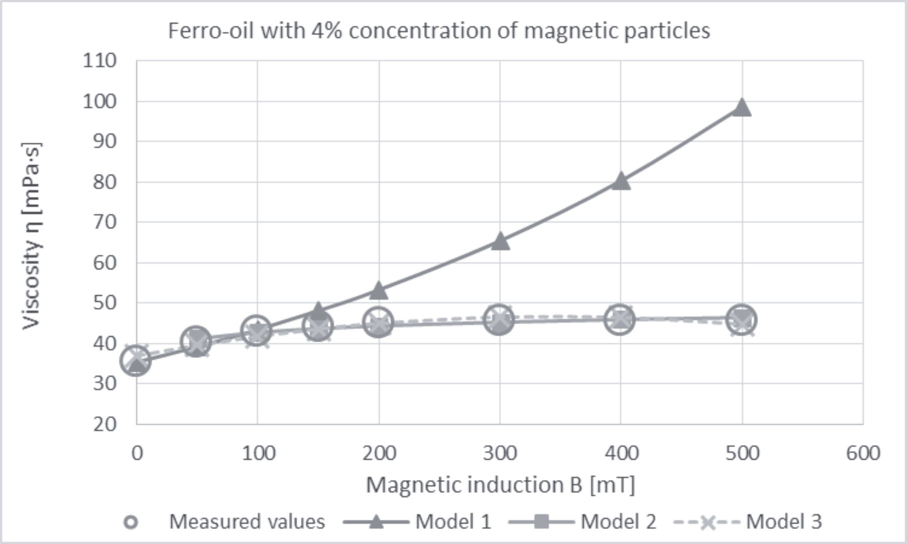

Fig. 3. Models of functions fitted for the results of changes in the viscosity due to magnetic induction for 4% ferro-oil

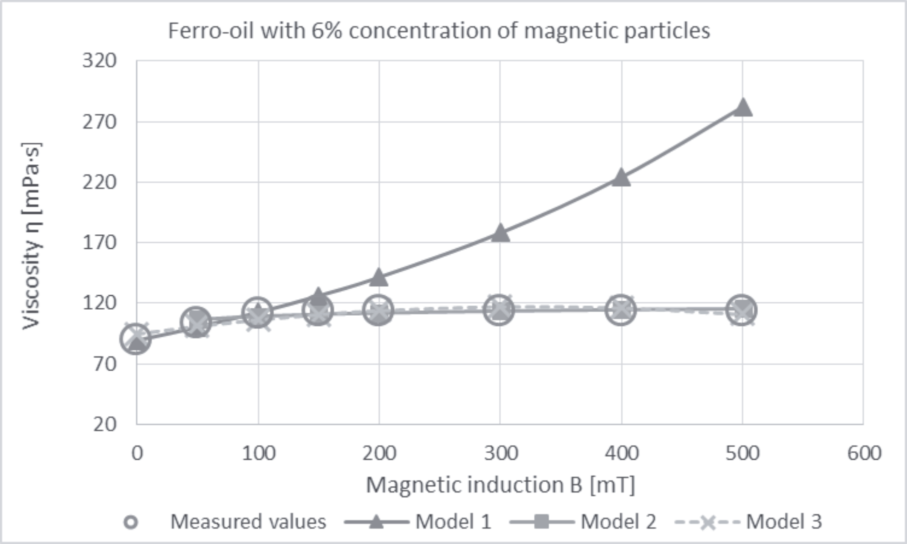

Fig. 4. Models of functions fitted for the results of changes in the viscosity due to magnetic induction for 6% ferro-oil

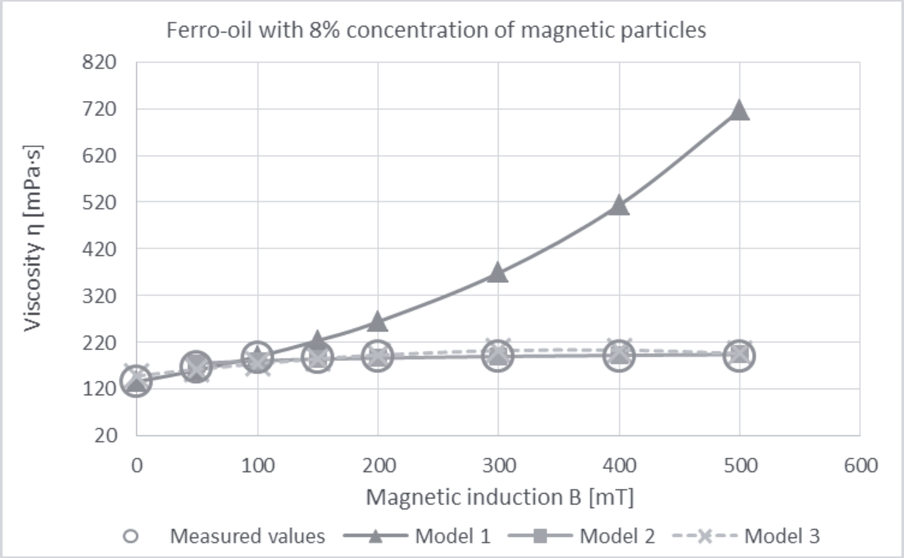

Fig. 5. Fitted functions models for the results of changes in the viscosity due to magnetic induction for 8% ferro-oil

The following Tab.1 presents a summary of the coefficients' values obtained for selected models of features.

Tab. 1. The values of the coefficients for the matched models of features

Concentration of magnetic particles	Model 1		Model 2		Model 3		
	η_0 [mPa·s]	δ_{B1} [1/T]	δ_{B2} [1/T]	z_2 [Pa·s]	δ_{B3} [Pa·s/T^2]	z_3 [Pa·s/T]	c [Pa·s]
1%	20.5	$8.93\cdot10^{-4}$	$1.58\cdot10^{10}$	$7.93\cdot10^{-4}$	$-1.50\cdot10^{-8}$	$1.26\cdot10^{-5}$	$2.09\cdot10^{-2}$
2%	26.6	$1.10\cdot10^{-3}$	$5.51\cdot10^{11}$	$9.07\cdot10^{-4}$	$-3.01\cdot10^{-8}$	$2.11\cdot10^{-5}$	$2.65\cdot10^{-2}$
4%	35.4	$2.05\cdot10^{-3}$	$1.29\cdot10^{16}$	$2.29\cdot10^{-3}$	$-8.04\cdot10^{-8}$	$5.69\cdot10^{-5}$	$3.69\cdot10^{-2}$
6%	89.3	$2.30\cdot10^{-3}$	$1.69\cdot10^{10}$	$3.88\cdot10^{-3}$	$-2.15\cdot10^{-7}$	$1.40\cdot10^{-4}$	$9.45\cdot10^{-2}$
8%	135.6	$3.33\cdot10^{-3}$	$2.18\cdot10^{7}$	$8.38\cdot10^{-3}$	$-4.24\cdot10^{-7}$	$3.09\cdot10^{-4}$	$1.48\cdot10^{-1}$

4. Observations and conclusions

The aim of this study was to identify and describe the nature of mathematical depending on changes in dynamic viscosity of ferro-oil with different concentrations of magnetic particles under the action of an external magnetic field.

It has been proposed three categories of functions mapping the waveforms of the results obtained experimentally: the exponential function, logarithmic with basis of the normal and the polynomial function. The great advantage of the first one - the exponential function, is that the nature of the changes is the same as for the characteristics of viscosity derived from changes in pressure or temperature. Application of such a model would greatly facilitate the subsequent analytical and numerical calculation. Unfortunately, the convergence of mapping the viscosity changes due to the magnetic induction using the exponential model satisfying only to a very limited extent of rising magnetic saturation of ferro-oil.

The other two proposed models of function well represent the waveforms of change in viscosity throughout the whole studied area. Particularly coincides with experimental data has proved the model of logarithmic. Lack of indication of this function for the magnetic induction value B=0, however, can mean the inability to make subsequent calculations of analytical and numerical occurring due to the discontinuity.

In this context, the most perspective model appears the polynomial one. Although the fact that mapping accuracy in this model, comparison with the logarithmic model is smaller, particularly in the area of full magnetic saturation of ferro-oil, the nature of this function, its continuity and simplicity of the model square may prove essential for performing mathematical operations on this model.

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