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TEMPERATURE DEPENDENT KINEMATIC VISCOSITY OF DIFFERENT TYPES OF ENGINE OILS

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Abstract

SEVERA, L., HAVLÍČEK, M., KUMBÁR, V.: *Temperature dependent kinematic viscosity of different types of engine oils.* Acta univ. agric. et silvic. Mendel. Brun., 2009, LVII, No. 4, pp. 95–102

The objective of this study is to measure how the viscosity of engine oil changes with temperature. Six different commercially distributed engine oils (primarily intended for motorcycle engines) of 10W–40 viscosity grade have been evaluated. Four of the oils were of synthetic type, two of semi–synthetic type. All oils have been assumed to be Newtonian fluids, thus flow curves have not been determined. Oils have been cooled to below zero temperatures and under controlled temperature regulation, kinematic viscosity (mm^2/s) have been measured in the range of –5 °C and +115 °C. Anton Paar digital viscometer with concentric cylinders geometry has been used. In accordance with expected behavior, kinematic viscosity of all oils was decreasing with increasing temperature. Viscosity was found to be independent on oil's density. Temperature dependence has been modeled using several mathematical models – Vogel equation, Arrhenius equation, polynomial, and Gaussian equation. The best match between experimental and computed data has been achieved for Gaussian equation ($R^2 = 0.9993$). Knowledge of viscosity behavior of an engine oil as a function of its temperature is of great importance, especially when considering running efficiency and performance of combustion engines. Proposed models can be used for description and prediction of rheological behavior of engine oils.

engine oil, kinematic viscosity, modeling

Motor oil, or engine oil, is an oil used for lubrication of various internal combustion engines. While the main function is to lubricate moving parts, motor oil also cleans, inhibits corrosion, improves sealing and cools engine by carrying heat away from the moving parts. Motor oils are derived from petroleum and non–petroleum synthesized chemical compounds used to make syntehetic oil. Motor oil mostly consists of hydrocarbons, organic compounds consisting entirely of carbon and hydrogen (Wikipedia, 2009).

For satisfactory lubrication of the engine the oil should possess some functional properties of which viscosity of oil is one of the most important properties, as it brings out the oil's capacity to lubricate (Stewart, 1977). That is why the first lubricant standard J300 that was developed by SAE in 1911 was Viscosity Classification of Motor Oils, and although this standard was revised and updated many times it is still used today world–wide for Motor Oil applications. Now, an oil's viscosity is identified by its SAE's (Society for Automotive Engineer's) number. The thinner the oil is, lower its number, e.g. SAE 10 W. The numerical relates to viscosity at particular temperature and the alphabet 'W', indicates the oil's suitability for colder temperature. With the viscosity index improver, the viscosity increases at higher temperature and at lower temperature it does not increase significantly, thus achieving optimum viscosity at lower and higher temperature. Such oils are called multigrade oils, for instance '20 W40' shows thinness at low temperature and thickness at higher temperature (Leugner, 2005).

However, there are other service classification of oil apart from viscosity, developed by API– American Petroleum Institute, which indicates service characteristics. It is graded on a scale from SA (the lowest) to SJ (the highest) for gasoline engines, it is graded on a scale from CA to CG (Spearot, 1992). Both the recommendations for viscosity and service classification can be found on label of the oil container

Following general recommendations apply (Thibault, 2001): SAE viscosity grade motor oil: 5W–30; Temperature conditions: Below –18°C; Description: Provides excellent fuel economy and low temperature performance in most late–model engines. Especially recommended for new car engines. SAE viscosity grade motor oil: 10W–30; Temperature conditions: Above –18°C;

Description: Most frequently recommended motor oil viscosity grade for most automobile engines, including high–performance multivalve engines and turbo–charged engines. SAE viscosity grade motor oil: 10W–40; Temperature conditions: Above –18°C;

Description: The first multigrade introduced. A good choice for controlling engine wear and preventing oil breakdown from oxidation. SAE viscosity grade motor oil: 20W–50; Temperature conditions: Above –7°C; Description: Provides maximum protection for high–performance, high–RPM racing engines. Excellent choice for high temperature and heavy loads such as driving in the desert or towing a trailer at high speeds for long periods of time. SAE viscosity grade motor oil: SAE 30 & SAE 40; Temperature conditions: Above 5°C & Above 16°C; Description: For cars and light trucks, where recommended by manufacturers. Not recommended when cold–temperature starting is required.

Adding anything foreign to the oil can change its viscosity. Some types of after–market oil additives cause a quite high viscosity at operating temperature. While an additive might improve bearing wear, it can often cause poorer upper–end wear. Other changes to viscosity can result from contamination of the oil. Moisture and fuel can both cause the viscosity to increase or decrease, depending on the contaminant and how long it has been present in the oil. Antifreeze often increases an oil's viscosity. Exposure to excessive heat (leaving the oil in use too long, engine overheating) can also increase viscosity (Khonsari, 2007).

There are several different methods for measuring oil's viscosity. Except traditional methods (such us capillary, falling ball, rotary etc) – in detail described in Spearot (1989), Dawson (2000), or Troyer (2002), there are new approaches described eg. in ASTM Standard (2005), Anonymous (2006), or Albertson et al. (2008).

Fluid temperature stability is essential to the success of mechanical systems. All lubricating fluids have practical limits on the acceptable operating temperature range – both high and low levels. The machine loses stability and experiences conditional failure whenever the system's fluid temperature violates these limits. If left unabated, the conditional failure ultimately results in both material and performance degradation of machine components.

Temperature extremes have a pronounced effect on component materials as well as machine performance. When temperature is too low, fluid viscosity is high. At low temperatures, the fluid often reaches the point where it actually congeals and will no longer flow (pour point). High temperature also accelerates wear, destroys hydrodynamic lubrication regimes, increases the oxidation rate, fosters additive depletion and affects other critical aspects of the machine.

Fluid temperature also grossly affects chemical stability and particularly the oxidation rate of the basic elements of the oil. The primary accelerator of all oxidation reactions is temperature. Like any other reaction, the oxidation rate of hydrocarbons will approximately double for every 18 degrees Celsius increase in temperature. Below 60 °C, the reaction is comparatively slow, but the life of an oil is reduced 50 percent for every 15 degrees Celsius temperature rise above 60 °C, according to the Arrhenius equation for chemical reaction rates. Hence, for high–temperature applications, the oxidation stability of an oil can have great significance (Fitch, 2002).

The thermal stability of a fluid is its ability to resist decomposition due to temperature alone. It establishes the ultimate high–temperature limit for a tribological system fluid that will ensure continual unimpaired service. The most significant change in fluid properties caused by thermal decomposition of organic molecules is an increase in vapor pressure caused by the shearing of molecules into smaller, more volatile fragments.

This study considered the effects of variations in lubricant viscosity under different temperatures. Such knowledge is critical for description of processes running in the combustion engines. Quantification of variations in oil's viscosity during the engine cycle are useful for description of ring–pack friction and wear.

The influence of viscosity on ring/liner friction stems from a trade–off between hydrodynamic and boundary effects – increased viscosity causes an increase in shear losses but a decrease in asperity contact, and vice versa. Because other factors, such as piston speed, are changing throughout the engine cycle, the "ideal" viscosity that provides the lowest friction is also changing (Takata and Wonk, 2006).

MATERIAL AND METHODS

Engine oils

Six different commercially available motorcycle engine oils were used. Four oils were of synthetic type, two were of semi–synthetic type. The oil samples were purchased in local distribution network. The description of the oils is given in Table I.

Prior to viscosity measurement, the oils were cooled to below zero temperatures. Since the oils are supposed to be Newtonian liquids (Noria, I: *Basic description of tested oils*

Assigned No.	Oil type	Mark/Manufacturer	Viscosity Grade	Country of origin
1	Synthetic	Moto 4T Off Road / Repsol	10W–40	Spain
2	Synthetic	Motex 4T–X / Chevron	10W–40	Belgium
3	Synthetic	Silkolene Comp 4 / Fuchs	10W–40	UK
4	Synthetic	5100 Ester 4T / Motul	10W–40	France
5	Semi–synthetic	Power 1 GPS / Castrol	10W–40	EU
6	Semi–synthetic	DuraBlend 4T / Valvoline	10W–40	Netherlands

2008), no pre–treatment or pre–shear was necessary. Although oils were assumed to be Newtonian, it is known that in the case of additives supplement, a side effect of such additives is to cause shear thinning – the oil viscosity becomes dependent on its shear rate, where high shear rates cause the oil viscosity to be reduced (Takata and Wong, 2006). Obviously there are differences between new and used engine oil. All tested samples were new (unused) oils. Measuring of kinematic viscosity of used oils is described in Maggi (2006).

Viscosity measurement

The procedure of sample preparation for viscosity measurements corresponded to a typical sampling procedure. The adequate volume (250 ml) of oil was put into the apparatus cuvette without previous heavy mixing or any other kind of preparation.

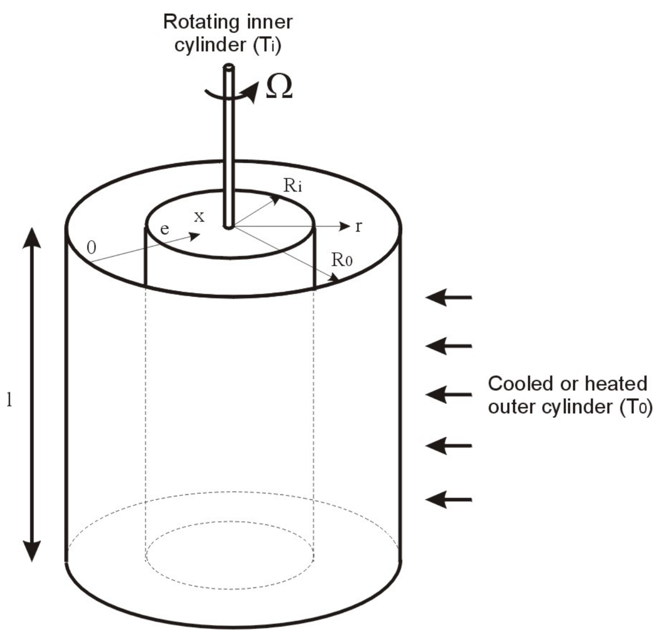
There are several methods to measure kinematic viscosity of fluid or semi fluid materials and different geometries may be utilized: concentric cylinders, cone and plate, and parallel plates. Presented data have been obtained from measurements performed on laboratory digital viscometer Anton Paar DV–3 P (Austria), which is designed to measure dynamic or kinematic viscosity (η, ν), shear stress (τ), and shear rate (). The DV–3 P is a rotational viscometer, based on measuring the torque of a spindle rotating in the sample at a given speed. Shear stress is expressed in [g/(cm.s^2)], shear rate in [s^{-1}], kinematic viscosity in [mm^2/s], and speed of spindle in revolutions per minute [rpm]. The experiments have been performed with use of R3 spindle. Due to the parallel cylinder geometry shear stress, except other values, can be determined. Kinematic Viscosity is the ratio of absolute or dynamic viscosity to density – a quantity in which no force is involved. Kinematic viscosity can be obtained by dividing the absolute viscosity of a fluid with it's mass density

$$\nu = \eta/\rho,$$

where
ν = kinematic viscosity
η = absolute or dynamic viscosity
ρ = density.

In the SI–system the theoretical unit is m^2/s or commonly used Stoke (St). Schematic of the measuring geometry is shown in Fig. 1.

The viscosity data were obtained for temperature range –5 and +115°C.



1: *Schematic of the measuring geometry*

Mathematical models

Mathematical models have been created with use of software MATLAB® v. 7.1.0.246(R14) Service Pack 3, Curve fitting application (The MathWorks, Inc., USA). The suitability of the fitted models was evaluated by the determination coefficient (R^2) and the significance level ($p < 0.05$).

RESULTS AND DISCUSSION

Kinematic viscosity as a function of temperature of 6 different synthetic and semi–synthetic oils have been considered. Figure 2 shows the overview of experimental data of viscosity–temperature dependence. Fig. 3 shows the values of kinematic viscosity as a function of density and temperature. It is obvious that density is not the ruling or determinative factor influencing viscosity. This effect can be explained by partially different chemical composition of individual oils. The viscosity of oil is highly temperature dependent and for either dynamic or kinematic viscosity to be meaningful, the reference temperature must be quoted. In ISO 8217 the reference temperature for a residual fluid is 100 °C. For a distillate fluid the reference temperature is 40 °C. Table II lists the values of kinematic viscosity at reference temperature of 40 °C and oils density.

II: *Kinematic viscosity at reference temperature 40 °C*

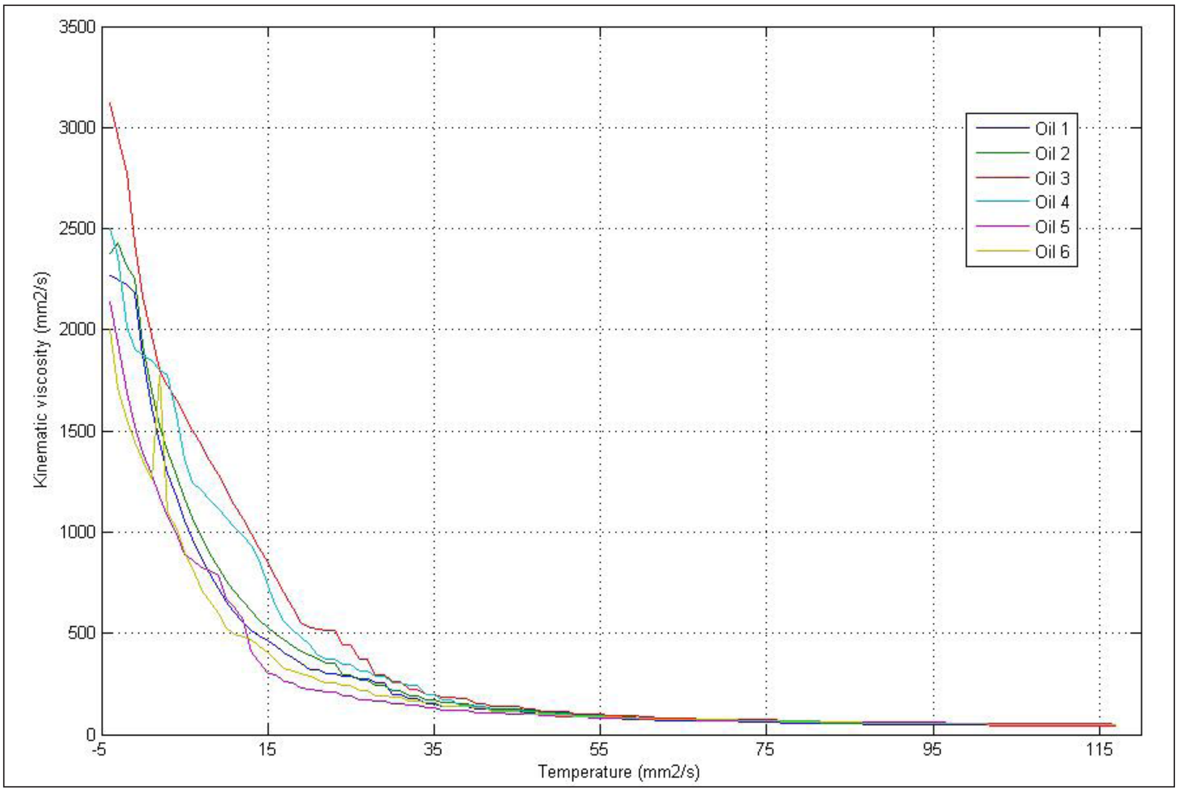
Oil No.	**1**	**2**	**3**	**4**	**5**	**6**
ν (mm^2/s)	116	127	142	120	104	116
ρ (kg/m^3)	830	834	852	839	840	860

Decrease of oil viscosity with increasing temperature was expected and corresponds with conclusions reported in literature (Guo et al., 2007; Mann, 2007). It is obvious that dependence is far to be linear. The reason can be explained as an effect of chemical processes proceeding in the oil.

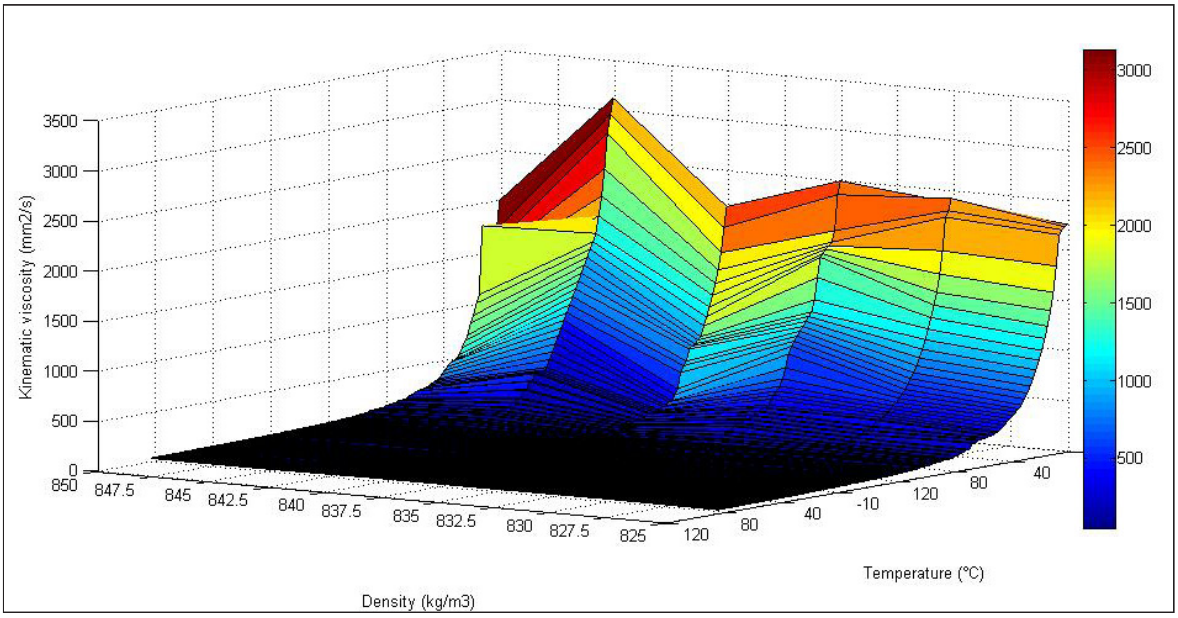
Influence of temperature on oil kinematic viscosity can be modeled. Modeling provides a means of representing a certain quantity of rheological data in terms of a simple mathematical expression. Many forms of the equations are possible and one master model, suitable for all situations, does not exist (Steffe, 1996). The temperature–dependence of the viscosity can be modeled e.g. with the Vogel equation:

$$\nu = z \cdot e^{\left(\frac{T_1}{T_2 + T}\right)},$$

where ν is the kinematic viscosity of the lubricant, z is an oil "thickness" parameter, T_1 is an overall temperature–viscosity dependence parameter, T_2 is a lower bound parameter that is related to the glass transition temperature of the lubricant, and T is the lubricant temperature. Increasing T_1 increases the change in viscosity for a given temperature change, while increasing T_2 has the opposite effect. For a small T_1 or



2: *Temperature dependent viscosity of 6 tested oils*



3: *Kinematic viscosity as a function of density and temperature*

large T_2, the viscosity can become virtually independent of temperature (Takata and Wonk, 2006). Use of this approach yields in $R^2 = 0.92 \pm 0.04$ of match between experimental and tested data (for all tested oils).

The influence of temperature on the viscosity of Newtonian fluids (including engine oils) can be also expressed in terms of an Arrhenius type equation involving the absolute temperature (T), the universal gas constant (R), and the energy of activation for viscosity (E_a):

$$\nu = f(T) = A\exp\left(\frac{E_a}{RT}\right).$$

E_a and A are determined from experimental data. Higher E_a values indicate a more rapid change in viscosity with temperature. Considering an unknown viscosity (ν) at any temperature (T) and a reference viscosity (ν_r) at a reference temperature (T_r), the constant (A) may be eliminated and the resulting equation written in logarithmic form:

$$\ln\left(\frac{\nu}{\nu_r}\right) = \left(\frac{E_a}{R}\right) - \left(\frac{1}{T} - \frac{1}{T_r}\right).$$

Such or similar approach has been used for description of temperature dependent viscosity of Newtonian fluids by many authors (Friso and Bolcato, 2004; Hlaváč, 2007; Severa and Los, 2008). Use of this approach yields in $R^2 = 0.96 \pm 0.08$ of match between experimental and tested data (for all tested oils).

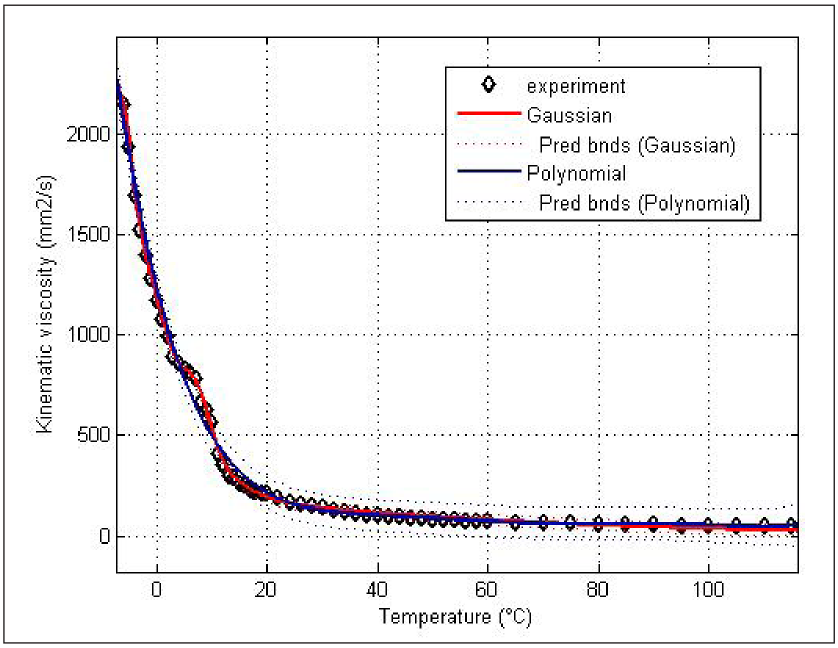
Very good match between experimental and computed values can be obtained using Gaussian or polynomial model. Satisfying result of $R^2 = 0.993 \pm 0.007$ (for all tested oils) was achieved with polynomial fit of 6^{th} degree. Even better match with $R^2 = 0.9993 \pm 0.003$ was gained in the case of Gaussian fit and following formula:

a1*exp(−((x-b1)/c1)^2) + ... + a4*exp(−((x-b4)/c4)^2.

Example of polynomial and Gaussian fit for oil No. 3 is given in Fig. 4. Prediction bounds are also included.

The similar mathematical relationships have been used by many researchers (e.g. Marcotte et al., 2001; Tavares et al., 2007) to describe the temperature dependency of rheological parameters of different materials. Tendency of viscosity decrease with increasing temperature was analogical in above mentioned works and presented study.

It can be concluded that knowledge of viscosity behavior of an engine oil as a function of its temperature is of great importance, especially when considering running efficiency and performance of combustion engines. Viscosity influences the oil's ability to flow which in–turn influences the motivating force, or pressure, required to push the oil sufficiently to develop the necessary flow. The rate of oil flow is important to the life of an engine. Previously, engine oil viscosity was of interest only to provide good hydrodynamic lubrication of load–bearing surfaces and to assure adequate flow throughout the engine. With recent advancements in engine controls that use engine oil for precise timing, oil viscosity has become increasingly important (Albertson et al., 2008). Such advancements include cam phasing, active fuel management, and two–step valve actuation. These are all positive displacement devices that require an oil flow source to develop sufficient pressure which provides hydraulic actuation of components within an engine. Thus, their function can be sensitive to the viscosity characteristics of the oil.



4: *Experimental data and mathematical models for oil No. 3*

SUMMARY

Motor oil lubricates, cleans, inhibits corrosion, improves sealing and cools engine by carrying heat away from the moving parts. This study is primarily focused on quantification of how the viscosity of motor oil changes with temperature. Six different commercially distributed engine oils were used: Moto 4T Off Road / Repsol, Motex 4T–X / Chevron, Silkolene Comp 4 / Fuchs, 5100 Ester 4T / Motul, Power 1 GPS / Castrol, and DuraBlend 4T / Valvoline. The oils used are primarily intended for motorcycle engines and belong to same viscosity grade (10W–40). The first four aforementioned oils were synthetic, two last were semi–synthetic. The flow curves have not been constructed since the fluid was (according to literature results and own measurements) considered to be Newtonian. Due to this fact, no special pretreatment, such as pre–shear, of specimens was necessary. Oils have been cooled to below zero temperatures and under controlled temperature regulation, kinematic viscosity (mm^2/s) have been measured in the range of −5 °C and +115 °C. In accordance with expected behavior, kinematic viscosity of all oils was decreasing with increasing temperature. Since the viscosity of oil is highly temperature dependent and for kinematic viscosity value to be meaningful, the reference temperature (in accordance with ISO 8217) was chosen as 40 °C. Viscosity value at this reference temperature changed from 104 to 146 mm^2/s. Viscosity was found to be independent on oil's density. Several mathematical models have been used for modeling of oils' temperature dependence. Following matches between experimental computed values have been achieved: $R^2 = 0.92$ for Vogel equation, $R^2 = 0.96$ for Arrhenius equation, $R^2 = 0.993$ for polynomial fit of 6th degree, and $R^2 = 0.9993$ for Gaussian equation. Description of viscosity behavior of an engine oil as a function of its temperature is of great importance, especially when considering running efficiency and performance of combustion engines. Proposed models can be used for description and prediction of rheological behavior of engine oils.

SOUHRN

Teplotní závislost kinematické viskozity různých druhů motorových olejů

Motorové oleje slouží k mazání a čištění spalovacích motorů. Dále chrání motory před korozí, zdokonalují těsnění a odvádějí teplo od jednotlivých částí a prvků motoru. Tato práce je primárně zaměřena na kvantifikaci vlivu teploty na kinematickou viskozitu motorových olejů. Sledováno bylo šest komerčně distribuovaných olejů různých výrobců: Moto 4T Off Road / Repsol, Motex 4T–X / Chevron, Silkolene Comp 4 / Fuchs, 5100 Ester 4T / Motul, Power 1 GPS / Castrol a DuraBlend 4T / Valvoline. Použité oleje jsou určeny především pro motocyklové motory a patří do stejné viskozitní třídy 10W–40. Čtyři oleje jsou syntetické, dva polosyntetické. Tokové křivky sestavovány nebyly, protože (v souladu s literaturou a vlastním měřením) byly oleje považovány za Newtonovskou kapalinu.

Vzhledem k této skutečnosti nebylo třeba provádět žádné speciální úpravy vzorků před začátkem měření (např. zatěžování definovanou rychlostí deformace po definovanou dobu, odstávání vzorků apod.). Oleje byly zchlazeny na teploty pod 0 °C a dále u nich byla v řízených teplotních podmínkách stanovena kinematická viskozita (mm²/s) v rozsahu teplot –5 °C až +115 °C. V souladu s očekáváním u všech olejů hodnota kinematické viskozity klesala se zvyšující se teplotou. Vzhledem k tomu, že je viskozita motorového oleje výrazně teplotně závislá a za účelem objektivizace jejího vyjádření, byla v souladu s normou ISO 8217 stanovena referenční teplota 40 °C. Hodnoty viskozit testovaných olejů se při této referenční teplotě pohybovaly od 104 do 146 mm²/s. Bylo zjištěno, že viskozita různých olejů přímo nekoreluje s jejich hustotou. Teplotní závislost olejů byla modelována pomocí několika matematických modelů. Mezi naměřenými a vypočtenými hodnotami byly zjištěny následující korelace: $R^2 = 0{,}92$ pro Vogelův vztah, $R^2 = 0{,}96$ pro Arrhéniův vztah, $R^2 = 0{,}993$ pro polynom šestého stupně a $R^2 = 0{,}9993$ pro Gaussův vztah. Popis a znalost teplotní závislosti kinematické viskozity motorových olejů jsou velmi významné, a to zvláště při hodnocení provozní účinnosti spalovacích motorů. Navržené modely mohou být použity pro popis a predikci tokového chování motorových olejů.

motorový olej, kinematická viskozita, modelování

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