Rheology of multigrade engine oils

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Received 20 April 2005; revised received 6 December 2005; accepted 11 January 2006

Rheology of multigrade engine oils, SAE 15W-40, SAE 20W-40, SAE 20W-50 and SAE 25W-50 has been examined experimentally in the temperature range of -20 to 20°C. Experiments have been carried out to observe the dependence of shear rate, time and temperature on the apparent viscosity of these multigrade engine oils. The oils SAE 15W-40 and SAE 20W-40 are found to behave as Newtonian fluids above a temperature of about 5°C. The oils SAE 20W-50 and SAE 25W-50 are found to behave as Newtonian fluids above a temperature of about 10°C. Below these temperatures, they behave as dilatant fluids. These oils also exhibit a rheopectic behaviour. The apparent viscosity of these multigrade engine oils decreases with increase in temperature.

Keywords: Rheology, Multigrade engine oil, Viscosity, Shear rate

IPC Code: C10M107/00

Multigrade engine oils are formulated by mixing base oils and additives. Base oil is the major component constituting 90 to 98 percent and provides desirable tribological characteristics. The requirements on viscosity or on its temperature behaviour of multigrade engine oils are characterized by comparatively low viscosities at low temperatures. Taking into account the specific requirements of engines, particularly their cold start behaviour, subsequent oil supply to all frictional contacts after such cold starts as well as their regular operation, relatively low viscosities at low temperatures should prevail at low shear rates whereas relatively high viscosities at high temperatures should prevail at high shear rates. An additional requirement is the sufficient shear stability of polymer containing multigrade engine oils. In order to meet the various requirements of multigrade engine oils, several additives are required, which include viscosity index (VI) improvers, antioxidants, dispersants etc. These chemicals are supplied in solution in an oil of the type as base oil. These enhance the desirable functional characteristics of the oil. Their influence is such that base oil specifications are somewhat neglected1. VI improvers are used in multigrade engine oils for improving viscometric and rheological properties. These modify the rate of change of viscosity with temperature, i.e. they cause a minimal increase in engine oil viscosity at low temperature but cause considerable increase at high temperature. Some of the types of polymers generally used commercially as VI improver are: (i) Polyisobutenes, (ii) Styrene-butadiene copolymers, (iii) Olefin copolymers, e.g. ethylene-propylene copolymer, (iv) Esters of styrene-maleic anhydride copolymers and (v) Polyalkylmethacrylates. Antioxidants are largely based on sulphur, zinc and phosphorus compounds. Dispersant additives are based on different succinimide structures. They are used for the dispersal of deleterious insoluble particles formed by fuel combustion and oil oxidation.

Rheology plays an important role in the flow behaviour of multigrade engine oils during preparation and processing. It can also be used in the prediction of the structural characteristics. Besides all of these, rheological testing can provide the present behaviour of the oil as well as its behaviour after weeks, months, years and even decades2. The preparation of multigrade engine oils requires mixing of liquids by mechanical agitation. The rheology of liquids plays an important role in governing the hydrodynamics in the mixing vessel. The influence of rheology on the performance of the mixer has been reported in terms of power consumption, circulation capacity and mixing times. The variables like power consumption and circulation capacity not only serve as a useful basis for selection of a mixer for a specific purpose but also help in correlating and scaling up some other physical quantities such as heat- and mass-transfer coefficients. Mixing time, which may be defined as the time necessary to achieve the required uniformity in all parts of the vessel, is mainly useful for comparing different agitation systems2.

It is, therefore, important to study the rheological behaviour of multigrade engine oils available commercially in Indian market. These investigations are expected to generate some results useful for the design of equipments and pipelines handling these
fluids and may work as a base for further research in the same field.

A series of engine oils of different viscosity classes (e.g., SAE 10W-40, SAE 15W-40 and SAE 20W-50) were examined by Fall and Voelkel. They found that oils of identical viscosity class (produced using different base oils) had similar basic physico-chemical characteristics. Bercea and Bercea presented some experimental data consisting interaction behaviour for lubricants with polymer additives. The rheological response of lubricants without polymer additives and with additives as a function of polymer concentration, pressure and temperature based on the laboratory data is discussed. They presented a quasi-empirical approach which predicts elastic shear modulus, limiting shear stress and characteristic shear stress of a lubricant with polymer additives. Bartz formulated some SAE 15W-40 multigrade oils, using polymethacrylate of different molecular weights as VI improver, with a mixture of 150N and 500N as the base oil. They found that viscometric properties as well as shear stability depended strongly on the polymer concentration and molecular weight of the VI improvers. The evaporation losses were found to be dependent on the volatility of the base oil.

The literature on the mixing of rheologically complex non-Newtonian fluids in stirred tanks has been reviewed by Nienow and Elson. They described a number of novel experimental techniques; cavern formation in plastic fluid; power consumption; the effect of fluid viscoelasticity on the weissenberg effect, flow pattern and scale up; mixing time; the effects of gassing on power and cavity structure, bulk flows, mixing times, mass transfer and hold-up; mixing of shear thickening, dilatant slurries and on the average shear rate concept in mixing vessels.

The work on shear stability of polymers used as viscosity modifiers in lubricating oils has been reported by Ghosh et al. Multigrade engine oils exhibit less reduction in viscosity with increase in temperature than the monograde oils. This is mainly due to presence of several kinds of polymers, such as polyalkyl methacrylates, olefin copolymers, as viscosity modifiers in lubricating oil compositions. The hydrodynamic volume of the polymers in the multigrade oil increases with increase in temperature thereby resulting in an increase in viscosity, which greatly compensates the opposing effect of commonly observed reduction in viscosity of a fluid with rise in temperature. Two kinds of viscosity losses have been reported in a lubricant under shear, namely, a temporary viscosity loss (TVL) or a permanent viscosity loss (PVL). The PVL occurs due to mechanical degradation of polymer molecules being used as viscosity modifiers in lubricating oil compositions. The PVL values are more frequently expressed in terms of permanent shear stability index (PSSI).

**Experimental Procedure**

A schematic diagram of the experimental set-up designed to investigate the rheological behaviour of multigrade engine oils is depicted in Fig. 1. It consists of Brookfield Synchro-Lectric Viscometer and Ultra Cryostat. The ultra cryostat equipment is used to maintain required temperature for viscosity measurements of multigrade engine oils in the temperature range of -20 to 20°C. For this temperature range the bath fluid taken in the ultra cryostat reservoir is kerosene. The sample is taken in a mild steel vessel of dimensions (inside diameter = 73 mm and height = 137 mm). The vessel filled with multigrade engine oils is put in the ultra cryostat reservoir, where the vessel is surrounded by the circulating bath fluid. The sample is maintained at the constant desired temperature by an automatic temperature controller. When the temperature of the sample reaches at desired level, Brookfield Viscometer’s dial reading is taken at the time intervals of 1, 3, 5, 7, 10, 15 and 20 min for a selected spindle at a fixed speed. After taking one set of readings at a fixed speed (say, 3 rpm), the speed is changed to next higher speed (say, 6 rpm). The viscosity of the multigrade engine oils is obtained by multiplying the dial reading by a factor which is specific to speed and spindle used. The spindle

![Fig. 1—Schematic diagram of experimental set-up for rheological behaviour of multigrade engine oils](image-url)
number 4 has been used. At higher speed the dial reading is taken by stopping the dial and the pointer by proper manipulation of the clutch and motor switch.

The following procedure has been employed to calculate shear rate and shear stress values for each measured value. Shear stress, $\tau$, is directly proportional to the spindle speed, $N$, raised to the power $n$, i.e.

$$\tau = \text{constant} \times (N^n)$$

To translate spindle speed, $N$, into shear rate, $\gamma$, shear stress (proportional to viscometer scale reading) is plotted against spindle speed on log-log coordinates. The slope of the straight line is taken as $n$. It is not necessary for this purpose to calculate the actual shear stress and the direct viscometer scale reading may be used instead. The shear rate corresponding to any spindle speed is then obtained from the expression:

$$\gamma = \frac{4\pi N}{n}$$

Shear stress is obtained by multiplying the apparent viscosity with the calculated shear rate.

$$\tau = \mu \gamma$$

Results and Discussion

The rheological behaviour of four multigrade engine oils [SAE 15W-40 (Castrol GTX 2), SAE 20W-40 (Castrol CRB Plus), SAE 20W-50 (Castrol GTX Extra), SAE 25W-50 (Castrol CRB Viscous)] has been studied. For these studies the effect of magnitude and duration of shear rate on the apparent viscosity and shear stress were observed in the temperature range of -20 to 20°C. The spindle speed, which is proportional to shear rate, was varied from 3 to 60 rpm. The duration of agitation was taken as 20 min as it gives steady values of the apparent viscosity/shear stress. From the observed values of the dial reading and spindle speed, shear stress and shear rate were calculated using the procedure described earlier in the experimental procedure.

Variation of apparent viscosity with shear rate

Figure 2a is a plot of apparent viscosity versus shear rate for SAE 15W-40 at several temperatures. The apparent viscosity of this oil first increases with increase in shear rate in the temperature range of -20 to 0°C and then it becomes nearly independent of shear rate. At temperatures of 5°C and above, the apparent viscosity of SAE 15W-40 is nearly independent of shear rate. These observations indicate that this multigrade engine oil behaves like a dilatant fluid below a temperature of about 5°C and it behaves like a Newtonian fluid above a temperature of about 5°C. For SAE 20W-40, a plot of apparent viscosity versus shear rate at several temperatures is given in Fig. 2b. It can be seen from this figure that this oil also behaves like a dilatant fluid below a temperature of about 5°C and it behaves like a Newtonian fluid above a temperature of about 5°C.
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Figure 2c shows the variation of the apparent viscosity of SAE 20W-50 with shear rate at different temperatures. The apparent viscosity of this oil first increases with increase in shear rate in the temperature range of -20 to 5°C and then it becomes nearly independent of shear rate. At temperatures of 10°C and above, the apparent viscosity of this oil is nearly independent of shear rate. Therefore, this multigrade oil behaves like a dilatant fluid below a temperature of about 10°C and it behaves like a Newtonian fluid above a temperature of about 10°C.

Figure 2d is a plot of the apparent viscosity of SAE 25W-50 with shear rate at several temperatures. This figure indicates that this oil also behaves like a dilatant fluid below a temperature of about 10°C and it behaves like a Newtonian fluid above a temperature of about 10°C.

Variation of apparent viscosity with duration of agitation

Figure 3 shows the variation of the apparent viscosity of SAE 20W-40 with time for spindle speeds in the range of 3-60 rpm at -5°C. This figure indicates that the apparent viscosity of this oil at -5°C increases with increase in the duration of agitation for spindle speeds of 12, 30 and 60 rpm. Ultimately, it reaches a fixed value which is different for different spindle speed. Therefore, SAE 20W-40 behaves like a rheopectic fluid at temperature of -5°C. A similar behaviour has been observed at temperature of 0°C. The apparent viscosity of this oil at 5, 10 and 20°C neither increases nor decreases with increase in the duration of agitation for spindle speeds of 3 to 60 rpm. Therefore, this oil behaves like a rheopectic fluid below a temperature of about 5°C. A rheopectic behaviour has also been observed for the SAE 15W-40 below a temperature of about 5°C.

The apparent viscosities of SAE 20W-50 and SAE 25W-50 increase with time for spindle speeds of 6, 12, 30 and 60 rpm at 5°C and lower. At temperature of 10°C and higher, there is no change in the apparent viscosity with duration of agitation for spindle speeds of 3 to 60 rpm. Therefore, these oils behave like a rheopectic fluid below a temperature of about 10°C. It has been reported that rheopexy is a flow phenomenon brought by small shearing rates, less
than about 10 s$^{-1}$. The maximum shear rate which is used in shearing is 14.64 s$^{-1}$ and minimum is 0.34 s$^{-1}$. The experiments have been done at very low shear rates. Therefore, these multigrade engine oils show rheopectic behaviour.

Effect of temperature on apparent viscosity

The effect of temperature on the apparent viscosity of SAE 20W-50 at various spindle speeds is shown in Fig. 4. In this figure the ultimate values of the apparent viscosity have been plotted. The apparent viscosity of this oil decreases with rise in temperature at all spindle speeds. The apparent viscosities of SAE 15W-40, SAE 20W-40 and SAE 20W-50 also decrease with rise in temperature. All these oils exhibit less reduction in viscosity with increase in temperature due to presence of several kinds of polymers. The hydrodynamic volume of the polymers in the multigrade engine oil increases with increase in temperature and results in an increase in viscosity, which greatly compensates the opposing effect of commonly observed reduction in viscosity of oils with rise in temperature.

Conclusion

Multigrade engine oils SAE 15W-40 and SAE 20W-40 are expected to behave as Newtonian fluids at temperatures higher than about 5°C. These oils behave as dilatant fluids at temperatures lower than about 5°C. These oils also exhibit rheopectic behaviour below a temperature of about 5°C. Multigrade engine oils SAE 20W-50 and SAE 25W-50 are found to behave as Newtonian fluids at temperatures higher than about 10°C. These oils behave as a dilatant fluids at temperatures lower than about 10°C. These oils also exhibit rheopectic behaviour below a temperature of about 10°C. The apparent viscosity of all these oils decreases with increase in temperature.

References

2. Information brochure on Rheological Testing, Rheometric Scientific, Inc., U.S.A.