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Study of HTHS Viscosity of Modern Motor Oils

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Abstract

The article presents the results of experimental studies of HTHS viscosity of modern motor oils belonging to different viscosity classes. Changes in viscosity due to shear rate increase from 10^6 s^{-1} to $1{,}8\cdot10^6$ s^{-1} are presented for oils of classes SAE 5W-30, 5W-40, 5W-50. The results can be used in designing the friction units of internal combustion engines, in particular, the bearings of the crankshaft.

Keywords: Properties of non-Newtonian multigrade oils; viscosity; shear rate; rheology; journal bearing.

1. Introduction

Currently, the multigrade motor oils, condensed by viscous polymer additives, are widely used in the operation of internal combustion engines (ICE). Such additives usually add to obtain a flatter viscosity-temperature characteristic and improve the viscosity index of multigrade oils. That is, at low temperatures, the viscosity should be not too high to ensure pumpability in the lubrication system, access nodes, and minimal frictional resistance during cranking. At the same time, at high temperatures, the viscosity must be sufficient to provide a lubricating layer in the friction unit, which can carry the load.

The rheological behaviour of multigrade oils has features that are called in the literature as non-Newtonian properties. The dependence of viscosity on shear rate (pseudo-plasticity, temporary decrease or anomaly in the viscosity), viscoelasticity (relaxation of shear stresses, the appearance of normal stresses in the shear) is among the most well-known properties of non-Newtonian multigrade oils. Due to the dependence of viscosity on shear rate,

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these oils are also called "energy efficient" because they reduce the power loss to friction in the engine, and therefore a fuel consumption.

Nomenclature

K_c	A parameter shear stability oil, Pa
μ_1	First Newtonian (low-shear-rate) viscosity, Pa·s
μ_2	Second Newtonian viscosity, Pa·s
$\dot{\gamma}$	Shear rate, s^{-1}
μ^*	Apparent viscosity, Pa·s
C_1, C_2, C_3	Temperature constants, which are characteristics of the lubricant
$\beta(T)$	Piezocoefficient viscosity, Pa^{-1}
T_p	Estimated temperature of the lubricant film, °C
p	Film pressure, Pa

Various rheological models are used to describe the rheological behaviour of multigrade engine oils. The power law of Ostwald-Weil [1], the dependencies proposed by Gecim [2], Coy [3] are the most known models for describing the rheological behaviour of multigrade oils. The dependence of the viscosity proposed by Gecim is the best for describing the behaviour of multigrade oils

$$\mu^*(\dot{\gamma}) = \mu_1 \frac{K_c + \mu_2 \cdot \dot{\gamma}}{K_c + \mu_1 \cdot \dot{\gamma}}. \tag{1}$$

The typical dependence of the multigrade oils viscosity on shear rate is presented in Fig. 1.

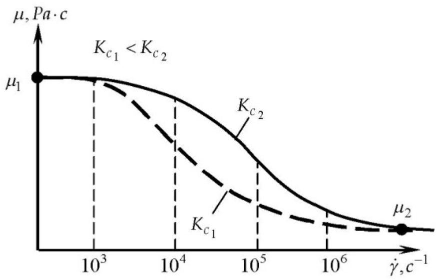

Fig. 1. Fundamental character of the non-Newtonian oils viscosity

Recently researchers have begun to develop various modifications of the models, taking into account not only the shear rate but also the temperature, the pressure in the tribo-unit, etc. [3, 7].

$$\mu^*(T,p,\dot{\gamma}) = \begin{cases} \mu_1 \cdot C_1 e^{\left(C_2/\left(T_p+C_3\right)\right)+\beta\left(T_p\right)\cdot p}, 1 \le \dot{\gamma} \le \dot{\gamma}_1; \\ \left(I_2\right)^{\left(n\left(T_p\right)-1\right)/2} \cdot C_1 e^{\left(C_2/\left(T_p+C_3\right)\right)+\beta\left(T_p\right)\cdot p}, \dot{\gamma}_1 \le \dot{\gamma} \le \dot{\gamma}_2; \quad \dot{\gamma} = \sqrt{I_2}. \\ \mu_2 \cdot C_1 e^{\left(C_2/\left(T_p+C_3\right)\right)+\beta\left(T_p\right)\cdot p}, \dot{\gamma} > \dot{\gamma}_2, \end{cases} \tag{2}$$

Researchers often use equation (1) in the modeling of the crankshaft bearings of the internal combustion engine [3-6]. A little information is contained in the literature about the values of the first and second non-Newtonian viscosity, about values of the shear stability of oils of different viscosity classes. However, the knowledge about the rheological behaviours of engine oils in a wide range of shear rates is important for substantiation of designs of friction units of internal combustion engines. The viscosity at shear rates (above 10^5 s^{-1}), achieved in real friction units of ICE under the maximum load, is of the particular interest.

In accordance with international viscosity classification SAE J300 the viscosity of the multigrade motor oil is measured at a temperature ~ 150 °C and the shear rate ~ 10^6 s^{-1}, which corresponds to the maximum engine loads. The viscosity are measured under such conditions is called HTHS viscosity. A large number of articles is devoted to experimental studies HTHS viscosity engine oils [7-19]. It is known that HTHS viscosity of the multigrade motor oils affects the wear of the ICE and affects the fuel efficiency. The minimum allowable values HTHS viscosity of the engine oils are listed in the classification SAE J300. For the simulation of friction units of ICE it is necessary to know the value of HTHS viscosity of the engine oil that you intend to use in the ICE and the viscosity at other shear rates.

The purpose of this study was to determine the character of the change in the viscosity of modern motor oils of classes SAE 5W-30, 5W-40, 5W-50 at elevated shear rates in the range from 10^3 to 10^6 s^{-1}.

2. Equipment for measuring viscosity at the high shear rate

The tapered bearing simulator TBS 2100E TANNAS was used to measure the viscosity of oils at shear rates from $6{,}58 \cdot 10^3$ s^{-1} to $1 \cdot 10^6$ s^{-1}. This device is a high-speed viscometer, which is used to determine the viscosity of engine oils at high shear rate ~10^6 s^{-1} and a temperature of 150 °C according to method ASTM D 4683 [10] on the international viscosity classification SAE J300. The tapered bearing simulator, schematically shown in Fig. 2, is the world's first industrial viscometer, able to define and provide very high gradient of the shear rate in the process of their work. This feature of the device TBS is unique.

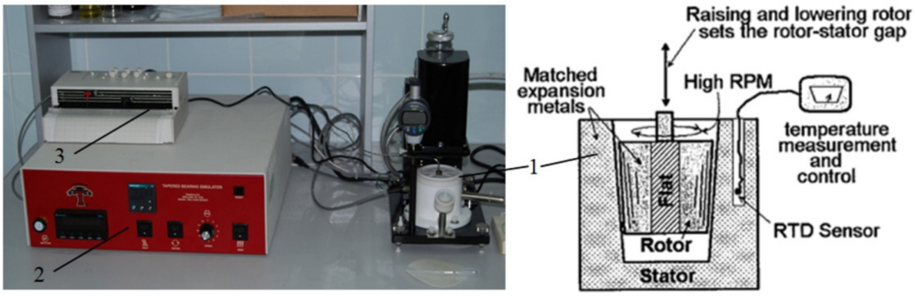

Fig. 2. The tapered bearing simulator TBS 2100E TANNAS [10]: 1 – viscometer; 2 – control block; 3 – printer

3. Calibration of the viscometer TBS 2100E TANNAS and measurement results

Accordingly the method of measurement ASTM D 4683 a calibration was conducted using a standard Newtonian oil with a known viscosity to construct the calibration lines and to determine the relationship between a torque and the viscosity.

Four Newtonian standard oils have been used for calibration. Two sets of the calibration lines were constructed. Ten lines were included in the first set. These straight lines were obtained at different rotation speeds of the rotor and the working positions of the stator at the shear rate ~10^6 s^{-1}. Twenty-two lines were included in the second set. These straight lines were obtained at different positions of the rotor relative to the stator of the viscometer and the rotor speed 3600 min^{-1}. Thus, the range of shear rates from $6{,}58 \cdot 10^3$ to $1{,}8 \cdot 10^6$ s^{-1} was covered at the experiment.

Six oils of viscosity class SAE 5W-40 were selected in view of the great complexity of the experimental work for the measurement. The value of the moment of resistance to rotation of the rotor measured in the sample of oil was the result of an individual measurement. Then the value of viscosity of the oil was determined by projection on the corresponding calibration line.

The results of measurements of the viscosity of oils at different speeds of rotation of the rotor are shown on Fig. 3, and at different positions of the rotor on Fig. 4.

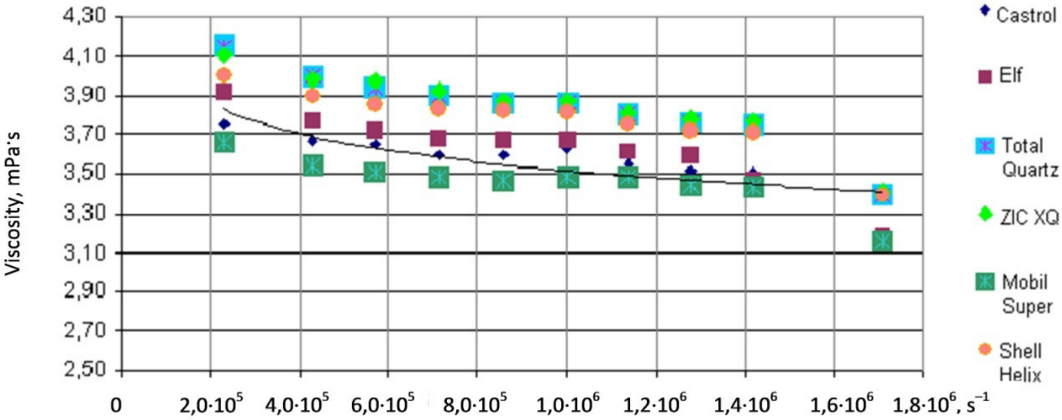

Fig.3. The dependence of viscosity on shear rate in the range from $2.0 \cdot 10^5$ to $1.8 \cdot 10^6$ s^{-1}

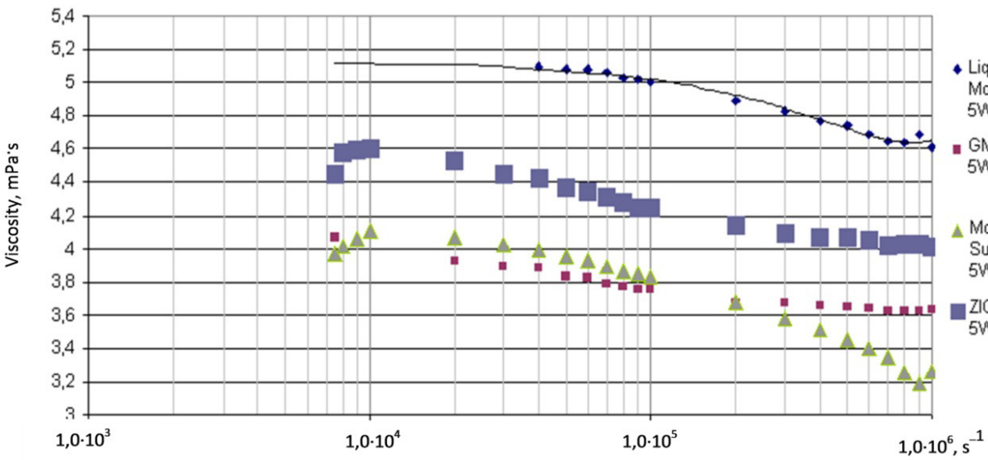

Fig.4. The dependence of viscosity on shear rate in the range from $6{,}58 \cdot 10^3$ to $1{,}0 \cdot 10^6$ s^{-1}

4. Conclutions

The results show that the HTHS viscosity of the modern multigrade oils may vary within the same class of viscosity at 10-12%. The values of viscosity are higher than the maximum permissible according to the classification SAE J300. The drop of the viscosity is not more than 5% when the shear rate is increasing from 10^6 s^{-1} to $1{,}8 \cdot 10^6$ s^{-1}. This suggests that with further increase in shear rate the viscosity is not changed, it corresponds μ_2 in equation (1).

The results can be used to assess the impact of non-Newtonian properties of the modern motor oil on hydro-mechanical characteristics of engines friction units. Not less important problem is the development of mathematical models describing the behavior of the lubricant into various friction units. The difference in the values of the second

Newtonian viscosity at high shear rates for oils of the same class must also be considered in the implementation of the design and checking calculations.

The main conclusion of the study is that knowledge of the rheological behavior of condensed engine oil is important for proper modeling of such friction units of internal combustion engines as the crankshaft bearings. If during operation of the internal combustion engine you intend to use condensed engine oil, you need already at the design stage of the engine crankshaft and bearings detailed to study the rheological behavior of each specimens of oils.

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