TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special IV, August, 2024

RHEOLOGICAL RESEARCH REGARDING INTERNAL COMBUSTION ENGINES OILS

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Abstract: *The purpose of this work is to study the degradation of lubricants used in internal combustion engines, using experimentally determined measurements of rheological parameters, namely, viscosity, flow index, consistency index, as well as the variation of apparent viscosity with temperature.*
Proper lubrication of the internal combustion engine is fundamental to minimize energy loss and wear, helping to increase fuel efficiency and extend engine life. One of the most important characteristics influencing the flow behavior of substances is viscosity. Changes in pressure and temperature can alter oil viscosity, and these changes are critical to the properties of the oil as it is used in the engine. Viscosity has a significant impact in the engine lubrication process because, with its help, we reduce the friction between the surfaces and after the friction, we avoid wear, and it can also register increases or decreases during the operation of the engine.
The tested oils in this work are BMW 5W30 and Castrol 5W30 engine oils, both fresh and used state, after a mileage of 10000 km for the first car and 12000 km for the second one. These were tested using the Brookfield CAP2000+ rotary cone and plate viscometer.
Key words: *Oil, Rheology, Thermal, Degradation, Viscosity*

1. INTRODUCTION

In tribology, lubrication has an important role, namely, to reduce friction and wear between the two surfaces in contact, to maintain a viscoelastic behavior and to maintain an efficient heat transfer, because lubricants have good thermal conductivity properties. Most of the lubricants used in industry are in a liquid state, such as mineral oils, synthetic oils, vegetable oils, water, etc. For machines, tools, vehicles to have a long life, it is important to choose the right lubricant. The choice of lubricant is made according to its properties, the lubrication method of the used machine, the working conditions, and its cost [1]. Properties such as viscosity, density or level of acids and bases are significant for their general applicability. The rise in viscosity is attributed to the products of condensation and polymerization reactions occurring under high thermal stress in the oil, along with the contributions of oxidation products. It has been found that soot produced in the engine can lead to the formation of hard sludge, increased viscosity of the lubricant or gelling of the oil. Generally, insoluble sludges do not result in a substantial increase in viscosity when the soot particles are dispersed individually due to the presence of dispersing additives. However, introducing lubricant-insoluble soot particles into the piston ring area can increase viscosity [2].

The flow behavior is also important and is influenced by the rheology of the oils, which can be Newtonian or non-Newtonian depending on the molecular mass. In some studies, it has been found that non-Newtonian behavior can improve load carrying capacity and reduce friction under certain conditions. Engine oils exhibit viscoelasticity under non-Newtonian flow conditions, which affects their viscosity and performance. Consequently, the physico-chemical properties, rheological and tribological behavior of motor oils are closely interconnected, influencing the optimal functioning of mechanical systems and vehicles [3], [5]. The composition of engine lubricants is influenced by changes in industry standards, OEM requirements and consumer requirements. These standards are often imposed by vehicle emissions legislation, which often requires the use of new technologies in engines. The challenges encountered in the manufacture of lubricants due to new technologies are reflected in engine performance tests and laboratory tests according to industry standards [5]. Lubricants are essential in the operation of motor vehicles, mainly engine oils that protect and reduce wear and tear on the components that come into contact with internal combustion engines. They not only reduce friction and wear, but also control the heat generated in engines [4].

Several methods are used to test the degree of wear of an oil (FTIR spectroscopic analysis, acidity analysis, alkalinity analysis, viscosity analysis, decontamination analysis and rheological study, etc.). The paper aims to identify a simple method for determining the degree of wear starting from the analysis of the rheological properties, but which is only the starting point for the complete analysis of the properties.

The purpose of this paper is to study the degradation of lubricants used in internal combustion engines, using experimentally determined measurements of rheological parameters, namely, viscosity, flow index, consistency index, as well as the variation of apparent viscosity with temperature.

From the performed tests, the variation of the shear stress with shear rate and the variation of the viscosity with the temperature were highlighted.

The variation of viscosity with shear rate gives us information about the rheological model of the lubricant which can be valid by extrapolation to very high-speed gradients specific to internal combustion engines. Shear rates specific to rheometers or viscometers are typically of the order of 10^{-3} to 10^{2} s^{-1} (for rheometers), and 1 to 10^{4} s^{-1} for viscometers.

2. MATERIALS AND METHODS

2.1 Materials

In the present work, two types of engine oils from two different cars were used, both in terms of brand and engine type and year of manufacture. The oil change was performed at 10000 km for the first car, which uses a BMW TPT 5W30 LL 04 type oil, and for the second car, the oil was changed at 12000 km, using a Castrol type oil 5W30.

The two cars have driven approximately close distances (the first car 10000 km, the second car 12000 km) under normal conditions of use and their engines have been regularly tested and checked during annual inspections. After carrying out the annual periodic technical inspection (ITP), the engines successfully respected the normal limits of wear and emissions in the environment. However, it is important to emphasize that this result does not provide an absolute guarantee regarding the similarity of other aspects of the performance or technical condition of the cars.

2.2 Methods

The rheological tests were carried out using the Brookfield Cap 2000+ viscometer, which can measure viscosity in a varied range of temperature and speed conditions, to numerically process the results using the CAPCALC32 software. The oil is inserted between the rotating cone and the stationary disk. The main quality of this equipment is to maintain a constant rate of deformation throughout the slot, even at large opening angles of the cone.

In the case of rheological tests, the cone used is number 3, having the following characteristics: cone radius 9.53 mm; cone angle 0.45°; shear rate 66 ... 13333 s^{-1}.

To determine the rheological behavior, the Ostwald-de Waele model (eq 1) and the Newtonian model (eq 2), were proposed.

$$\tau = m\left(\frac{du}{dy}\right)^{n} \tag{1}$$

Where τ is shear stress [Pa], m is consistency index, n is flow index and $\frac{du}{dy}$ is shear rate [s^{-1}].

$$\tau = \eta \frac{du}{dy} \qquad (2)$$

Where τ is shear stress [Pa], η is viscosity [Pa·s] and $\frac{du}{dy}$ is shear rate [s^{-1}].

To determine the variation of viscosity with temperature, an "imposed shear rate" type test was used, with a shear rate of 3333 s^{-1} and a temperature range between 20˚ and 75˚C. The experimental results obtained were processed numerically using the Reynolds model (eq 3).

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

Where η is fluid viscosity [Pa·s], η_{50} is viscosity at 50˚C [Pa·s], m is temperature parameter [˚C] and t is temperature [˚C].

3. RESULTS AND DISCUSSION

Figure 3.1 shows the rheogram of BMW 5W30 motor oil in both fresh and used state and Figure 3.2 presents the rheogram of Castrol 5W30 motor oil, also in fresh and used state. Using the rheometer calculation software (CAPCALC 32), the rheological parameters, namely oil viscosity, flow indices, and correlation coefficients, were obtained using eq. 1. Additionally, with the help of Excel software, the rheological parameters were obtained using eq. 2 for both oils in both states. All these results are presented in Table 3.1.

Analyzing the results from Table 3.1, it is observed that for both oils in both states, the Ostwald-de Waele model has correlation coefficients ranging between 96-98%, while the Newtonian model has correlation coefficients exceeding 99%. From this, it can be concluded that the Newtonian model best approximates the rheological behavior.

Another observation we can make regarding the Newtonian model is that the viscosity of the BMW 5W30 oil is approximately the same for it's two states, which means that from a rheological point of view this oil has not been exposed to degradation processes. For Castrol 5W30 oil, it is noted that the viscosity of the used oil is higher than that of the fresh oil.

The variation of viscosity with temperature of the oils used in internal combustion engines, are presented in Figure 3.3. In Figure 3.3 (a) the difference between the viscosity of fresh and used BMW 5W30 oil is insignificant. Figure 3.3 (b) we can see that, at a temperature of 20˚, there is a difference between the viscosities of fresh and used oil, but as the temperature increases, the difference between them tends to be smaller and smaller.

In Figure 3.1 and Figure 3.2, the appearance of the hysteresis loop is highlighted both during loading and unloading, thus suggesting the presence of thixotropy in the lubricant composition.

For the BMW 5W30 engine oil, in fresh and used states, thixotropy manifests at shear rates greater than 6000 s^{-1}, while for the Castrol 5W30 motor oil, thixotropy is observed at shear rates exceeding 5000 s^{-1}.

Considering that the slope of the obtained rheogram represents the apparent average viscosity of the lubricant, it can be observed that:

- for BMW 5W30 oil, the apparent average viscosity of the used oil increases by approximately 2% compared to the fresh one.
- for Castrol 5W30 oil, the apparent average viscosity of the used oil increases by approximately 21% compared to the fresh one. A possible explanation for this phenomenon is the effect of wear products that appear in the lubricant during the combustion process (decomposition of additives during operation, oxidation of the oil, wear, and degradation of engine components).

Table 3.2 presents the thermal parameters of BMW 5W30 and Castrol 5W30 oil using the Reynolds thermal model (eq 3). Analyzing the results, in terms of viscosity variation with temperature, the Reynolds model approximates very well the two states of the oils because it presents correlation coefficients of over 98%.

To obtain the graphs below, three sets of measurements data were used.

Table 3.1

Rheological parameters for BMW 5W30 and Castrol 5W30 oils

Type of oil	Wear degree	Newtonian model		Ostwald-de Waele model		
		Viscosity [Pa·s]	Corr. coeff. [%]	Consistency index [Pa·s^n]	Flow index	Corr. coeff. [%]
BMW 5W30	fresh	0.127	99.56	0.564	0.837	97.00
	used	0.129	99.56	0.744	0.806	96.70
Castrol 5W30	fresh	0.126	99.54	0.564	0.836	96.90
	used	0.152	99.63	0.700	0.833	98.40

Table 3.2

Thermal parameters according Reynolds model for BMW 5W30 and Castrol 5W30 oils

Type of oil	Wear degree	Reynolds model		
		Viscosity at 50°C [Pa·s]	Thermal coefficient [$°C^{-1}$]	Corr. coeff. [%]
BMW 5W30	fresh	0.045	0.034	98.17
	used	0.048	0.033	98.06
Castrol 5W30	fresh	0.048	0.033	98.22
	used	0.054	0.035	98.25

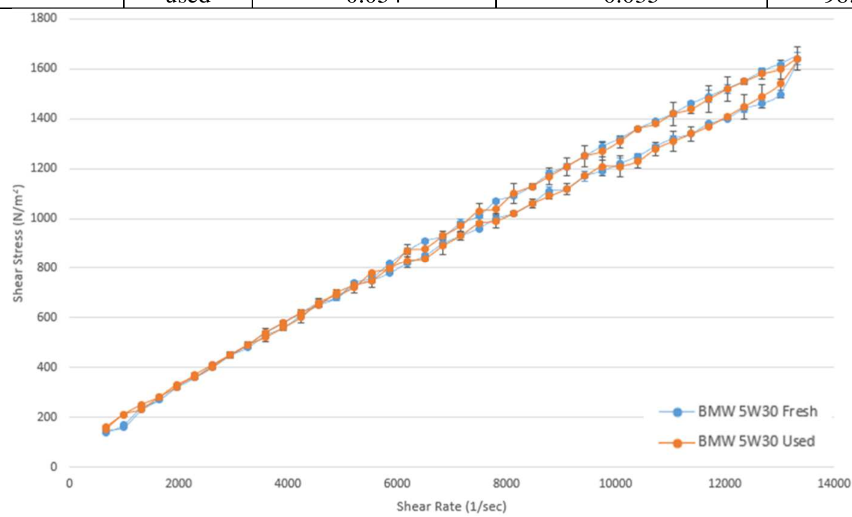

Fig. 3.1. Rheogram of BMW 5W30 internal combustion engine oil in fresh and used condition.

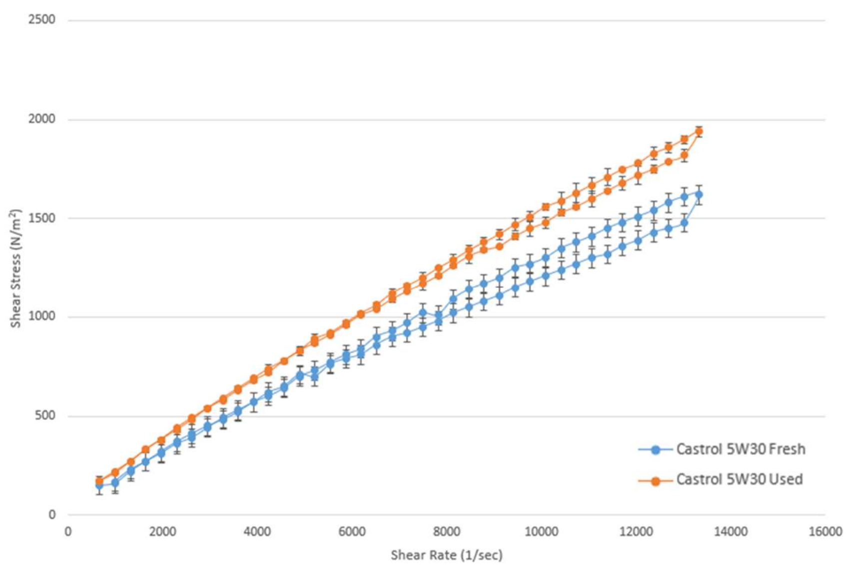

Fig. 3.2. Rheogram of Castrol 5W30 internal combustion engine oil in fresh and used condition.

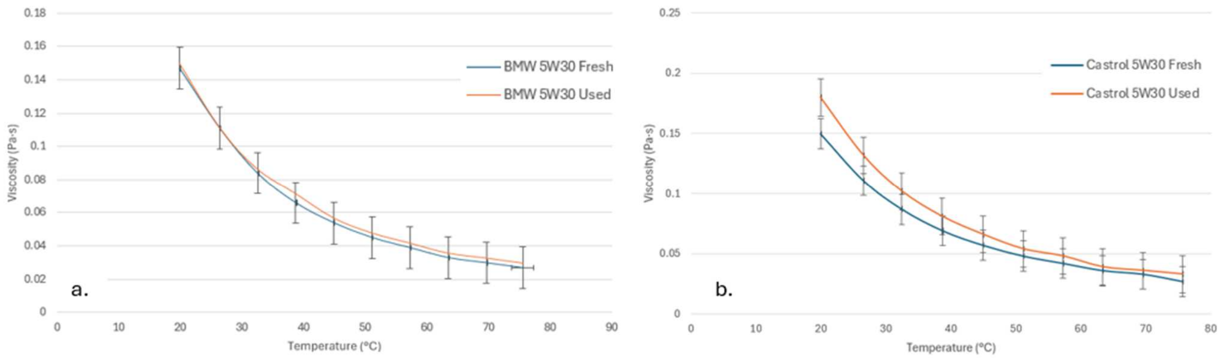

Fig. 3.3. Variation of viscosity with temperature of BMW 5W30 (a) and Castrol 5W30 (b) internal combustion engine oils in fresh and used condition.

4. CONCLUSION

In this work, two fresh and used engine oils BMW 5W30 and Castrol 5W30 were tested on the Brookfield Cap 2000+ viscometer. The oil change was performed for the first car at a mileage of 10 000 km using BMW 5W30 oil, and for the second one at 12 000 km using Castrol 5W30 oil.

Analyzing these results, it was determined that the rheological model that approximates most accurately the experimental results, is the Newtonian model, and from thermal point of view, Reynolds relation is the most appropriate for the variation of viscosity with temperature.

For lubricant BMW 5W30 there is almost no difference between fresh state and used state, both of them having the same viscosity for the whole range of the investigated shear rates and the same thermal rheological sssparameters.

Regarding the lubricant Castrol 5W30, there is a slight difference between the two states, observing that the viscosity of the used lubricant is always greater than for the fresh one, for any shear rate in the considered field. The same conclusion is valid for its thermal rheological parameters.

Castrol 5W30 used oil has a higher viscosity compared to it’s fresh state due to the appearance of certain substances resulting from chemical degradation, such as oxidation, nitration and especially sulphation processes. These chemical degradation products, unlike hydrocarbons, are polar in nature, which favors better adhesion of the lubricant to components requiring lubrication. Therefore, in some situations, used oils can provide more effective lubrication towards the end of the drain interval compared to fresh oils.

Regarding fresh internal combustion engine oils, it is observed that the dispersion of the results is approximately half that used ones, which is an indicator of the quality and degree of wear of the lubricant.

Both cars have been properly maintained with regular oil changes and periodic engine testing. The fact that both have passed their annual technical inspections with positive results suggests that they have been maintained in good working condition and have not suffered excessive wear or major technical problems. However, it is important to recognize that inspection results do not guarantee the identity of other aspects of the cars performance or technical condition, and ongoing monitoring and maintenance remain essential to keep vehicles running optimally.

5.ACKNOWLEDGMENT

"This work was supported by a grant from the National Program for Research of the National Association of Technical Universities - GNAC ARUT 2023".

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CERCETĂRI REOLOGICE PRIVIND ULEIURI DE MOTOARE CU ARDERE INTERNĂ

Rezumat: Scopul acestei lucrări este de a studia degradarea lubrifianților utilizați la motoarele cu ardere internă, utilizând măsurători determinate experimental ale parametrilor reologici și anume, vâscozitatea, indicele de curgere, indicele de consistență, precum și variația vâscozității aparente cu temperatura. Ungerea corectă a motorului cu ardere internă este fundamentală pentru a minimiza pierderile de energie și uzura, contribuind la creșterea eficienței combustibilului și la prelungirea duratei de viață a motorului. Una dintre cele mai importante caracteristici care influențează comportamentul în curgere a substanțelor este vâscozitatea. Schimbările de presiune și temperatură pot modifica vâscozitatea uleiului, iar aceste modificări sunt esențiale pentru proprietățile uleiului, așa cum este utilizat în motor. Vâscozitatea are un impact semnificativ în procesul de ungere a motorului deoarece, cu ajutorul ei, reducem frecarea dintre suprafețe iar după frecare evităm uzura, putând înregistra și creșteri sau scăderi în timpul funcționării motorului. Uleiurile testate în această lucrare sunt uleiuri de motor BMW 5W30 și Castrol 5W30, atât în stare proaspătă, cât și în stare uzată, după un kilometraj de 10000 km pentru prima mașină și 12000 km pentru al doilea. Acestea au fost testate folosind vâscozimetrul rotativ cu con și placă Brookfield CAP2000+.

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