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RHEOLOGICAL BEHAVIOR OF BIODEGRADABLE FLUIDS USED IN HYDRAULIC POWER INSTALLATIONS

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Abstract: *This paper presents the rheological properties for two hydraulic fluids: a hydraulic fluid based on mineral oils (H46) and a biodegradable hydraulic oil based on vegetable oils (HETG46). From a rheological point of view, the models used for these tests were the Newtonian model and the power law model, and from a thermal point of view, the model used is the Reynolds model.*
The tests were carried out with the help of the BROOKFIELD CAP 2000+ stand and the interpretation of the results was done with the help of the CAPCALC32 calculation program.
Following the experimental results, we can conclude that the biodegradable hydraulic fluid HETG46 has the same rheological behavior as the mineral fluid H46, but a viscosity reduced by approx. 20% For both fluids, the thermal Reynolds model of viscosity variation with temperature is found to approximate the experimental values with the same accuracy, leading to correlation coefficients greater than 96%.

Keywords*: rheology, hydraulic fluids, Newtonian model, power law model, viscosity*

1. Introduction

Lubricants are usually petroleum-based products and are considered to be a source of new carbon dioxide through their extraction, production and post-use in components and equipment. With global demand for lubricants expected to continue growing at an estimated annual rate of 2.6% through 2015, the importance of reducing environmental impact becomes apparent [1].

2. Hydraulic lubricants

Hydraulic lubricants play a critical role in the operation and performance of hydraulic systems [2]–[4]. In addition to viscosity and oxidative and thermal stability, hydraulic lubricants must protect pumps from wear and enable uninterrupted operation of actuators and valves. In addition, hydraulic oils must perform adequately at high temperatures and pressures; perform to tight tolerances, especially in advanced hydraulic systems; be compatible with a variety of metals and elastomers; protect different types of pumps from wear (piston, gear, vane, etc.); and operates in the presence of moisture that may contaminate the system. In certain operations, hydraulic oils must also be fire resistant [1].
Standard specifications for hydraulic fluids and components serve an important function in the fluid industry. Fluid standards validate the safety, durability, compatibility, cleanliness and functionality of hydraulic fluids [5]. The primary purpose of a hydraulic fluid is power transfer. The concept of fluid power is based on a principle articulated by Blaise Pascal, which is given as follows: "The pressure applied to an enclosed fluid is transmitted undiminished to every portion of that fluid and to the walls of the containing vessel" [6]. In the context of fluid power, pressure is related to the force acting on an enclosed fluid. This principle gave birth to the modern hydraulic system, which involves highly engineered systems for efficiently controlling fluid flow to transfer energy and accomplish work [5].
The heart of any hydraulic system is the pump, which draws fluid through its inlet and forces fluid through its outlet, usually against the pressure created by valves, plumbing, and actuators downstream of the pump. Pumps, actuators, and other system components have surfaces that

move relative to each other, often at high speeds, pressures, and temperatures. These components require cooling and lubrication for efficient performance and durability. Consequently, hydraulic fluids not only transmit power, but also have a critical function as a lubricant and heat transfer medium [5].

Most hydraulic fluids consist of a base fluid and a combination of additives that have been optimized to impart chemical characteristics and functionality to the finished product. Operating conditions and equipment manufacturer specifications generally dictate the type of fluid that is required and therefore the type of base stocks and additives that must be used [5].

2.1 Mineral oils

It is not known when mineral oil was first produced, but as a petroleum derivative, it must have been after the discovery of crude oil, but even that has already been known for thousands of years. Mineral oil is known by many different names. The reason for this is probably historical, as the product was created long before the common nomenclature was implemented. Synonyms include heavy mineral oil, light mineral oil, liquid paraffin, liquid petroleum jelly, mineral oil mist, paraffin oil, paraffinum liquidum, liquid petroleum jelly, petroleum oil, white mineral oil, and white oil. This is a complex mixture of highly refined saturated branched chain naphthenic hydrocarbons [7].

2.2 Vegetable oils (biodegradable)

Biodegradable hydraulic fluids are currently formulated with renewable products such as rapeseed, sunflower, corn, soybean and canola or synthetic ester. These types of fluids are now considered less toxic and more biodegradable than conventional hydraulic fluids.

Vegetable oils have excellent lubricating qualities, are non-toxic and biodegradable. Their chemical structures are triglycerides in which a variety of saturated, monounsaturated, or polyunsaturated fatty acids are esterified to a glycerol backbone. The physical properties of a vegetable oil depend on the nature of its fatty acid composition. These oils tend to oxidize at temperatures above 90°C and have a shorter life compared to conventional petroleum-based fluids [5].

3. Experimental procedure

3.1 The experimental stand and the mathematical models used

The experimental test stand is a Brookfield CAP 2000+ viscometer, shown in Fig. 1. This is a viscometer that measures the flow behavior of fluids and the viscosity of both liquid and semi-solid materials, using the cone-plane coupling as working geometry, shown in Fig. 2.

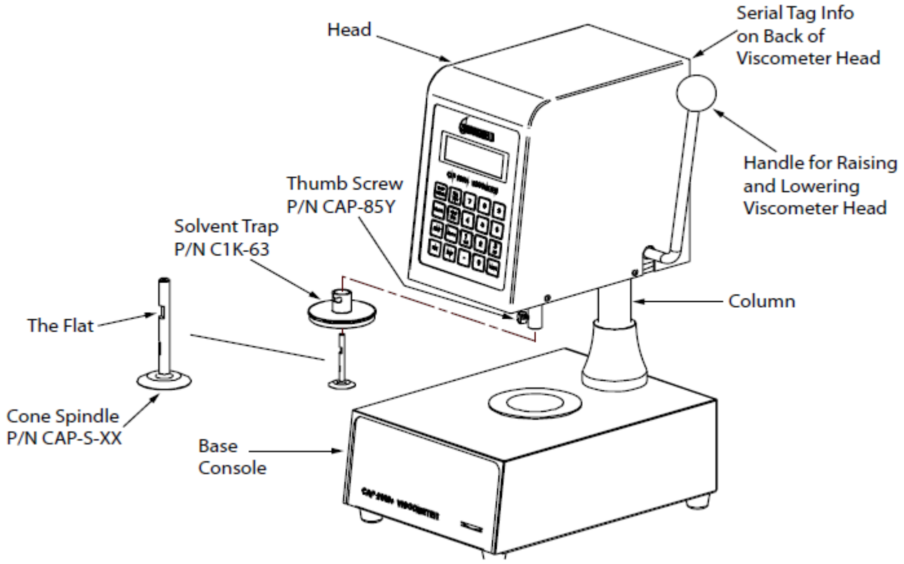

Fig. 1. Cone-plate Brookfield viscometer

Fig. 2. Work geometries

Table 1 shows the characteristics of the cones used at the Brookfield stand. In our case, the cone used is no. 8, characterized by a diameter of 15.11 mm and an angle of 3°.

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

To highlight the thixotropy of the fluids, a loading test was carried out starting from the minimum velocity gradient to a maximum velocity gradient, from where its discharge begins. The temperature range at which the tests were performed was 20-75°C.

From a rheological point of view, the models proposed to determine the rheological properties and to describe their behavior are:

- Newtonian model:

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

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

- Power Law model:

$$\tau = m \cdot \dot{\gamma}^{n}, \tag{2}$$

Where “m” and “n” are material constants, τ is shear stress, $\dot{\gamma}$ is shear rate, m- consistency index, n- flow index

From a thermal point of view, the proposed model is:

- Reynolds model:

$$\eta = \eta_{50} \cdot e^{-m(t-50)}, \tag{3}$$

Where η- dynamic viscosity of the fluid at temperature, η_{50}- viscosity at a temperature of 50°C, m- coefficient of variation of viscosity with temperature, t- temperature, 50- reference temperature.

3.2 The oils used

In this work, the oils used were [8]:

- H46 - It is a mineral oil that has been used as a benchmark. It has a density of 871 kg/m^3, and the kinematic viscosity at 40°C is between 41.4 - 50.6 cSt.
- HETG 46 - It is a hydraulic fluid based on vegetable oils, slightly biodegradable, environmentally friendly. The additives used provide excellent properties related to resistance to oxidation, corrosion, low temperature and extreme pressure. The density is 918 kg/m^3, the kinematic viscosity at 100ºC is 10 cSt.

3.3 Results

A change of the rheological properties induced by temperature or deformation in the structure of fluids refers to the phenomenon of thixotropy (thermal or deformation hysteresis). The phenomenon consists in the fact that the relationships between apparent viscosity and temperature or the velocity gradient measured when one of these parameters increases or decreases are not identical [9].

Figure 3 and Figure 4 show the variation of the tangential stress depending on the shear rate at a temperature of 20°C for H 46 and HETG 46 hydraulic fluids.

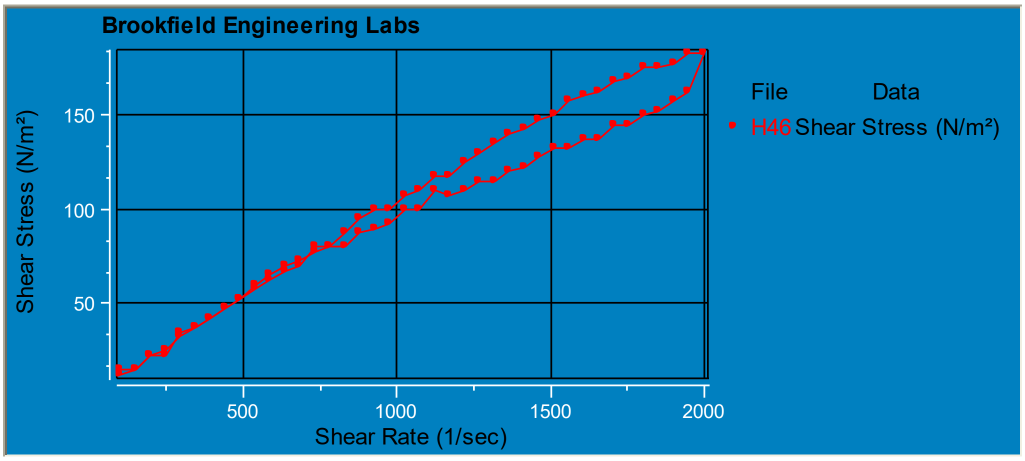

Fig. 3. Variation of the tangential stress versus shear rate at temperature of 20°C for the hydraulic oils H 46

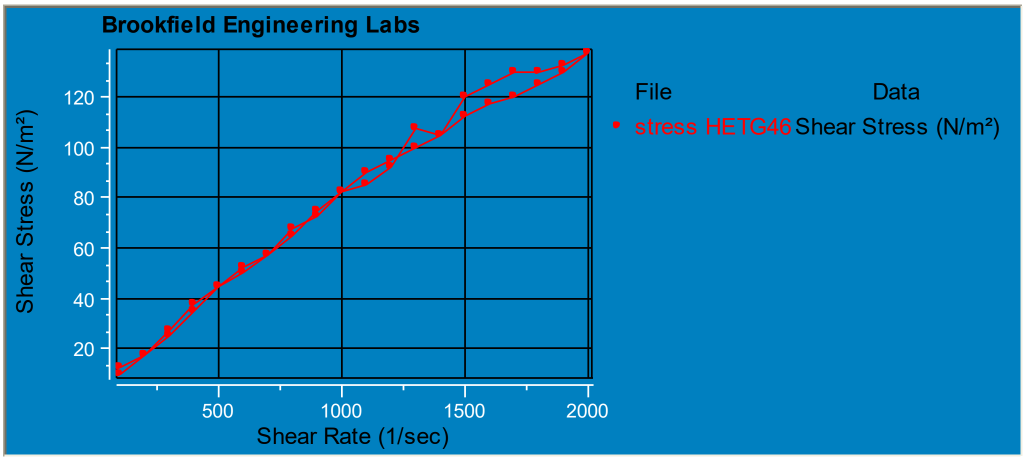

Fig. 4. Variation of the tangential stress versus shear rate at temperature of 20°C for the hydraulic HETG 46

For both fluids, the variation of viscosity with temperature at different speed gradients can be done in the area of speed gradients from 0 to 1000 s^{-1}, an area where the thixotropy of the lubricant is negligible (the hysteresis loop does not exist).

If the velocity gradient exceeds 1000 s^{-1}, thixotropy becomes much more obvious, which implies a limitation of the velocity gradient range on which the experimental determination of the viscosity variation with temperature will be made.

Figure 5 shows the comparison of the two hydraulic fluids based on the variation of the tangential stress and the shear rate.

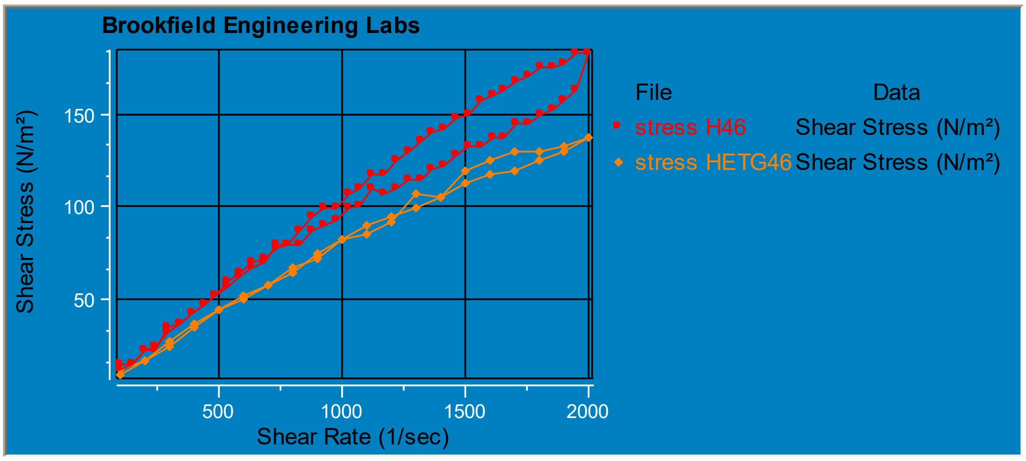

Fig. 5. Comparison of the two hydraulic fluids based on the variation of the tangential stress and the shear rate

Analyzing the two curves, we can see that the H46 fluid has a higher slope and the thixotropy is much more pronounced than that of the HETG46 fluid, which means that the viscosity of the H46 fluid is higher than that of the HETG46 fluid, where the slope and thixotropy are lower.

From the point of view of homogeneity, we can say that HETG46 fluid is much more stable than H46 because its thixotropy is very low.

Figure 6 and Figure 7 show the rheograms of H46 and HETG 46 hydraulic fluids at a temperature of 20°C using the power law rheological model. These were performed using the numerical regression of the experimental data, using CAPCALC 32 software, to determine the rheological parameters under the assumption of power law model variability.

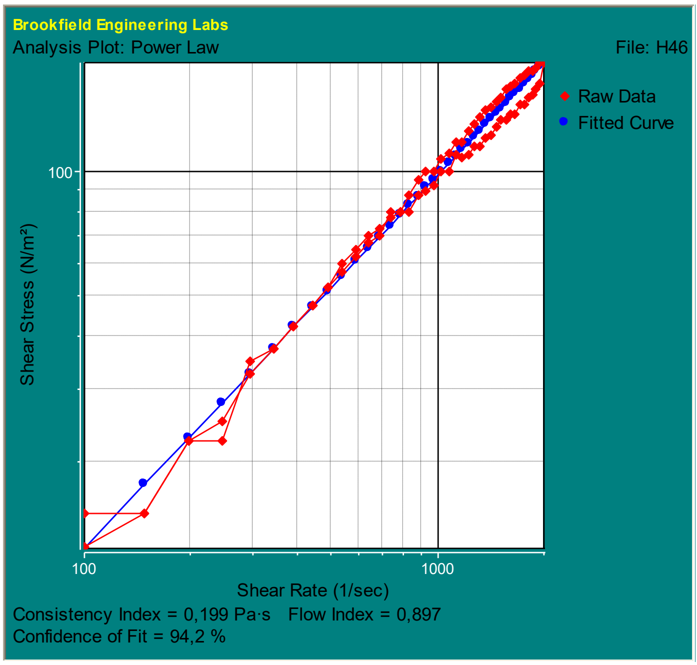

Fig. 6. Rheogram of hydraulic fluids H46 at a temperature of 20°C using the power law rheological model

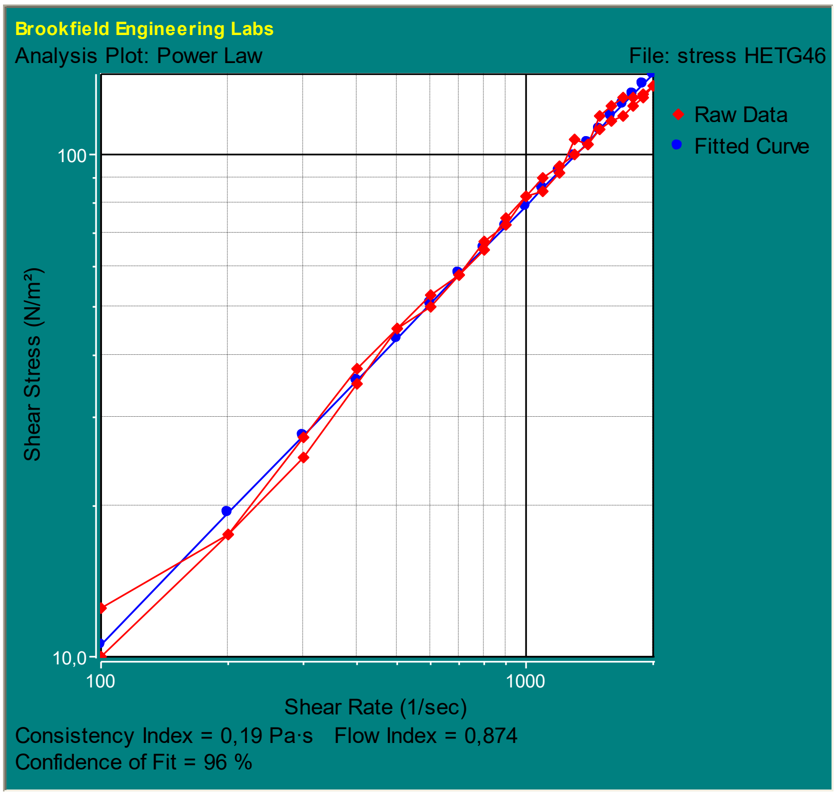

Fig. 7. Rheogram of hydraulic fluids HETG 46 at a temperature of 20°C using the power law rheological model

Figure 8 and Figure 9 show the variation of viscosity with temperature at four speed gradients (125 s^{-1}, 250 s^{-1}, 375 s^{-1}, 500 s^{-1}) for the two fluids. The observation we can make about the H46 fluid is that the viscosity decreases with the increase of the velocity gradient, where we can say that we have a strong pseudoplastic behavior. For the HETG 46 biodegradable fluid, this is a little obvious.

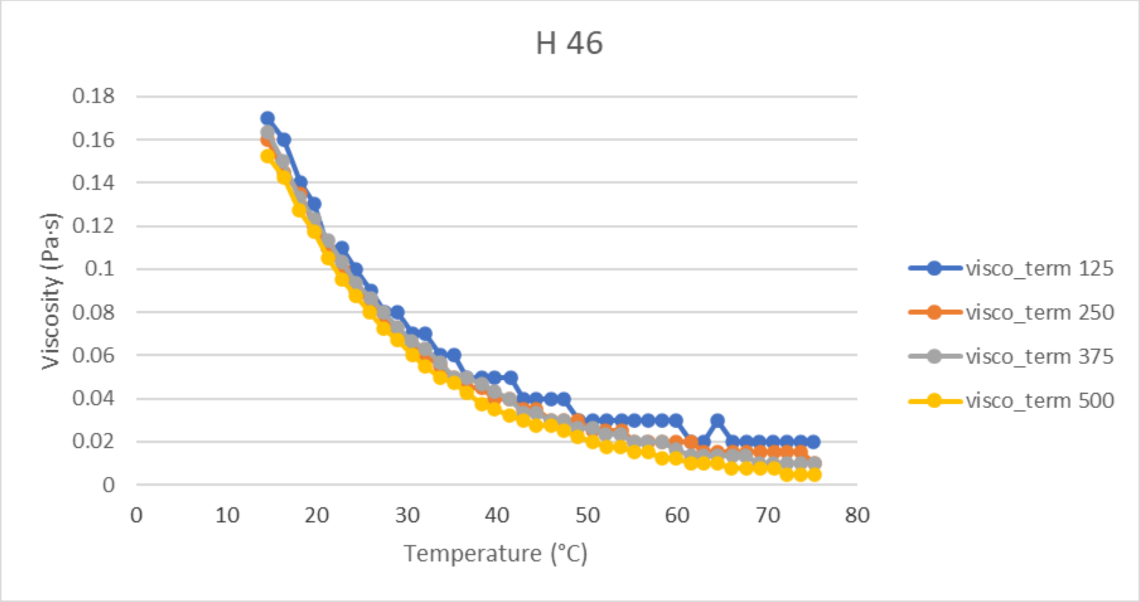

Fig. 8. Variation of the viscosity versus temperature for hydraulic oils H46

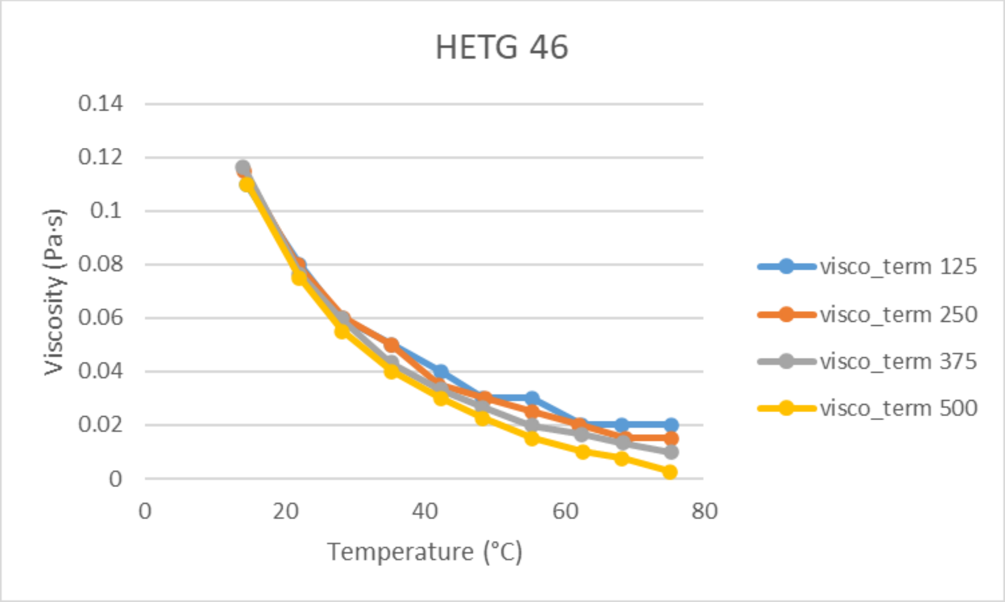

Fig. 9. Variation of the viscosity versus temperature for hydraulic oils HETG 46

Table 2 shows the parameters of the Reynolds model corresponding to the four viscosity variations for the two fluids. The observation we can make about these results is that the viscosity at the temperature of 50°C and the temperature coefficient decrease with the increase of the velocity gradient.

Table 2: Characteristic parameters for the variation of viscosity as a function of temperature using the Reynolds model for hydraulic fluids

Parameters **Shear rate [1/s]**	**H 46**		
	$\eta_{50^\circ}[Pa \cdot s]$	**Temperature parameter,** m[°C^{-1}]	**Correlation coefficient,** ρ[%]
125	0.030	-0.039	96.71
250	0.025	-0.045	98.40
375	0.027	-0.048	99.51
500	0.020	-0.057	99.89
Parameters **Shear rate [1/s]**	**HETG 46**		
125	0.030	-0.031	97.62
250	0.025	-0.034	98.64
375	0.020	-0.037	98.93
500	0.015	-0.049	99.83

4. Conclusions

The aim of the work is to test the two hydraulic fluids (mineral oil and biodegradable oil) from a rheological point of view.
Regarding the rheological models, the most appropriate is the Newtonian model, which has a correlation coefficient over 98%.
Both oils show a high correlation coefficient of up to 95% for the power law model.
Following the experimental results, we can conclude that the biodegradable hydraulic fluid HETG46 has the same rheological behavior as the mineral fluid H46, but a reduced viscosity with approx. 20%
For both fluids, it is found that the Reynolds thermal model of viscosity variation with temperature approximates the experimental values with the same accuracy, leading to correlation coefficients higher than 96%.

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