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THE FERRO-OILS VISCOSITY DEPENDED SIMULTANEOUSLY ON THE TEMPERATURE AND MAGNETIC OIL PARTICLES CONCENTRATION $\eta = \eta(T,\varphi)$ – PART I

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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 at context of temperature changes. These characteristics were determined for the following test conditions: atmospheric pressure, constant shear rate and absent of an external magnetic field. Tests were performed for selected concentrations of magnetic particles in ferro-oil ranging: 1%, 2%, 4%, 6% and 8%. Tested ferro-oil was product from Unterensingen FerroTec Company (Germany) which is a mixture of colloidal mineral engine oil LongLife Gold Penzzoil class SAE 15W-40 with addition of Fe_3O_4 magnetic particles and a surfactant. Analysis of the results, identifying and fitting of characteristics has been made by means of software StatSoft STATISTICA ver.9.1. There has been also undertaken comparison of the accuracy of estimation of reached results by selected mathematical models as well as these results have been rated according to their compliance with theoretical assumptions. Moreover, the waveform parameters of functions have been determined and their assessed quality has been done also. The obtained characteristics going to be used by author in his future work to build mathematical models of viscosity changes of ferro-oils in the aspect of changes of parameters like temperature, pressure, shear rate and the value of the external magnetic field. The determined parameters of physical properties will be used in analytical and numerical studies of flow and operating parameters of slide journal bearings lubricated with ferro-oils.

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

1. Introduction

The issue, which has been taken in this paper, in its broader context, refers to the research project on the analysis of changes in both flow and operating parameters of slide journal bearings lubricated by ferro-oils with different concentration of magnetic particles.

The possibility of applying of the particular oil, including ferro-oil as well, in the process of lubrication of bearings, is determined by their rheological properties, especially by their viscosity. Whereas the viscosity depends mainly on working parameters – temperature, pressure or shear rate. Equally important is internal structure of ferro-oil or its chemical composition, expressed, among others, the concentration of the magnetic particles. Additionally, in the case of ferro-oils, substantial impact on their viscosity has the presence of an external magnetic field, alternating the type, direction or values of induction, however, on context of this paper the investigation has been carried out in the conditions of its absence.

2. The theoretical foundations

In previous works, presented by the author of many publications, among others, in [2, 5, 6], there have been carried out the experimental studies of effect of concentration of the magnetic particles on the properties of ferro-oil viscosity both the presence or absence of an external magnetic field, in the aspect of changes in the basic operating parameters of bearing: i.e. temperature, pressure and shear rate $\eta = \eta(T, p, \theta)$. There have been also determined, experimentally, the coefficients of the magnetic susceptibility χ of ferro-oil, depending on the concentration of magnetic particles as well [1, 7]. The obtained results, observations and conclusions which have been made, both qualitative and quantitative terms, however, does not indicate clearly at the mathematical-physical relationship between the quantities which have been tested and the concentration of magnetic particles in of ferro-oil. The current phase of work requires the fitting of mathematical models of changes in dynamic viscosity of ferro-oil in terms of temperature, pressure and intensity of the external magnetic field and determine the appropriate factors: δ_T, δ_p, δ_B. In paper [3] has already been made appropriate analysis and determination of parameters δ_B defining dependence on dynamic viscosity of ferro-oils in the context of changes in the intensity of the external magnetic field $\eta = \eta(B)$. This paper is a proposal of selection and proper adjustment of mathematical functions regarding to the specific relationship between the dynamic viscosity of tested ferro-oil of the chosen concentrations of magnetic particles and temperature changes as well as the appointment of parameters and factors of these functions.

The taken review of the solutions proposed in the research literature can be reduced to a few basic models.

The most general model can be found, among others, in [8]. The authors propose to describe the function of the dynamic viscosity changes depend on the pressure and temperature using a generalized equation of the Roeland's form:

$$\eta_c(p,T) = \eta_{co} \cdot \exp[f(\eta_{co}, p, T, T_0, z, s_o)], \tag{1}$$

where:
f – Roeland's function obtained in experimental way [8],
η_c – dynamic viscosity of ferrofluid [Pa·s],
η_{co} – initial dynamic viscosity at standard conditions of pressure and temperature [Pa·s],
p – pressure in the oil film [Pa],
T – temperature in the oil film [K],
T_0 – reference temperature $T_0 = 293.15$ K,
s_o – temperature coefficient of viscosity $s_o = 1.1$,
z – pressure coefficient of viscosity $z = 0.68$.

Considering analysis of the above model, it should pay attention to some important facts. Firstly, there is not to miss the mathematical complexity of that model, which significantly affects the practical possibility of using it for further analytical-numerical research. Among the functions, describing physical phenomenon can be distinguished units of completely different mathematical characteristics: logarithmic, exponential, homographic or polynomial. Secondly, the obtained coefficients building above relationship are to the genesis of the empirical and, what obvious, the possibility of applying this formula is limited to liquids with similar characteristics. Thirdly, a major disadvantage of it is the lack of model parameter references taking into account the internal structure of ferro-fluid, with particular emphasis on the concentration of magnetic particles φ. There are taken into account only parameters describing the operating conditions of the liquid, i.e. pressure and temperature in the designed structure of this model. In the extended version of this model, it is additional taken into account the effect of the impact of an external magnetic field B by adding the unit of correcting.

$$\eta_f(p,T,H) = \eta_{f0} + k_1 \times \Delta\eta(H), \tag{2}$$

where:
η_f – dynamic viscosity of the ferrofluid in an external magnetic field [Pa·s],
η_{f0} – dynamic viscosity of the ferrofluid without the magnetic field [Pa·s],
k_1 – proportionality coefficient obtained experimentally,

$\Delta\eta$ – increase in dynamic viscosity under the influence of external magnetic field [Pa·s].

Much more "friendly" to further analytical and numerical investigations model of dependence $\eta = \eta(T, p, B)$ was presented in the works of A. Miszczak, especially in [9]. The dynamic viscosity of ferro-oil was presented as the product of multiplication of the units depending on the pressure, temperature and an external magnetic field:

$$\eta_1(B, p, T) = \eta_{1B} \cdot \eta_{1p} \cdot \eta_{1T}\,, \tag{3}$$

wherein, each of the main units has been appropriately modelled by the exponential function:

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

$$\eta_{1p}(\phi, z) = \exp(\zeta \cdot p_0 \cdot p_1) = \exp(\zeta_p \cdot p_1)\,, \tag{5}$$

$$\eta_{1T}(\phi, z, r) = \exp[-\delta_T \cdot (T - T_0)] = \exp(-Q_{Br} \cdot T_1)\,, \tag{6}$$

where:

$\eta_1(B, p, T)$ – the dimensionless dynamic viscosity depends on the magnetic induction, pressure and temperature,
$\eta_{1B}(\phi, z)$ – dimensionless dynamic viscosity depends on the magnetic induction,
$\eta_{1p}(\phi, z)$ – dimensionless dynamic viscosity depends on the pressure,
$\eta_{1T}(\phi, z, r)$ – dimensionless dynamic viscosity depends on the temperature,
δ_B – dimensional coefficient taking into account the effect of the magnetic induction B changes on the dynamic viscosity [T^{-1}],
δ_{B1} – dimensionless coefficient taking into account the effect of the magnetic induction B changes on the dynamic viscosity,
B_0 – magnetic induction [T],
B_1 – dimensionless magnetic induction,
ζ – dimensional piezocoefficient of the viscosity [Pa^{-1}],
ζ_p – dimensionless piezocoefficient of the viscosity,
δ_T – dimensional coefficient taking into account the effect of the temperature T changes on the dynamic viscosity [K^{-1}],
Q_{Br} – dimensionless coefficient of viscosity changes depends on temperature.

The above model is characterized by high susceptibility to the possibility of its application in further research of analytical and numerical. Unfortunately, this advantage has been paid with some inadequacy of that model in terms of the real nature of the physical phenomena. The discrepancies are particularly strongly affirmed in the case of the pressure η_{1p} and the magnetic η_{1B} units. In the paper [3] the author has pointed out the aforementioned inadequacy and has suggested some alternative arrangements. Likewise in [4] it has been shown that the exponential model of changes the viscosity of the pressure is possible to apply only to the value of pressure not exceeding 5 bars, both in accordance with the conclusions of the Barus dependence [10] and the results own self obtained on the way of empirical research. However, also for this model, its disadvantage is the lack of parametric references relative to the internal structure of the tested ferro-oil, in particular of the magnetic particles contained therein.

In the next part of this paper, the author will point to alternative ways of modelling the above-described relationships and will make their evaluation.

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.

Tests were performed on HAAKE MARS III rheometer for the constant shear rate 100 1/s and temperature's range up to 120°C.

There was used the configuration of rheometer chamber with the Peltier's system "cone-plate" type in the tests. Diameter of the used rotor was $d = 60$ mm and an apex angle of cone were 178°. With that above configuration, the characteristics of ferro-oil's dynamic viscosity changes have been obtained for the temperature changes from 0°C to 120°C every 10 K.

Analyses of the results identify and matching characteristic was calculated using StatSoft STATISTICA 9.1 software. Analyses of the results identify and matching characteristic was calculated using StatSoft STATISTICA 9.1 software. It has been applied Lavenberga-Marquard's nonlinear estimation with regression made the least squares method adopted for the maximum number of iterations equal to 250 and the ratio of $1 \cdot 10^{-6}$ convergence criterion. The confidence level has been equal $p = 0.95$.

There have been proposed four models of matching for the results obtained experimentally in this paper. The first of them – Model 1 that is the function of exponential form:

$$\eta_T = \eta_0 \exp[\delta_{T1} \cdot (T - T_0)], \tag{7}$$

where:

η_T – dynamic viscosity depends on the temperature [Pa·s],
η_0 – initial dynamic viscosity for $T_0 = 273.15$ K and $p_0 = p_{at}$ [Pa·s],
δ_{T1} – coefficient of the impact of the temperature T changes to the dynamic viscosity [K^{-1}],
T – temperature [K],
T_0 – reference temperature 273.15 K.

In Fig. 1 for Model 1, by virtue of (7) are presented viscosity variations depended on magnetic particles concentration versus temperature changes.

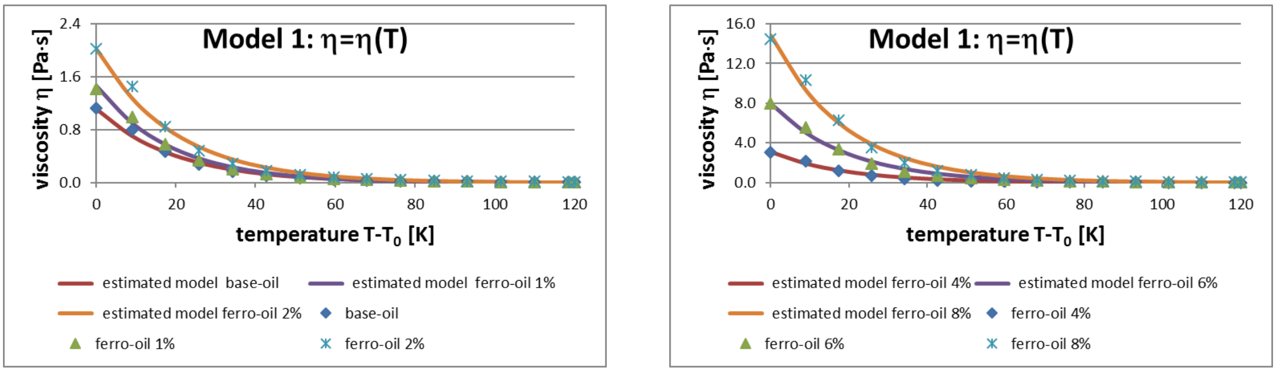

Fig. 1. Model 1 – fitted functions for the results of the viscosity changes due to the temperature for base-oil, 1% ferro-oil and 2% ferro-oil as well as for 4% ferro-oil, 6% ferro-oil and 8% ferro-oil

Used, adopted exponential function adjusts at a very good degree obtained experimental results. The share of variance R^2 is contained in the range of 0.98721179 of 2% ferro-oil to 0.9933633 of 1% ferro-oil. Also, the adoption in structure of a model of the actual conditions of the initial viscosity η_0 for $T_0 = 273.15$ K and $p_0 = p_{at}$ affects positively on the adequacy of the physical-mathematical model relative to the tested ferro-oil. An important advantage of this model is its monotonicity run, which gives the possibility to extrapolate the results in both the lower and higher temperatures outside the range of the actually been examined. The obtained values of the parameters and their corresponding values of variance are presented in Tab. 1.

As the second of the tested models was adopted polynomial fourth-degree model form like:

$$\eta_T = \delta_{T2}\Delta T^4 + a_2\Delta T^3 + b_2\Delta T^2 + c_2\Delta T + \eta_0 , \tag{8}$$

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

Concentration of magnetic particles	base-oil	1% ferro-oil	2% ferro-oil	4% ferro-oil	6% ferro-oil	8% ferro-oil
R^2 – values of variances	0.9873806	0.9933633	0.9852118	0.98794454	0.98951706	0.989144
η_0 – initial dynamic viscosity	1.12482	1.47555	2.029651	3.066061	7.947788	14.83158
δ_{T1} – parameter depends on temperature	–0.050718	–0.053731	–0.051013	–0.0529964	–0.0511494	–0.051989

where the symbols introduced in (8) are described in the following form:

η_T – dynamic viscosity depended on the temperature [Pa·s],

δ_{T2} – major coefficient of the impact of the temperature changes ΔT on the dynamic oil viscosity [Pa·s/K^4],

a_2 – 1st minor coefficient of the impact of the temperature changes ΔT on the dynamic oil viscosity [Pa·s/K^3],

b_2 – 2nd minor coefficient of the impact of the temperature changes ΔT on the dynamic oil viscosity [Pa·s/K^2],

c_2 – 3rd minor coefficient of the impact of the temperature changes ΔT on the dynamic oil viscosity [Pa·s/K],

η_0 – initial dynamic viscosity coefficient [Pa·s],

ΔT – temperature changes interpreted as reduced temperature $T - T_0$ in [K].

In Fig. 2 for Model 2, by virtue of (8) are presented viscosity variations depended on magnetic particles concentration versus temperature changes.

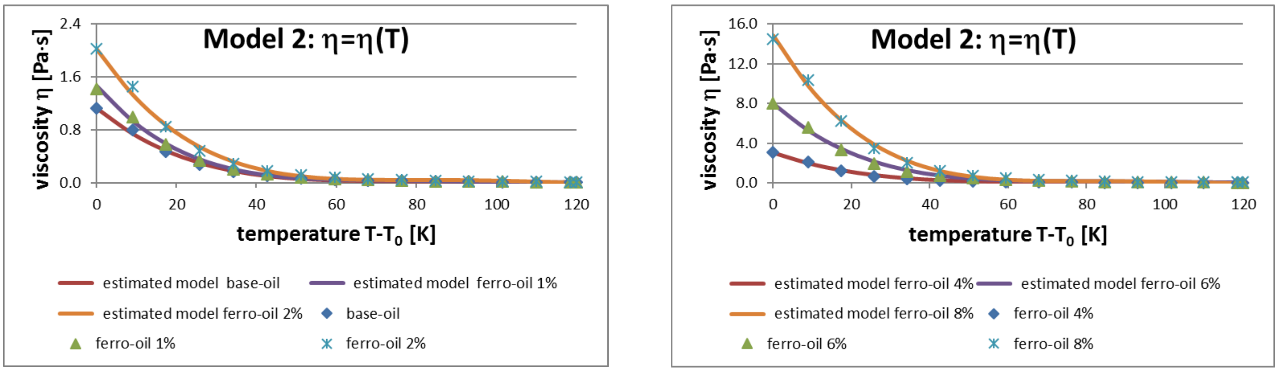

Fig. 2. Model 2 – fitted functions for the results of the viscosity changes due to the temperature for base-oil, 1% ferro-oil and 2% ferro-oil as well as for 4% ferro-oil, 6% ferro-oil and 8% ferro-oil

Polynomial model at a very good degree matches the curves empirically acquired. The values of variance not descend below $R^2 = 0.9921$ for 2% ferro-oil. Unfortunately, over the range of temperature actually studied that function on both left- and right- sides changes its course and in practice, there is no possibility of extrapolating the results. In addition, for this model, the mathematical adjustment does not have his physical justification other than the exception in the form of free expression η_0, which is the value of initial viscosity. Tab. 2. presents the parameter values and the corresponding values of variance.

The last analysis was subjected to homographic function model of two forms: the second and third degree. The first is the Model 3 described the following relationship:

$$\eta_T = \delta_{T3} \cdot \frac{1}{(T - T_0)^2 + a_3} + b_3 , \tag{9}$$

Tab. 2. The values of the coefficients for the matched Model 2 of features

Concentration of magnetic particles	base-oil	1% ferro-oil	2% ferro-oil	4% ferro-oil	6% ferro-oil	8% ferro-oil
R^2 – values of variances	0.99341608	0.99731735	0.99216836	0.99387873	0.99542041	0.99604713
η_0 – initial dynamic viscosity	1.12482	1.47555	2.029651	3.066061	7.947788	14.83158
δ_{T2} – parameter depends on temperature	$1.6204 \cdot 10^{-8}$	$2.9862 \cdot 10^{-8}$	$2.7726 \cdot 10^{-8}$	$5.2884 \cdot 10^{-8}$	$1.1693 \cdot 10^{-8}$	$2.1303 \cdot 10^{-8}$
a_2 – values of 1st minor coefficient	$-6.041 \cdot 10^{-6}$	$-1.011 \cdot 10^{-5}$	$-1.056 \cdot 10^{-5}$	$-1.878 \cdot 10^{-5}$	$-4.323 \cdot 10^{-5}$	$-7.976 \cdot 10^{-5}$
b_2 – values of 2nd minor coefficient	$0.826 \cdot 10^{-3}$	$1.261 \cdot 10^{-3}$	$1.468 \cdot 10^{-3}$	$2.452 \cdot 10^{-3}$	$5.877 \cdot 10^{-3}$	$10.54 \cdot 10^{-3}$
c_2 – values of 3rd minor coefficient	–0.04945	–0.06953	–0.08898	–0.14067	–0.35087	–0.65757

where:

δ_{T3} – coefficient taking into account the impact of the temperature T changes to the dynamic viscosity for Model 3 [Pa·s·K^2],

a_3 – coefficient of the peak scale [K^2].

b_3 – coefficient of the displacement [Pa·s].

In Fig. 3 for Model 3, by virtue of (9) are presented viscosity variations depended on magnetic particles concentration versus temperature changes.

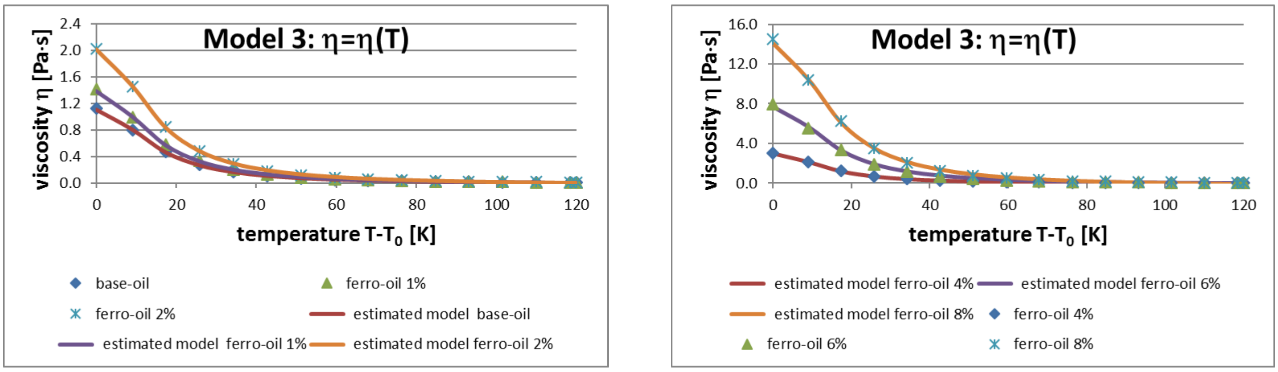

Fig. 3. Model 3 – fitted functions for the results of the viscosity changes due to the temperature for base-oil, 1% ferro-oil and 2% ferro-oil as well as for 4% ferro-oil, 6% ferro-oil and 8% ferro-oil

Adopted in Model 3 the homographic function of the second degree of which image is hyperbole, in the best, almost perfect degree, matching the course of the changes of viscosity in the studied ferro-oils in aspect to the temperature changes. In none of the cases the shear of variance is not below the value of $R^2 = 0.999$. The lowest adjustment value related to the characteristics of 8% ferro-oil and the highest for 2% ferro-oil. A significant disadvantage of this model is the lack of left side monotonicity of the course. A certain drawback of this model is the large number of adjustment coefficients. Tab. 3. presents both the fitted values of coefficients and the variances of this model.

As a result the observations made associated with the Model 3, it has been analysed further Model 4 also established on the basis of homographic function, but in this case the third degree. This Model 4 is described following relation:

$$\eta_T = \delta_{T4} \cdot \frac{1}{(T-T_0)^3 + a_4} + b_4, \tag{10}$$

Tab. 3. The values of the coefficients for the matched Model 3 of features

Concentration of magnetic particles	base-oil	1% ferro-oil	2% ferro-oil	4% ferro-oil	6% ferro-oil	8% ferro-oil
R^2 – values of variances	0.99964182	0.99943672	0.99964303	0.99958495	0.99941927	0.99903277
δ_{T3} – parameter depends on temperature	252.3881	306.9263	454.0764	637.2955	1843.750	3496.829
a_3 – values of peak scale coefficient	225.2309	218.6148	222.1909	208.9493	236.876	242.748
b_3 – values of coefficient of displacement	–0.0150	–0.0185	–0.0318	–0.0448	–0.139	–0.332

where:

δ_{T4} – coefficient taking into account the impact of the temperature T changes to the dynamic viscosity for Model 4 [Pa·s·K^3],

a_4 – coefficient of the peak scale [K^3].

b_4 – coefficient of the displacement [Pa·s].

Figure 4 presents the appropriate adjustment made using the relation (10).

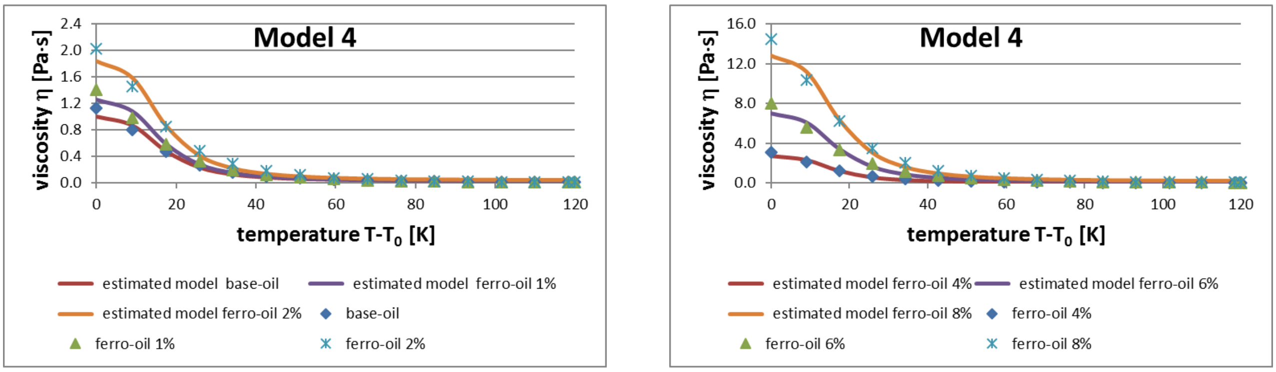

Fig. 4. Model 4 – fitted functions for the results of changes in the viscosity due to the temperature for base-oil, 1% ferro-oil and 2% ferro-oil as well as for 4% ferro-oil, 6% ferro-oil and 8% ferro-oil

This model also has a relatively high degree of fit ($R^2 \geq 0.9881042$), though not as in the case of Model 3. Applying it avoids the drawback, which was characteristic for Model 3, i.e., the left side immediately change of the function monotonic. However, this advantage turned out to be associated with another handicap. The estimated values of the dynamic viscosity slightly extend to the negative values for right side of function course, what from the physical point of view of the analysis is not acceptable. In the author's opinion, this fact discredits the Model 4, and it will not be subjected to further deeper analysis in the context of this work.

3. Observations and conclusions

All of the models have being analysed in this paper are characterized by a high degree of mathematical matching due to the characteristics obtained experimentally. In particular, this statement applies to the model created on the basis of homographic function of the second order – Model 3. In the specialist, literature it cannot be actually encountered models built in this way. It is dominated by models of the nature of exponential. The results of this study also confirm that exponential function highly matches real course of the physical processes of change in the dynamic viscosity of ferro-oils in terms of temperature changes. Moreover, exponential model, unlike the models of polynomial or homographics, also fulfils the physical expectations posed before such adjustment to the extent significantly higher. From among the models analysed, only Model 4 has been discredited, at this stage, in the context of further analysis because of the inadequacy of relative to described physical phenomena.

The derived and described in the I-st part of the paper models need further study aimed at finding a binding parametrically relationship between concentration of particles in the ferro-magnetic oil with the dynamic viscosity $\eta = \eta(T, \varphi)$. This aim has been erected and realized in the II-nd part of this paper.

In the future research works in this subject, it is necessary to take into account also the actual viscosity changes on the temperature in the aspect of the oil film thickness. This topic has already been partially described in dedicated works, for example in [11].

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