

Estimation of Oil Supply Time during Engine Start-Up at Very Low Temperatures

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ABSTRACT

The adequate lubrication of engine parts is critical for the engine durability, and insufficient oil supply to various friction areas might result in catastrophic engine failure.

However, when the environment temperatures are very low, the presence of oil between friction surfaces may be significantly delayed, especially during the engine start-up after a longer period of time when the vehicle was not driven. The capability of the oil pump to transport oil within the engine depends on the low-temperature rheological properties of oil, as well as the geometry of the passages.

There are testing methods that estimate the ability of an oil to provide lubrication at low temperatures by measuring the yield stress and viscosity in controlled conditions (ASTM D4684, D5293, D5133), but they provide limited data generally used as a guideline for the selection of an appropriate oil.

This paper presents a methodology to computationally estimate the time needed for the low-temperature lubricant to reach the lubrication circuit, using measured rheological properties of the engine oil. For this study, the oil properties were determined using a hybrid rheometer. At very low temperature, the lubricant behavior is strongly non-Newtonian, that in undisturbed state exhibits gel characteristics, and starts to flow only after a yield point was reached. This complex rheological behavior is generally difficult to model in computational codes. Since the time necessary for the oil from the pan to reach the oil pump is critical at start-up, an accurate multiphase modeling is needed. The approach shown in the present work permits to realistically model the oil behavior and get insight into lubricant flow inside a cold engine.

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INTRODUCTION

Engine oils must provide lubrication of various critical engine parts (piston/rings/liner zone, bearings, etc.), and their properties are well-understood within a wide range of temperatures, with the general knowledge that the viscosity increases with decreasing temperature. However, under very cold conditions (-20... -40°C), the lubricating oils exhibit a complex rheological behavior, which is particular to each type of oil. The oil behavior becomes non-Newtonian, and it appears to gel to a quasi-solid state in the oil pan. If the oil fails to flow and the pump absorbs only air, catastrophic engine damage is likely to occur. The difficulties in starting and cranking automotive engines at temperatures around -18°C due to formation of gel structures (caused by the polymers used as additives in multi-grade oils) have been long recognized [1]. The particular cold-temperature behavior is due to the fact that the engine oils, especially the multigrades, are formulated by mixing base (stock) oil with additives that are various types of polymers. Base oils are different (Fig.1), and for mineral base oil the exact composition may vary from one batch to another. The chemical structure and amount of added polymers that serve as viscosity-index (VI) improvers is quite

diverse [2], and impacts the low-temperature lubricant properties. Among other roles, the viscosity modifiers reduce viscosity changes with temperature, and also help the engine ability to start at low temperature. Some of the most common polymers include olefin co-polymers (OCP) and poly-alkyl-methacrylates (PMA). The mechanism that enables polymers to perform the VI improver function is not completely understood [3]. Additionally, the properties of used oil differ from those of the fresh oil, because the presence of particulate contaminants and soot impacts the low-temperatures behavior [4].

In order to provide an assessment of motor oil operability at low temperatures, a number of standard testing methods are available (Fig.2). The standard ASTM D5293 concerns the ability of oil to permit a satisfactory cranking speed at start-up. It is thus assumed that oil is present in bearings, and its viscosity is small enough as to permit engine cranking. ASTM D5293 indicates viscosity limits for various types of oils. Since the bearings are working at a significant speed, this test implies higher shear rates (10^4 - 10^5 s⁻¹). ASTM D4684 refers to the ability of the oil to start flowing and reach the oil

pump at start-up, and measures the yield stress and viscosities for controlled cooling temperatures and cooling profiles. Since the oil is initially undisturbed, this test envisages low shear rates ($0.4 \dots 15 \text{ s}^{-1}$). Maximum viscosity for the test is 400 Pa.s. Another standard is ASTM D5133, based on the Scanning Brookfield Technique (SBT) that can provide a viscosity curve from -5 to -40°C , and calculates the Gelation Index of the sample. SBT is a low-shear rate test (0.2 s^{-1}). The Gelation Index reveals changes in viscosity when temperature is decreased, and is indicative of structures formation in the oil. It was observed that a low cooling rate (e.g., 1°C/h) helps develop solid structures [4], which further decreases oil operability. The ASTM standards specify the type of equipment to be used for the testing.

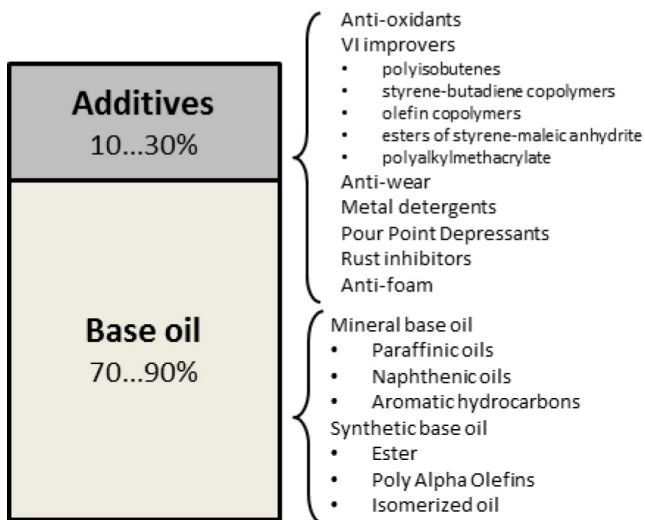


Figure 1. Overview of the chemical structure of engine oils

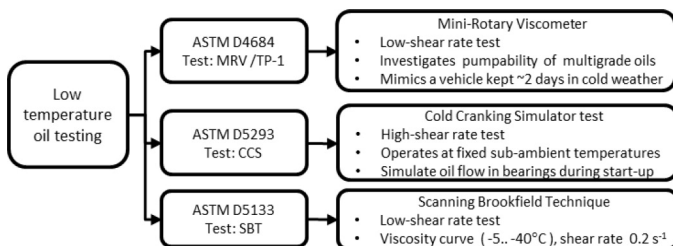


Figure 2. Standard testing methods for engine oil at low temperature

The tests mentioned above are useful in selecting a particular type of oil for a certain application at a given temperature, as well as for comparing different oils. However, the rheological behavior may depend on the manner the shear stress increases with time, but cannot be tested because of equipment limitations. Another aspect concerns the yield point, which is the pair (shear rate, shear stress) where the flow is initiated. Oils at low temperatures present a strongly non-Newtonian behavior [2]. The range of shear rates tested per ASTM standards is limited, such that the measurements do not necessarily identify the yield point. In order to characterize the general flow curve, a wider range is necessary (an experimental method that addresses this aspect will be presented later).

RHEOLOGICAL MODELING AND MEASUREMENTS AT LOW TEMPERATURES

A number of rheological models are available to predict the flow curve [5,6,7], each providing approximations for particular media. The models most commonly used to describe the rheological behavior of the engineering fluids are the Newtonian, Bingham, power-law, and Herschel-Bulkley models (Eq. 1, a and b). The Bingham plastic fluid is similar to a Newtonian fluid, exhibiting a linear shear stress vs. shear-rate curve, after an initial shear stress threshold, τ_0 , ('yield stress') has been reached. The power-law model describes a fluid for which the stress is proportional to the shear rate raised to an exponent.

Among these models, the most complex is Herschel-Bulkley fluid (Fig. 3), which incorporates the elements of Newtonian, power-law, and Bingham fluid models. The parameters of the Herschel-Bulkley equation are usually determined by fitting experimental points.

When the vehicle remains stationary for a sufficiently long time, the oil may flow back to the pan, such that the oil pump is not primed.

Prior to the engine start-up, the lubricant is at rest, such that the shear rate is zero, and will increase during the engine cranking. The flow in the engine sump is driven by the weak suction created by the oil pump (entraining air), and the values of the shear rate, $\dot{\gamma}$, in the oil are very low. Thus, in order to realistically simulate the pumping at start-up, accurate test data are needed for low values of the shear rate. A testing procedure was developed, and is presented below.

The equipment used for oil testing was a parallel-plate design, controlled-stress rheometer (TA Instruments) with an environmental test chamber that permits the accurate control of the temperature, as well as of the lubricant soaking time at a given temperature. For this work, generic 10W30 oil was chosen, formulated to perform at API SN level. The oil was submitted to a temperature of -40°C . This value represents an extreme case of cold start-up, when the oil is in gelled state. The pumpability of oil is difficult, and it may cause engine damage during start-up.

Since at a very low temperature the oil is (when at rest) in a quasi-solid state, a 'yield point' can be intuitively defined as the pair (shear rate, shear stress) $(\dot{\gamma}_0, \tau_0)$ where the lubricant starts to flow, such that after the yield point (i.e., for $\dot{\gamma} > \dot{\gamma}_0$) it behaves as a fluid. The Herschel-Bulkley model may be used:

$$\tau = \tau_0^{(e)} + k\dot{\gamma}_0^n = \tau_0 + k(\dot{\gamma}^n - \dot{\gamma}_0^n), \text{ if } \dot{\gamma} > \dot{\gamma}_0 \quad (1a)$$

where k is a consistency parameter, and n is a power-law index, and $\tau_0^{(e)}$ is the extrapolation of the power-law curve on the stress axis.

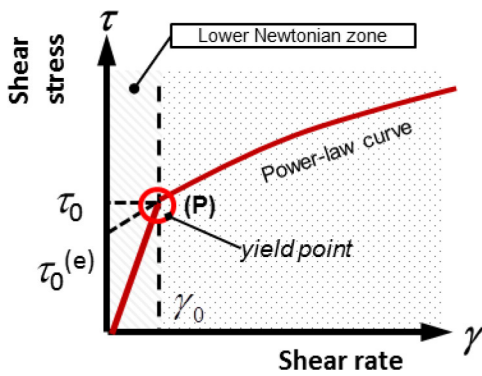


Figure 3. Herschel-Bulkley fluid model

Measurements with a 10W30 engine oil showed that cold lubricant is a viscoelastic medium that exhibits both a storage (elastic) modulus and a loss (viscous) modulus when submitted to a small oscillatory shear rate. Thus, in the context of CFD the region $\gamma < \gamma_0$, may be modeled as either a Hookean or a viscous (Newtonian) medium. For applications such as the pumping during engine start-up, it is more convenient to model this region as a lower Newtonian medium [5] using the Herschel-Bulkley fluid model:

$$\tau = \text{const} \cdot \gamma = \mu_0 \gamma, \text{ if } \gamma < \gamma_0 \quad (1b)$$

where μ_0 is the “zero-shear” viscosity. This modeling describes a medium that exhibits two different, discontinuous fluid-behavior regions. From a practical standpoint, the yield point is difficult to determine from measurement results. Also, the presence of this discontinuity means that the Herschel-Bulkley might not provide a satisfactory approximation for cold oil behavior for numerical simulations.

Two types of measurement were performed using the rheometer in order to characterize the initial lubricant behavior: oscillatory shear rate amplitude sweep, and linear shear-stress ramp. For the measurements presented below, the oil sample was initially exposed to -40°C for a period of four hours.

In the oscillatory shear-rate amplitude sweep test, the motion is applied as an oscillatory (sinusoidal) rotation of the shaft with an angular frequency of 10 rad/s, such that the shear strain increases linearly with time from 10^{-4} to 10 s^{-1} . The oscillation amplitude is small, in order to avoid the destruction of the gel structures. The results are shown in Fig.4. The viscoelastic characteristics of the cold oil are characterized by the complex shear modulus,

$$G^* = G' + i G'' \quad (2)$$

where G' is the storage (elastic) modulus that represents the ability of the material to store energy, while G'' is the loss (viscous) modulus that represents the ability of the material to dissipate energy. At low shear rates, the storage (G') and loss (G'') moduli are constant, but they start decreasing as shear rate increases. The yield point for the oscillatory tests is defined as the 5% drop in the value of the storage modulus. It can be seen that during the oscillatory motion for low

shear rates, the lubricant exhibits a significant elastic behavior, with the phase angle $\delta=23^\circ$ (since $\delta=0^\circ$ for a purely elastic response, and $\delta=90^\circ$ for a purely viscous (Newtonian) behavior).

In the shear-stress linear ramp test, the stress is linearly increased with time from 10^1 Pa to 10^4 Pa (equipment limitations preclude testing at higher stress values). The experimental results (Fig.5) show that the viscosity initially increases slightly up to a maximum value, μ_{max} , after which it starts decreasing. The shear rate initially increases quasi-linearly, but changes slope at almost the same value of stress that corresponds to the maximum viscosity. The yield point is taken as the location of the maximum viscosity.

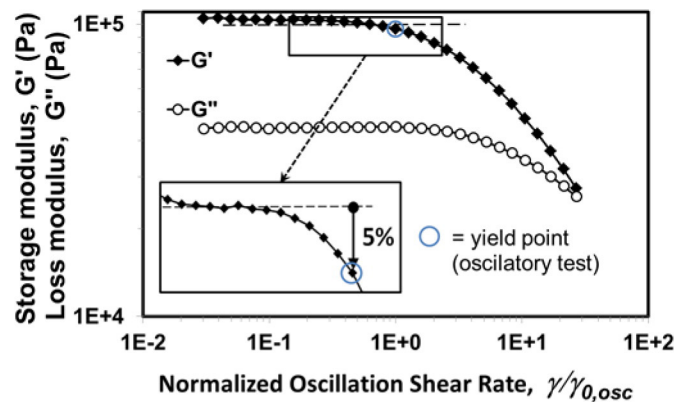


Figure 4. Measurement data of the oscillatory test (10W30 oil)

The values of yield stress and yield strain rate differ significantly for the two methods. The ratio of yield stresses, $R_\tau = \tau_{0,osc} / \tau_0$, is 0.5, while the ratio of shear rates, $R_\gamma = \gamma_{0,osc} / \gamma_0$, is about 18. This indicates that in oscillatory conditions, when the gel structures are not destroyed, the solid character of the oil is preserved up to larger values of shear rate. For the problem of oil pumping at start-up, characterized by a slow continuous motion, the results from the linear stress ramp method are more appropriate, since the continuous motion with increasing stress is expected to destroy the gel structures.

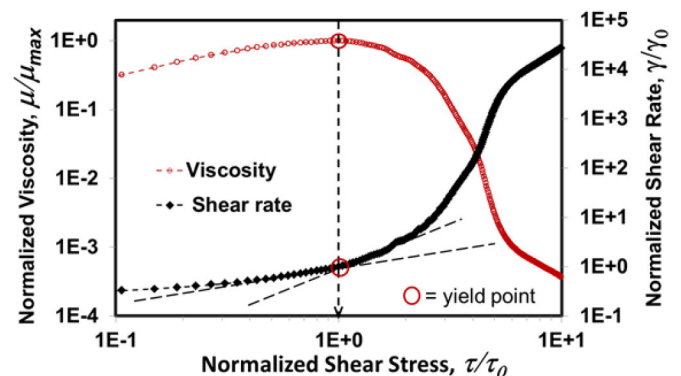


Figure 5. Measurement of a linear shear-stress ramp test (10W30 oil)

The Herschel-Bulkley approximation can be used to model the oil behavior (Fig.6). A curve-fitting technique was used to calculate the parameters (k and n). It can be observed that both τ and μ predicted by Herschel-Bulkley do not provide a satisfactory approximation of the experimental values, mainly in the low shear-rate region prior to the yield point. The viscosity in Herschel-Bulkley is approximated