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COMPARATIVE THERMAL ANALYSIS OF HYDRAULIC OILS

Andreea Mirela TELEAȘĂ[1], Sorin CĂNĂNĂU[1], Cătălin DUMITRESCU[2],
Alexandru Valentin RĂDULESCU[1], Alina Maria STOICA[1], Geanina Mihaela MATEESCU[1]

[1] National University of Science and Technology POLITEHNICA Bucharest, Dept. of Machine Elements & Tribology, Romania, andreea.teleasa@upb.ro

[2] INOE 2000 - IHP, Hydraulics and Pneumatics Research Institute, Bucharest, Romania, dumitrescu.ihp@fluidas.ro

Abstract: *In this work, the experimental and theoretical results of the apparent viscosity for three hydraulic oils are presented. The experimental determinations were made in the laboratory using the Brookfield CAP2000+ experimental equipment. The determination of the apparent viscosity with temperature was made in the temperature range 20...75 °C, and the theoretical determinations were made with the help of three proposed thermal models, namely, Jarchov and Theissen, Cameron, and Reynolds, using numerical regression.*

Keywords: *Apparent viscosity, hydraulic fluids, temperature, thermal model*

1. Introduction

Rheological characteristics has an important role in understanding heat transfer and in planning, evaluating and modeling continuous treatment processes [1].

It is well recognized that the rheological characteristics of oils depend on a multitude of factors, including temperature, cutting speed, concentration, time, pressure, chemical properties, additives and catalysts. With the maturation of the petrochemical industry, petroleum oils emerged as the preferred choice, supplanting vegetable oils on account of their superior lubricity, stability, and economic feasability [2].

Viscosity is the measure of internal resistance within a fluid. This resistance becomes apparent when layers of fluid move in relation to each other, and the greater the resistance, the more force is needed to initiate this movement, known as shear. One of the most significant factors influencing the rheological behavior of a material is temperature [3]. Apparent viscosity can be described as a macroscopic property that reflects a fluids resistance to high shear rates. It corresponds to the viscosity measured in the experimental setup [4]. Increasing temperature tends to increase molecular interaction, while decreasing the attractive forces between molecules [2].

The purpose of this study is to assess the effects of shear rate and temperature on the apparent viscosity of three hydraulic oils, using three thermal models that will be analyzed through numerical regression. Subsequently, these apparent viscosity results will be compared with the viscosity measured on the experimental stand.

2. Theory

To determine the rheological behavior of the three hydraulic oils, we proposed the Newtonian model, equation (1).

$$\tau = \eta \cdot \dot{\gamma} \tag{1}$$

Where τ is shear stress, η is viscosity, and $\dot{\gamma}$ is shear rate.

From the thermal point of view, three thermal models are proposed with the help of which we determine the variation of the rheological parameters.

- Modelul Jarchov and Theissen

$$\eta = \eta_{50} \cdot e^{B\frac{50-t}{95+t}} \tag{2}$$

Where η is lubricant viscosity, η_{50} is lubricant viscosity at 50 °C, B is non-dimensional parameter, and t is temperature.

- Modelul Cameron

$$\eta = K \cdot e^{\frac{b}{95+t}} \tag{3}$$

Where η is lubricant viscosity, K is viscosity parameter, b is temperature parameter and t is temperature.

- Modelul Reynolds

$$\eta = \eta_{50} \cdot e^{-m(t-50)} \tag{4}$$

Where η is lubricant viscosity, η_{50} is lubricant viscosity at 50 °C, m is coefficient of variation of viscosity with temperature, t is temperature and 50 is reference temperature.

The experimental data were numerically processed using the numerical regression method to obtain the main values of the specific characteristic parameters of the Newtonian model, equation (1) and of the three thermal models, equations (2, 3 and 4).

3. Experimental equipment

The experimental test stand is a Brookfield CAP 2000+ cone and plate rotary viscometer, shown in Fig. 1. This device is ideal for evaluating the rheological behavior of fluids, whether Newtonian or non-Newtonian, and allows the identification of yield strength and thixotropy. It uses as working geometry the cone and plate coupling, shown in Fig. 2. The relevant data is presented on the device screen and the CAPCALC32 software can be used to generate the flow/viscosity graphs [5].

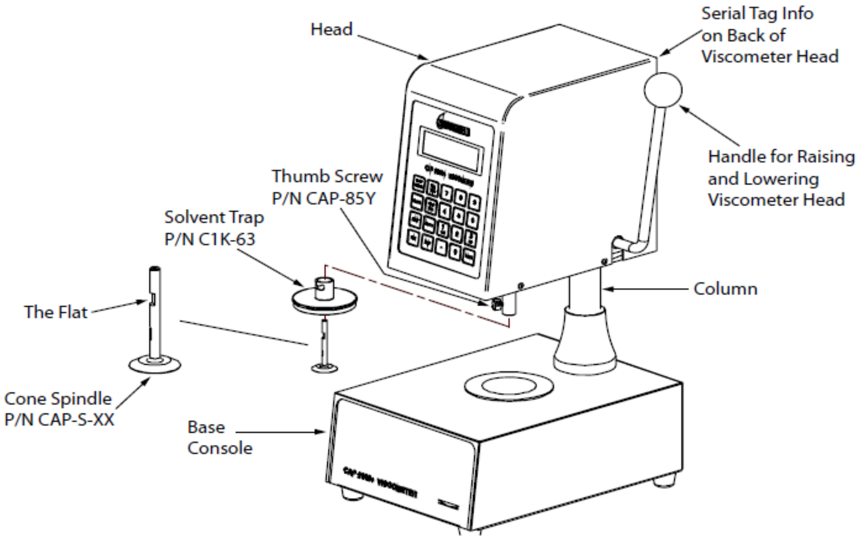

Fig. 1. Viscometer Brookfield CAP2000+ [5]

Fig. 2. Work geometries [5]

Tabel 1: Geometry and viscosity range of testing cones

Cone number	Cone radius, [mm]	Cone angle, [°]	Viscosity range, [Pa·s]
3	9.53	0.45	0.083...1.87
5	9.53	1.8	0.333...7.50
6	7.02	1.8	0.833...18.7
8	15.11	3	0.312...3.12

In this work, three hydraulic oils were tested, namely: H46- mineral oil, HETG46-biodegradable oil and HF-E46- non-flammable biodegradable oil. Table 2 shows their properties.

Tabel 2: Physico-chemical properties of tested hydraulic oils [6]-[8]

Oil / Properties	H46	HETG46	HF-E46
ISO viscosity class	46	46	46
Density 15 ^{o}C, max	0.876	918	921
Viscosity index, min.	98	210	188
Kinematic viscosity at 40°C, cSt	44	-	47.2
Kinematic viscosity at 100°C, cSt	6.6	10	9.41
Flash point, °C, min.	226	>270	320
Pour point, °C, max.	-24	-30	-42
Part of renewable raw materials, %	-	95	76

4. Results

Fig. 3. shows the rheogram of mineral hydraulic oil H46 and the biodegradable ones HETG46 and HF-E46 at a temperature of 20 °C. From this graph it can be seen that the H46 oil has a pronounced thixotropy and a high viscosity, but its thermal stability is low, compared to the other two biodegradable hydraulic oils, where the thixotropy is not so pronounced (thermal stability is high) [9].

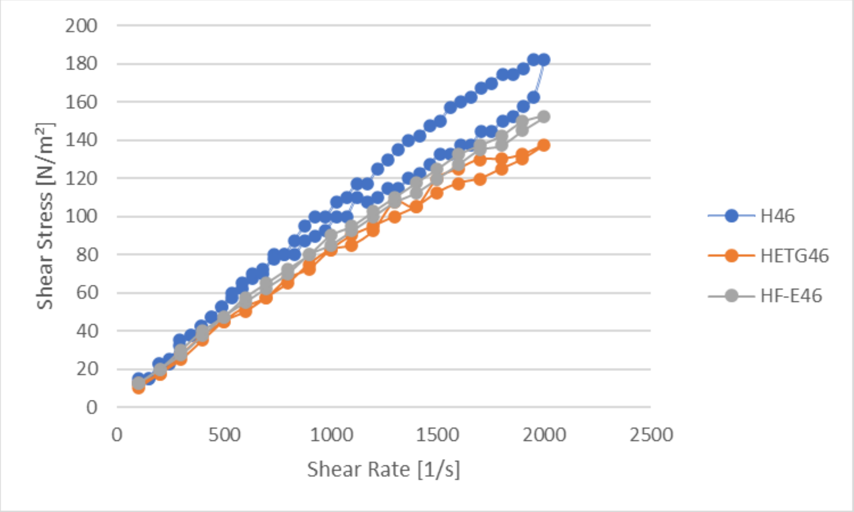

Fig. 3. Rheogram of the three hydraulic oils at a temperature of 20°C [9]

Fig. 4. present the variation of the apparent viscosity with the temperature of the H46 hydraulic oil at four different shear rates (250 s^{-1}, 500 s^{-1}, 750 s^{-1}, 1000 s^{-1}) in the temperature range of 20 ºC...70 ºC, where we can see that the viscosity decrease with the increase of temperature.

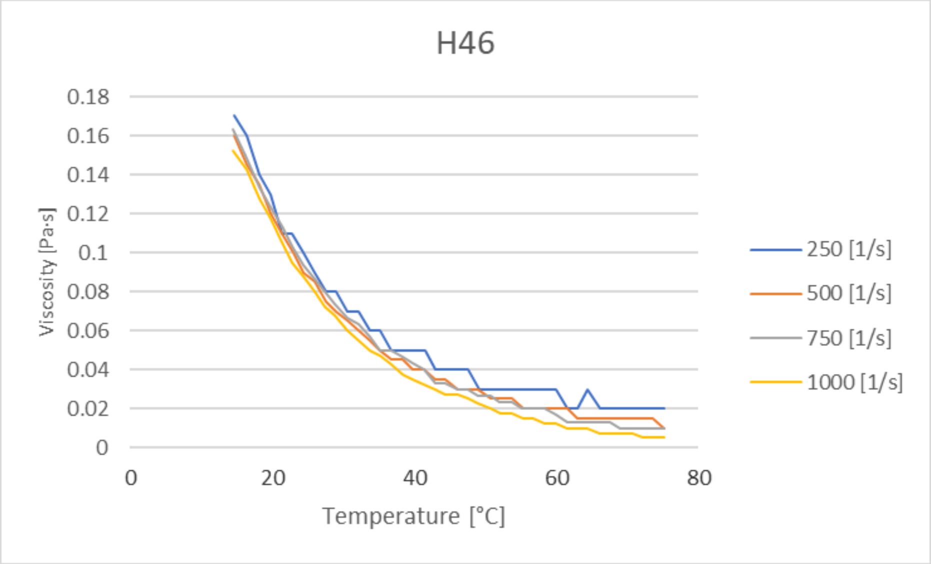

Fig. 4. Variation of the apparent viscosity as a function of the temperature of the H46 mineral hydraulic oil

Fig. 5. and Fig. 6. shows the variation of the apparent viscosity with the temperature of the biodegradable hydraulic oils at four different shear rates. Also, in this graph we can observe the same behavior of biodegradable oils as that of mineral oil, namely decreasing viscosity while the temperature increases. An observation for the biodegradable hydraulic oil HF-E46, is that the viscosity at shear rate of 750 s^{-1} and 1000 s^{-1} tend to have the same shape.

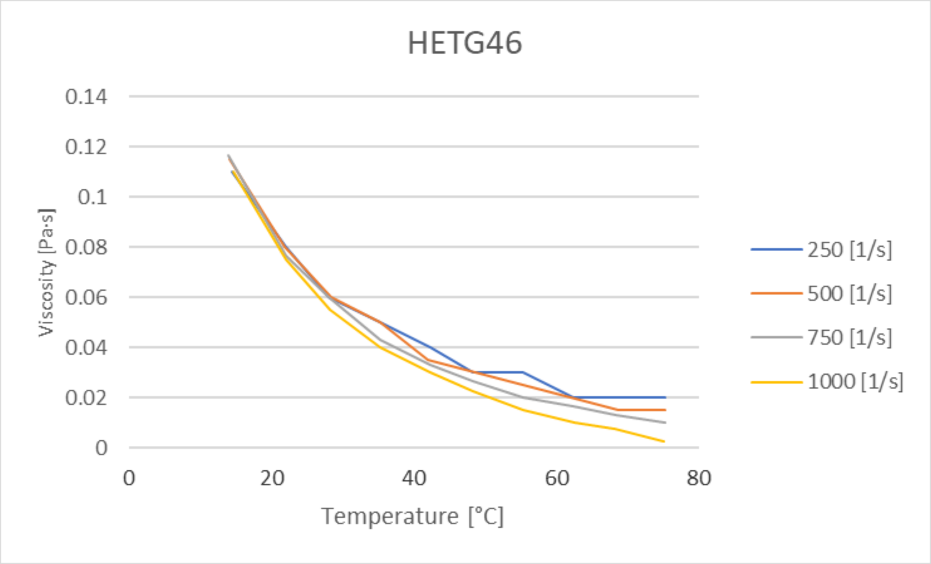

Fig. 5. Variation of apparent viscosity with temperature of HETG46 biodegradable oil

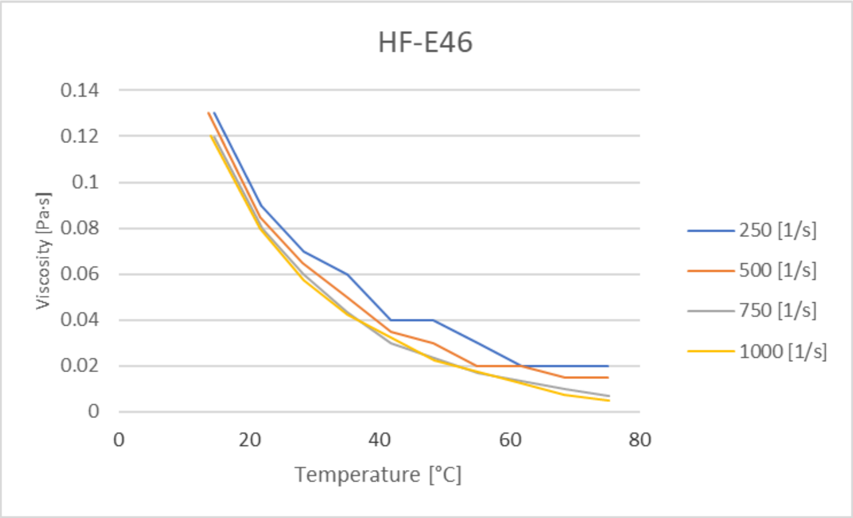

Fig. 6. Variation of apparent viscosity with temperature of HF-E46 biodegradable oil

Table 3, Table 4, and Table 5 shows the results of the thermal rheological parameters of the hydraulic lubricants, according to the Jarchov and Theissen, Cameron and Reynolds thermal models.

Tabel 3: Characteristic parameters of H46 hydraulic oil using the three thermal models

Parameter / **Shear rate, s^{-1}**	**Jarchov and Theissen model**			**Cameron model**			**Reynolds model**		
	η_{50}, [Pa·s]	***B***	**Corr. Coef [%]**	***K*, [Pa·s]**	***b*, [°C]**	**Corr. Coef [%]**	**η_{50}, [Pa·s]**	**m, [°C^{-1}]**	**Corr. Coef [%]**
250	0.030	4.745	99.17	$3.038 \cdot 10^{-4}$	688.21	99.17	0.030	0.039	96.71
500	0.025	5.549	99.80	$1.061 \cdot 10^{-4}$	804.74	99.80	0.025	0.045	98.41
750	0.027	6.245	99.30	$0.479 \cdot 10^{-4}$	905.55	99.30	0.027	0.048	99.51
1000	0.020	7.319	98.21	$0.480 \cdot 10^{-4}$	905.53	99.31	0.020	0.057	99.89

Tabel 4: Characteristic parameters of HETG46 hydraulic oil using the three thermal models

Parameter / **Shear rate, s^{-1}**	**Jarchov and Theissen model**			**Cameron model**			**Reynolds model**		
	η_{50}, [Pa·s]	***B***	**Corr. Coef [%]**	***K*, [Pa·s]**	***b*, [°C]**	**Corr. Coef [%]**	**η_{50}, [Pa·s]**	**m, [°C^{-1}]**	**Corr. Coef [%]**
250	0.030	3.832	99.49	$6.808 \cdot 10^{-4}$	555.64	99.49	0.030	0.031	97.62
500	0.025	4.403	99.70	$3.418 \cdot 10^{-4}$	638.38	99.70	0.025	0.036	98.96
750	0.020	5.037	99.65	$1.538 \cdot 10^{-4}$	730.31	99.65	0.020	0.042	99.52
1000	0.015	7.076	96.28	$0.130 \cdot 10^{-4}$	1026.10	96.28	0.015	0.058	99.36

Tabel 5: Characteristic parameters of HF-E46 hydraulic oil using the three thermal models

Parameter / **Shear rate, s^{-1}**	**Jarchov and Theissen model**			**Cameron model**			**Reynolds model**		
	η_{50}, [Pa·s]	***B***	**Corr. Coef [%]**	***K*, [Pa·s]**	***b*, [°C]**	**Corr. Coef [%]**	**η_{50}, [Pa·s]**	**m, [°C^{-1}]**	**Corr. Coef [%]**
250	0.030	4.219	99.17	$4.950 \cdot 10^{-4}$	611.72	99.19	0.030	0.035	98.18
500	0.020	4.710	99.72	$2.464 \cdot 10^{-4}$	682.96	99.72	0.025	0.041	99.00
750	0.017	6.001	98.99	$0.491 \cdot 10^{-4}$	870.07	99.89	0.017	0.050	99.89
1000	0.018	6.404	98.00	$0.299 \cdot 10^{-4}$	1135.30	99.89	0.018	0.052	99.84

Analyzing the results from the tables, we can observe that all three proposed models are effective in approximating the variation of apparent viscosity as a function of temperature, showing correlation coefficients of over 96%.

Fig. 7. present the comparative results between the viscosity determined experimentally and the theoretical one according to the three thermal models. For this oil, we can observe that there are no noticeable differences between the experimentally determined viscosity and the theoretical ones.

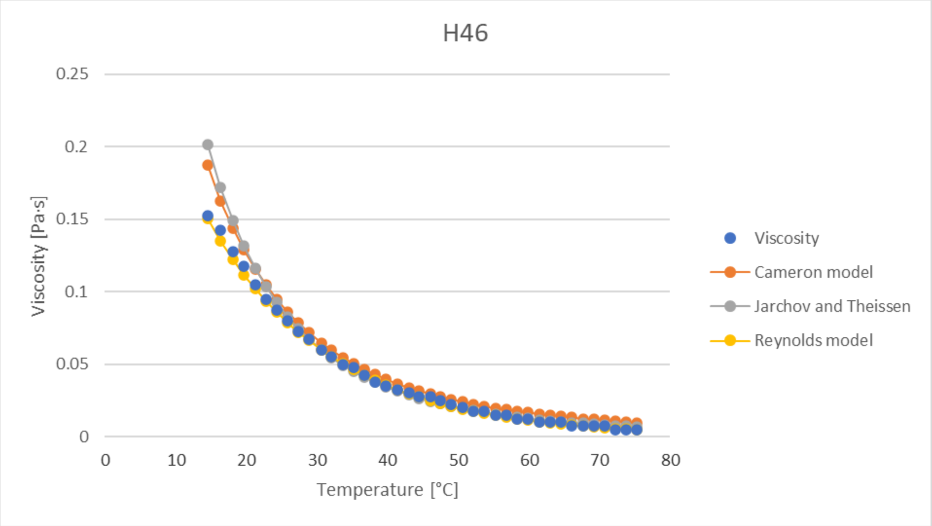

Fig. 7. Comparative results between the theoretical viscosity curves and the experimental ones for H46 mineral hydraulic oil

Fig. 8. and Fig. 9. present the comparative results between the viscosity determined experimentally and the theoretical one according to the three thermal models. For these biodegradable oils, we can observe that there are small differences between the experimentally determined viscosity and the theoretical one, considering the Cameron and Jarchov and Theissen thermal models.

Another observation is that the viscosity determined using the Reynolds thermal model has the same shape as the experimentally determined viscosity.

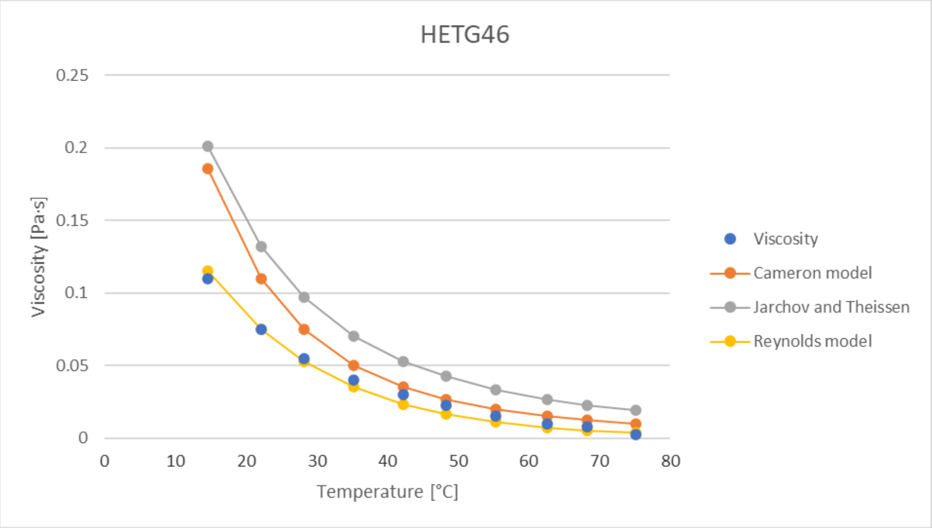

Fig. 8. Comparative results between the theoretical viscosity curves and the experimental ones for the biodegradable hydraulic oil HETG46

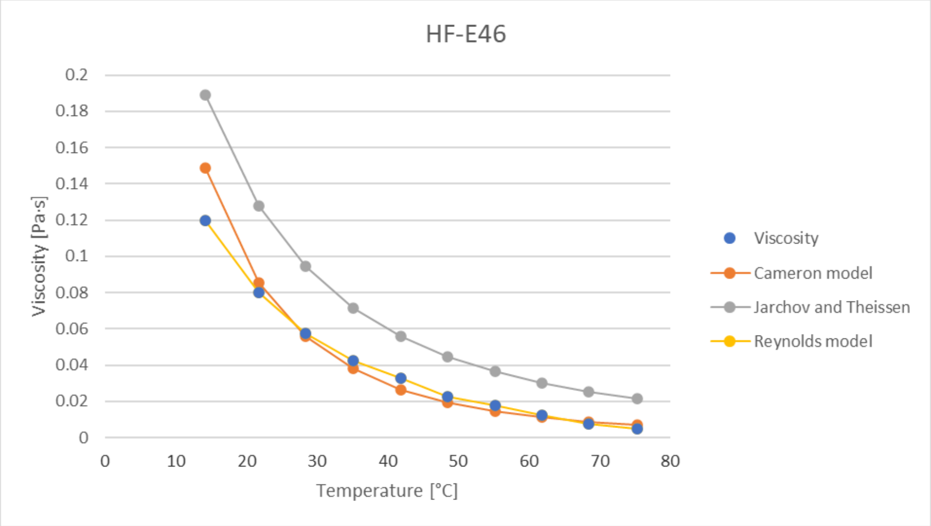

Fig. 9. Comparative results between the theoretical viscosity curves and the experimental ones for the biodegradable hydraulic oil HF-E46

Fig. 10., Fig. 11., Fig. 12. and Fig. 13. show the rheological parameters of the thermal models Reynolds (Fig. 10.), Jarchov and Theissen (Fig. 11.) and Cameron (Fig. 12. and Fig. 13) according to the shear rates at which they were tested hydraulic oils, obtained with the help of numerical regression.

For the Reynolds thermal model, the rheological parameter is "m", for the Jarchov and Theissen thermal model, the rheological parameter is "B", and for the Cameron model the rheological parameter is "b". These are the temperature parameters that indicate us the increase in temperature with the increase in shear rate.

Also, for the Cameron thermal model, we have another rheological parameter noted by "K" and which is a viscosity parameter. As can be observe from Fig. 13., this parameter decreases with the increase of the shear rate.

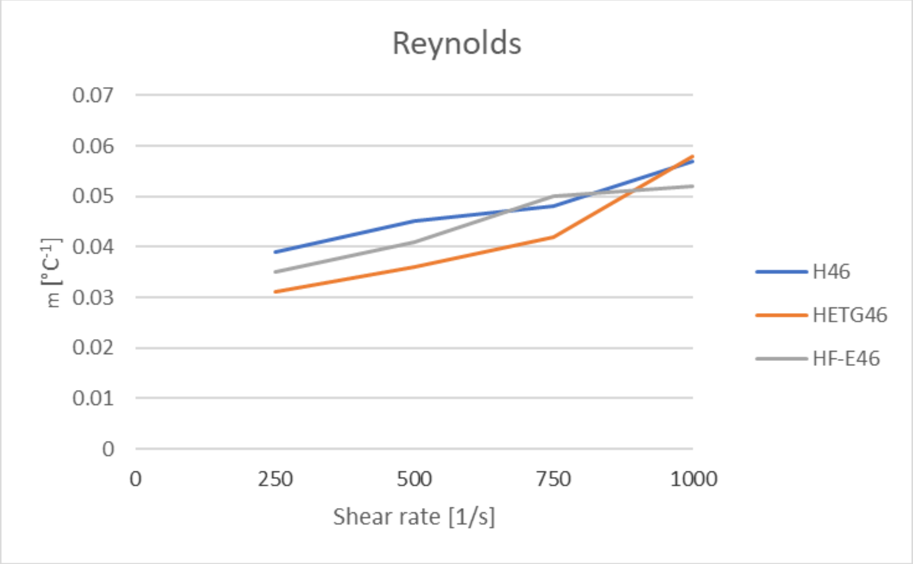

Fig. 10. Variation of the rheological parameter of the Reynolds thermal model depending on the shear rate for the three hydraulic oils

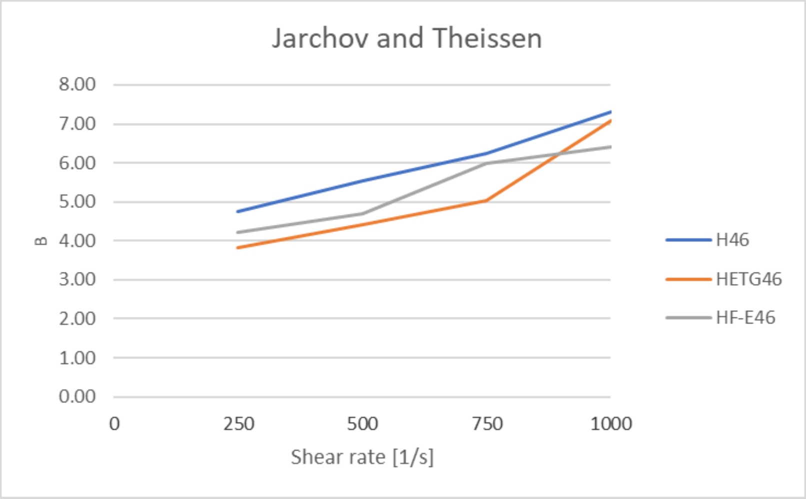

Fig. 11. Variation of the rheological parameter of the Jarchov and Theissen thermal model depending on the shear rate for the three hydraulic oils

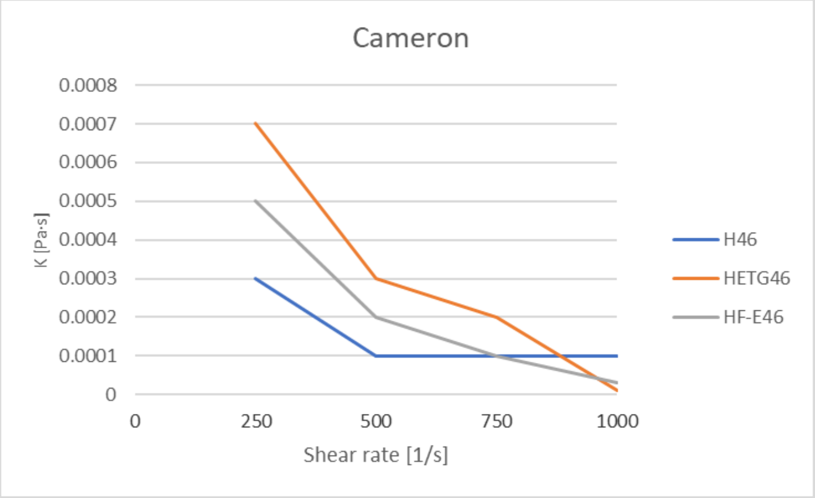

Fig. 12. Variation of the rheological viscosity parameter of the Cameron thermal model as a function of shear rate for the three hydraulic oils

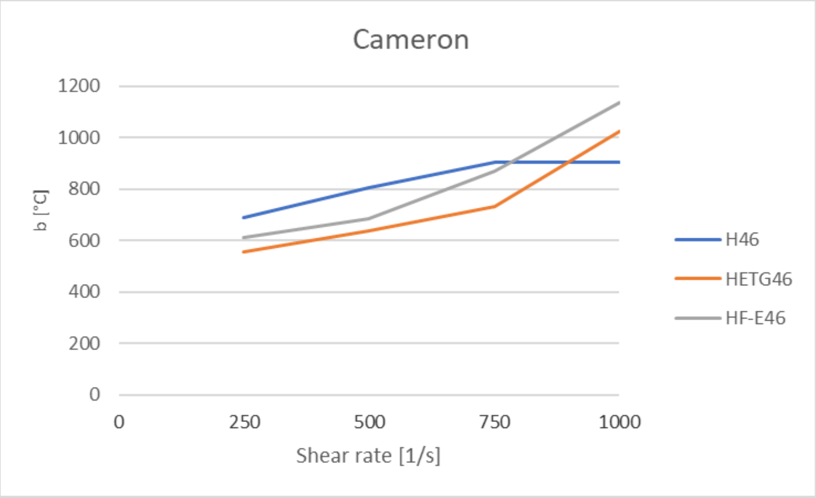

Fig. 13. Variation of the temperature rheological parameter of the Cameron thermal model as a function of shear rate for the three hydraulic oils

5. Conclusion

From a rheological point of view, it was found that:

- Biodegradable oils HF-E46 and HETG46 demonstrate significantly reduced thixotropy when compare with hydraulic oil H46, which exhibits exceptionally high thixotropy.
- The apparent viscosity of the biodegradable oil HF-E46 is higher than that of the biodegradable oil HETG46, and lower than the hydraulic oil H46, where its slope is higher, indicating a higher viscosity;

Analyzing the experimental data presented in table 1, table 2, and table 3 reveals a decrease in the apparent viscosity of hydraulic lubricants concerning the shear rates. For all three lubricants tested, the oil viscosity decreases with the increase of the shear rate, which means that they have a normal behavior.

Regarding the variability of apparent viscosity with temperature, three theoretical models have been proposed to model the experimental results. All these models fit in approximating the viscosity variation, as they have correlation coefficients exceeding the 96% threshold. However, among the three proposed thermal models, the Cameron relation shows correlation coefficients above 99%.

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References

[1] Marcotte, M., A. R. Taherian, M. Trigui, and H. S. Ramaswamy. “Evaluation of rheological properties of selected salt enriched food hydrocolloids.” *Journal of Food Engineering* 48, no. 2 (May 2001): 157–167.
[2] Wan Nik, W. B., F. N. Ani, H. H. Masjuki, and S. G. Eng Giap. “Rheology of bio-edible oils according to several rheological models and its potential as hydraulic fluid.” *Industrial Crops and Products* 22, no. 3 (November 2005): 249–255.
[3] Rădulescu, Alexandru Valentin, Corneliu Bălan, and Irina Rădulescu. “Thermal regression models for the rheological parameters of lubricants.” Paper presented at International Science Conference of Material Science and Manufacturing Technology (MiTech), Prague, Czech Republic, June 26-27, 2007.
[4] Lefebvre, Aline, and Bertrand Maury. “Apparent viscosity of a mixture of a Newtonian fluid and interacting particles.” *Comptes Rendus Mécanique* 333, no. 12 (December 2005): 923–933.
[5] AMETEK Brookfield.“BROOKFIELD CAP2000+, Viscometer Operating Instructions.” Accessed November 17, 2023. http://www.brookfieldengineering.com.
[6] Nuto™ H Series Mobil. “H46 Hydraulic Oils - Product Data Sheets”. https://www.mobil.com/en/lubricants/for-businesses/industrial/lubricants/products/products/nuto-h-46#lightbox-pdsdatasheet.
[7] Kajo. “Kajo-Bio-Hydrauliköl HETG 46.” https://www.lubricon.com.au/product/biodegradable-lubricants/bio-hydraulic-oil/kajo-bio-hydraulikol-hetg-46/.
[8] Shell plc. “Shell Naturelle HF-E 46.” https://shop.sclubricants.com/pub/media/pds/shell/Shell-Naturelle-Fluid-HF-E-46-datasheet.pdf.
[9] Teleașă, Andreea Mirela, and Alexandru Valentin Rădulescu. “Experimental Analysis of the Rheological Properties of Hydraulic Oils.” *Acta Technica Napocensis* (2023) - publication in progress.