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INVESTIGATIONS ON THE RHEOLOGY OF ADDITIVATED HYDRAULIC OILS

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Abstract: *The purpose of this paper is to characterize the rheological behavior of the hydraulic oils additivated with viscosity index improvers. This type of lubricants exhibits typical non-Newtonian properties, depending on the concentration of additives. The samples have been tested on a Brookfield rheometer, with a cone and plate geometry, by measuring the variation shear stress versus shear rate. Finally, the rheological parameters of the lubricant have been determined, according to different rheological models.*

Keywords*: Rheology, hydraulic oil, experiment*

1. Introduction

The primary purpose of hydraulic oils is to transfer the potential or kinetic energy, to create volume flow between pump and hydrostatic motor and to reduce the friction and wear between moving parts. In addition, they protect the system from corrosion and help carry away the heat produced during energy transformation [1, 2].

Generally, the rheological properties of hydraulic oils depend on many factors that include temperature, shear rate, concentration, time, pressure, chemical properties and additives [3, 4]. Most of the researches focusing on the effects of temperature, shear rate, concentration and pressure. However, it is normally found that the effect of temperature is much more apparent on the fluid viscosity.

It is known that additives of different types are added to improve the properties of lubricants in almost all types of oils. In the case of hydraulic oils with viscosity index enhancers (long chain polymers and high molecular weight polymers), the resulting fluid exhibit non - Newtonian properties [5, 6].

The aim of this paper is to characterize the rheological behavior of the hydraulic oils additivated with viscosity index improvers. The lubricant being tested is a general purpose hydraulic oil suitable for lubrication of lightly loaded units in machines and installations with flow and circulation systems [7]. This type of oil is produced from specially selected high-grade selective and hydro-refined naphthenic, paraffin-naphthenic base fractions.

The additive used as a viscosity index enhancer is based on polybutene, which is a synthetic transparent liquid polymer obtained by the selective polymerization process of isobutylene containing in the butane-butane stream. The main properties of the additive are: solubility in oils, nontoxicity, thermal stability and high anticorrosion properties [8]. The physical and chemical properties of the base hydraulic oil and additive are presented in Table 1 [7, 8].

Table 1: Physical and chemical properties of the hydraulic oil and additive

Characteristic parameter	Hydraulic oil	Additive
Density at 15°C	900 kg/m^3	887 kg/m^3
Viscosity at 40°C	41.4 – 50.6 cSt	-
Viscosity at 100°C	24.2 – 31.4 cSt	580 – 660 cSt
Viscosity Index	92	-
Viscosity CCS at 30°C	5500 cP	-
Pour point	-25° C	-67° C

Characteristic parameter	**Hydraulic oil**	**Additive**
Flash point COC	200° C	170° C
TBN	9.4 mg KOH/g	-
Water (ppm)	-	70
Volatile factions	10 %	-
Viscosity HTHS (150°C)	3.3 cP	-
Molecular weight (g/mol)	-	1300
Colour (ASTM)	L 3.5	15

2. Experimental stand and methodology

The measurements were carried out on a Brookfield rotating viscometer CAP 2000+. Brookfield Viscometers (Amettek, USA) are included in a large number of international standards. All their laboratory viscometers have an accuracy of not less than the entire scale of ± 1,0% and a reproducibility of not less than 0,2% [9]. CAP 2000+ viscometer series (Figure 1) are medium to high deformation tools and operate according to the scheme cone - plate. With this apparatus, the cone angle provides a constant speed of deformation of the fluid placed between the two elements of the device: the rotating element (cone) and the fixed one (stationary plate).

Fig. 1. Brookfield cone-plate viscometer

The measurement range the viscosity depends on the angular velocity and the shape and size of the cone used. The minimum range is from 0.02 Pa.s and reaches 1500 Pa.s, the rotation speed is in range from 5 to 1000 rpm and the shear rate of 10 to 13000 s^{-1}, respectively. The necessary sample volume is in the range of 0.5 to 2 ml. The viscometer has ports for turning on a computer and a printer.

The advantages of the viscometer include built-in temperature control (from 5 ^{0}C to 75 ^{0}C) of the sample, easy adjustment and cleaning, small sample volume, automatically computer controlled software. The Capcalc 32 software allows automated testing, recording and storage of experimental data (up to 1000 data points for test). The data can be visualized graphically, allowing the software to be built several comparative graphs simultaneously. Several mathematical features are embedded in the software models for rapid and easy analysis of rheological fluid behavior.

The hydraulic oil was tested in pure state (0% of additive) and in modified state (five different concentrations of additive: 1%, 2%, 3%, 4% and 5%). To determine the lubricant rheological model in pure and modified state (with additive), it was used an "imposed velocity gradient" test, with the variation limits 1333 ... 13333 s^{-1} and 20^{0}C reference temperature. The tests were carried out with a load up to 13333 s^{-1} and unloading up to 1333 s^{-1}, in order to highlight the effects of lubricant thixotropy.

There were calculated the lubricant rheological parameters, using the regression analysis method with MathCAD software, according to three different rheological model:

- Newtonian model: $$\tau = \eta \frac{du}{dy} \quad (1),$$

where: τ - shear stress
$\frac{du}{dy}$ - shear rate
η - viscosity

- Power law model: $$\tau = m\left(\frac{du}{dy}\right)^n \quad (2),$$

where: τ - shear stress
$\frac{du}{dy}$ - shear rate
m - consistency index (which is equivalent to the Newtonian fluid viscosity)
n - flow index (equal to 1 if the fluid is Newtonian).

- Rabinowitsch model: $$\tau + k\tau^3 = \eta \frac{du}{dy} \quad (3),$$

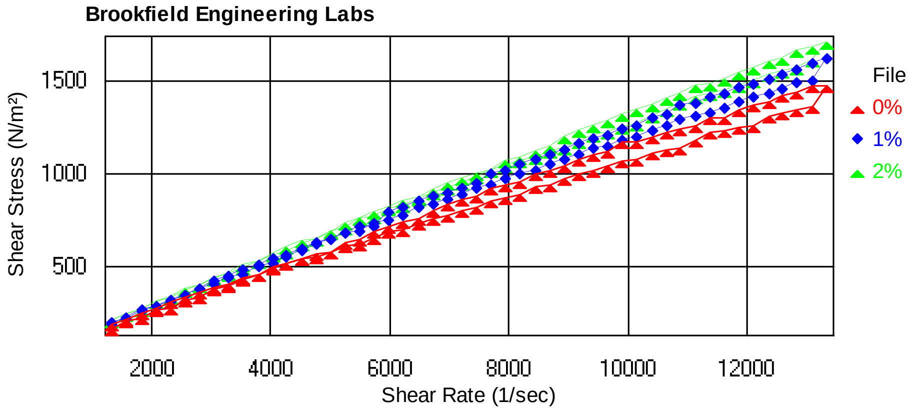
where: τ - shear stress
$\frac{du}{dy}$ - shear rate
k – coefficient of pseudo-plasticity (equal to 0 if the fluid is Newtonian)
η - viscosity

3. Results and discussions

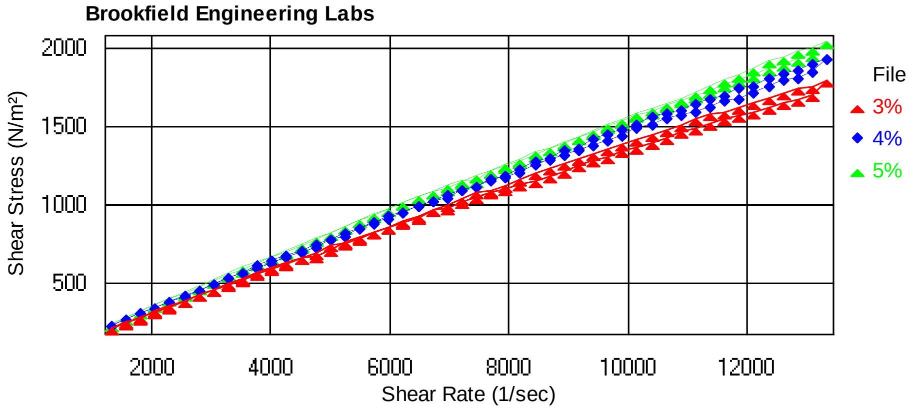
The results refer to experimentally obtained dependencies for the influence of the shear rate on the shear stress and viscosity of the investigated hydraulic oil with additive. Part of the results relate to the impact of the concentration of the additive on the investigated physical properties of the lubricants, as well as the influence of time factor. The work does not take into account thermal effects on the rheological characteristics of the hydraulic oil, the results presented referring to the isothermal mode at 20 ^{0}C.

Figure 2 a and b present rheograms that provide a relationship between the shear rate and shear stress for hydraulic oil in pure state (0% of additive) and in modified state (five different concentrations of additive: 1%, 2%, 3%, 4% and 5%). From these diagrams, it can be seen that when loaded to maximum shear rate and unloading to the initial one, are observed non-matching ascending and descending parts of the rheogram. This shows that the hydraulic oil with different concentration of additives have typical thixotropic properties.

Figure 2 gives also information about the hysteresis of the hydraulic fluid with additive. It can observe that the hysteresis disappears at approx. 7000 s^{-1}, representing about 55% of the total range of shear rate.



a) Additive: 0%, 1% and 2%



b) Additive: 3%, 4% and 5%

Fig. 2. Rheograms for hydraulic oil in pure and modified state

Table 2 presents the rheological parameters obtained by regression analysis method, corresponding to rheological models Newtonian, power law and Rabinowitsch.

Table 2: Rheological parameters of the investigated fluid

Additive, %	**Newtonian model**		**Power law model**			**Rabinowitsch model**		
	η, Pa·s	**Corr. coeff.**	**m, Pa·s^{-n}**	**n**	**Corr. coeff.**	**k, Pa^{-2}**	**η, Pa·s**	**Corr. coeff.**
0	0.112	98.6%	0.279	0.900	97%	$4.60\cdot10^{-8}$	0.119	99.6%
1	0.123	99%	0,276	0.911	98%	$4.38\cdot10^{-8}$	0.131	99.8%
2	0.129	99.2%	0.289	0.912	98.4%	$3.83\cdot10^{-8}$	0.139	99.8%
3	0.138	99.3%	0.295	0.917	98.7%	$3.69\cdot10^{-8}$	0.148	99.9%
4	0.147	99.5%	0.300	0.922	99.1%	$2.83\cdot10^{-8}$	0.157	99.9%
5	0.156	99.6%	0.304	0.927	99.3%	$2.37\cdot10^{-8}$	0.165	100%

Analyzing the values presented in Table 2, it can observe that the greatest values of the correlation coefficient are obtained in the case of Rabinowitsch model. In this way, it results that the rheological model that best approximates the behavior of the analyzed hydraulic fluid is the Rabinowitsch model.

Therefore, the variation of the rheological parameters versus concentration of the additive is presented only for the Rabinowitsch model: viscosity in Figure 3 and pseudoplastic coefficient in Figure 4.

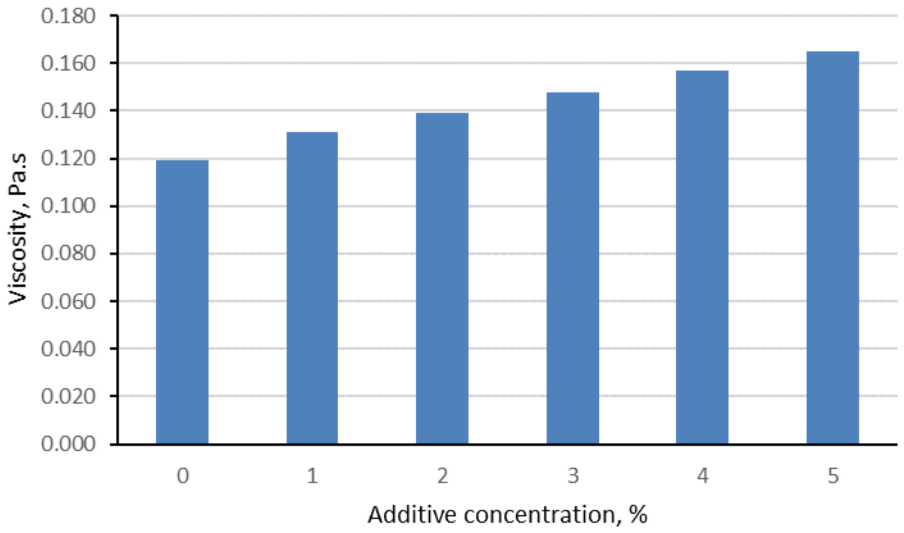


Fig. 3. Variation of the viscosity of hydraulic fluid with the additive concentration

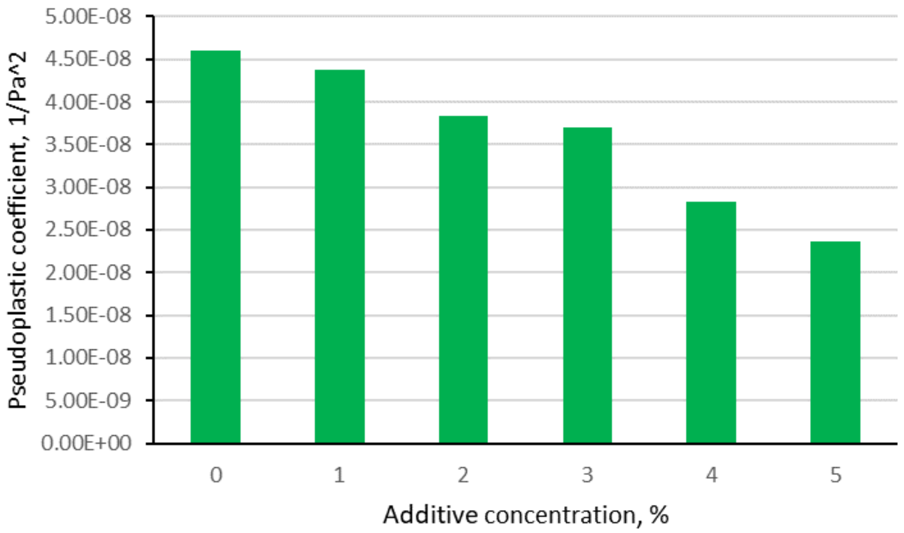


Fig. 4. Variation of the pseudoplastic coefficient with the additive concentration

Analyzing Figures 3 and 4, it is clearly observed that the viscosity increases with the increase of additive concentration, while the pseudoplastic coefficient decrease with the same concentration of additive.

4. Conclusions

An experimental study was performed in order to characterize the rheological behavior of the hydraulic oils additivated with viscosity index improvers.

The graphical dependencies for the shear stress versus shear rate as well as the viscosity and pseudoplastic coefficient function of the additive concentration are presented.

Experimental tests showed the lubricant thixotropy, at high shear rates, which is present for the hydraulic oil in pure and modified state.

The investigated hydraulic oil with additive has pseudoplastic fluid behavior and it is described with high accuracy by the Rabinowitsch model.

The increasing of the concentration of the incorporated additive results in an increase in viscosity and a decrease of the pseudoplastic coefficient.

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