Flow of Lubricating Greases in Centralized Lubricating Systems*

Michio Hoshino**

Summary: This work was undertaken to determine the effects of the composition of lubricating greases on their flow behavior in centralized lubricating systems and to obtain criteria for the selection of suitable greases for these systems. Flow properties of several lubricating greases of various composition were measured by the ASTM apparent viscometer and a conic-cylindrical rotating viscometer over a wide range of temperature and shear-rate expected to be encountered in applications. Effects of the composition of greases on the pumpability in pipe lines were studied by the calculation of the pressure drop of hypothetical systems assuming flow conditions, and their effects on the slumpability in the reservoir were investigated experimentally on a small scale system and considered by applying the Bingham plastic model on the grease flow in the reservoir. Conclusions were as follows:

1. Pressure drop of a pipe line mainly depends on the viscosity of the base oil at low temperatures and at high shear-rates, but at relatively high temperatures and at low shear-rates the thickener content of the grease has a large effect.

2. These effects can be evaluated quantitatively by the values of constants of an empirical flow equation.

3. Slumpability evaluated by the ratio of discharged grease to the capacity of a reservoir is affected by the yield value of the grease and the viscosity of the base oil, and in the small reservoir a good discharge ratio is expected when the yield value is relatively high and the viscosity of the base oil is low.

4. These effects may be explained by the consideration of the flow mechanism in the reservoir applying the Bingham plastic model.

Introduction

The widespread use of grease in centralized lubricating systems (CLS)* has increased the need for methods of predicting flow properties in such systems.

In CLS, lubricating grease stored in a reservoir is sucked out from an opening located at its bottom by a dispensing pump and sent through a long pipe line to the distributors which apply suitable amounts of grease to all lubricating parts. Consequently, there are two problems concerning the flow behavior of lubricating greases in CLS, i.e. the slumpability in the reservoir and the pumpability in the pipe line.

The pumpability is the ability of a lubricating grease to flow under pressure through the line of the system. It is evaluated by pressure drop developed in the system at a given flow condition. Many studies have been devoted to the establishment of methods for the prediction of the pressure drop, and it is the conclusion of these studies that the pressure drop in a pipe line may be calculated from the apparent viscosity of grease using the Hagen-Poiseuille's equation for laminar flow. 1), 2) On the other hand, the slumpability has been said to correlate with the yield value of the grease, but the term slumpability has neither been clearly defined nor the consideration based on experimental data has been done until now.

In this study, the effect of the composition of a lubricating grease on the pumpability in CLS was studied from the pressure drop predicted by the apparent viscosity determined at supposed flow conditions. Then, the slumpability was measured using a small-scale dispensing system and the correlation of the slumpability with flow properties of lubricating greases was considered with respect to a flow mechanism in the reservoir.

Method for Measurement of the Apparent Viscosity of Greases

Measurements of apparent viscosity of lubricating greases were carried out over a shear-rate

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** Research Laboratory, Mitsubishi Oil Co., Ltd. (12-1, Ohgimachi, Kawasaki, Japan)
range, $10^{-2}$-$10^4$ sec$^{-1}$. In the high shear-rate range from 10 to $10^4$ sec$^{-1}$, a capillary-type ASTM apparent viscometer was used, and in the low shear-rate range from $10^{-2}$ to $10^2$ sec$^{-1}$, a conicylindrical type coaxial rotating viscometer was used. The latter viscometer was constructed in the author's laboratory for the supplemental measurement at low shear-rates that cannot be relaxed by the former viscometer.

The principal structure and dimensions of the rotating viscometer are shown in Fig. 1. A sample was introduced within the gap between two coaxial rotors and sheared by rotating the outer rotor at various speeds. Thus, apparent viscosity of the sample at various shear-rates was calculated from the torque applied to the inner rotor.

The measuring ranges of both viscometers are shown in Fig. 2. By using these viscometers, it is possible to obtain the flow properties of greases covering the whole range of conditions encountered in CLS.

**Pumpability in a Pipe Line**

*Measurement of Apparent Viscosity of Greases*

To make clear the correlation of grease composition to the pumpability in a pipe line, flow properties of three lubricating greases for CLS were measured at the temperature of 25, 0 and -25°C. These greases are all soap thickened NLGI 00 grade greases, but their compositions, especially viscosity and V.I. of their base oils, are different from each other as shown in Table 1.

Apparent viscosity $\eta$ (poise) versus shear-rate $\dot{\gamma}$ (sec$^{-1}$) curves obtained for $A$, $B$ and $C$ greases are shown in Fig. 3, 4 and 5 respectively. Horizontal dotted straight lines in figures show viscosity of base oils at each temperature.

**Table 1 Properties and Composition of Grease A, B and C**

<table>
<thead>
<tr>
<th>Grease</th>
<th>Base Oil</th>
<th>Thickener</th>
<th>Viscosity, cSt</th>
<th>V. I.</th>
<th>Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Li-Soap</td>
<td>Ca-Soap</td>
<td>375, 5</td>
<td>17,93</td>
<td>31</td>
</tr>
<tr>
<td>B</td>
<td>Ca-Soap</td>
<td></td>
<td>107,3</td>
<td>8,172</td>
<td>13</td>
</tr>
<tr>
<td>C</td>
<td>Ca-Soap</td>
<td></td>
<td>23,10</td>
<td>4,111</td>
<td>76</td>
</tr>
</tbody>
</table>

**Application of an Empirical Equation on the Viscosity Data**

To characterize these flow curves quantitatively, an empirical equation (1) was applied to the obtained data and the correlation between values of constants of the equation and the composition of greases was examined.

$$\eta = a + b\dot{\gamma}^{n-1} + c\dot{\gamma}^{m-1}$$ (1)
The equation (1) is the modified form of an equation proposed by Sisko et al., adding the last term in order to fit to the experimental data better at the intermediate range of the shear-rates. Values of constants in the equation were determined in the following way. First of all, $b$ and $n$ are determined from the intercept and the inclination of the straight line part of the flow curve respectively, and a value of $a$ is assumed with reference to the apparent viscosity of the grease at a high shear-rate and the viscosity of the base oil. Then, $\log (\eta - a - b\eta^{n-1}) (= \log c \eta^{m-1})$ is calculated from the observed apparent viscosity and the constants determined above and plotted against $\log \dot{\gamma}$. The relation between them becomes nearly a straight line, then $c$ and $m$ can be determined in the same way. If the flow curve calculated using these constants does not fit well to the observed data, another value of $a$ is assumed and similar operation is performed until good agreement is obtained.

In the case of grease A and grease B at $-25^\circ$C, observed data are insufficient in the ranges of high and low shear-rates. In those cases, value of $n$ is assumed to be equal to the value at higher temperature, which seems to be reasonable from the result of grease C, and value of $a$ is determined with reference to the base oil viscosity alone.

Values of constants in the equation applied to each experimental data are shown in Table 2. The first term of the equation (1) corresponds to the limiting viscosity of greases at $\dot{\gamma} \to \infty$. In such a state, a three-dimensional structure formed by the thickener is destroyed and thickener particles are suspended individually in the base oil. Consequently, $a$ has a value near the viscosity of the base oil as shown in Table 3. Thus $a$ represents the Newtonian part of the viscosity of the lubricating greases and has a large effect on the pumpability at the high shear-rates and at low temperatures. On the other hand, the second term $b\eta^{n-1}$ represents the non-Newtonian part of the lubricating greases at $\dot{\gamma} \to 0 (n > m)$. $b$ and $n$ depend on the strength of the thickener structure and on the change of the strength with shear-rate, respectively. Consequently, they are affected very much by the content and the type of the thickener. Thus the effect of $b$ and $n$ is predominant at the low shear-rates and the high temperatures. The third term $c\eta^{m-1}$ is a correction term as stated before and has a slight effect on the pumpability at the
Table 2. Values of Contents in the Empirical Flow Equation (2)

<table>
<thead>
<tr>
<th>Temp, °C</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>n</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>-25</td>
<td>2.5 × 10^4</td>
<td>8.0 × 10^3</td>
<td>2.3 × 10^4</td>
<td>0.167</td>
<td>0.686</td>
</tr>
<tr>
<td>0</td>
<td>2.4 × 10^2</td>
<td>7.9 × 10^2</td>
<td>2.0 × 10^2</td>
<td>0.167</td>
<td>0.686</td>
</tr>
<tr>
<td>25</td>
<td>1.3 × 10</td>
<td>2.4 × 10^2</td>
<td>4.2</td>
<td>0.167</td>
<td>0.686</td>
</tr>
<tr>
<td>-25</td>
<td>3.0 × 10^3</td>
<td>1.2 × 10^3</td>
<td>3.7 × 10^3</td>
<td>0.137</td>
<td>0.809</td>
</tr>
<tr>
<td>0</td>
<td>3.6 × 10</td>
<td>5.6 × 10^2</td>
<td>1.0 × 10^2</td>
<td>0.137</td>
<td>0.818</td>
</tr>
<tr>
<td>25</td>
<td>4.0</td>
<td>1.3 × 10^3</td>
<td>4.8 × 10</td>
<td>0.137</td>
<td>0.606</td>
</tr>
<tr>
<td>-25</td>
<td>1.8 × 10^4</td>
<td>1.3 × 10^4</td>
<td>2.6 × 10^2</td>
<td>0.230</td>
<td>0.747</td>
</tr>
<tr>
<td>0</td>
<td>2.1</td>
<td>1.2 × 10^2</td>
<td>2.6 × 10</td>
<td>0.230</td>
<td>0.747</td>
</tr>
<tr>
<td>25</td>
<td>5.0 × 10^-1</td>
<td>3.6 × 10^2</td>
<td>9.6</td>
<td>0.230</td>
<td>0.747</td>
</tr>
</tbody>
</table>

Table 3. Comparison of Values of a with the Viscosity of the Base Oil

<table>
<thead>
<tr>
<th>25°C Viscosity of the Base Oil</th>
<th>Ratio</th>
<th>60°C Viscosity of the Base Oil</th>
<th>Ratio</th>
<th>25°C Viscosity of the Base Oil</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grease A</td>
<td>2.5 × 10^4</td>
<td>1.95 × 10^4</td>
<td>1.38</td>
<td>2.4 × 10^2</td>
<td>1.91 × 10^2</td>
</tr>
<tr>
<td>Grease B</td>
<td>3.0 × 10^3</td>
<td>1.93 × 10^3</td>
<td>1.55</td>
<td>3.6 × 10</td>
<td>2.40 × 10</td>
</tr>
<tr>
<td>Grease C</td>
<td>1.8 × 10^4</td>
<td>1.18 × 10^4</td>
<td>1.53</td>
<td>2.1 × 10</td>
<td>1.40 × 10</td>
</tr>
</tbody>
</table>

*Extrapolated values from viscosities at 37.8 °C and 98.9 °C on the ASTM viscosity-temperature chart.

Moderate shear-rates.

Grease A composed of the thickener of the low content and the high viscosity base oil shows a flat flow curve (i.e. a is high and b is low) and its apparent viscosity is relatively low at the low shear-rates, but it increases excessively at the high shear-rates at the low temperatures. On the other hand, grease C composed of the thickener of the high content and the low viscosity oil shows a steeper flow curve than the former (i.e. a is low and b is high) and its apparent viscosity at the high shear-rates is low especially at the low temperatures. Grease B has an intermediate composition and flow properties between A and C, but the particularly low value of b at -25°C when compared with those of others may be due to the low pour point of its base oil.

Calculation of the Pressure Drop in a Hypothetical System

To confirm the characteristics of these greases discussed above, it is desirable to measure the pressure drop on actual centralized lubricating systems at various conditions, but the control of the conditions of such large systems is very difficult. Therefore, in this study the pressure drops were calculated on two hypothetical systems supposing typical flow conditions. The result obtained will show the performance characteristics of these greases at actual application because calculated pressure drop agrees well to that of actual pipe line as mentioned before. Flow conditions are considered as follows.

<table>
<thead>
<tr>
<th>Condition 1</th>
<th>Condition 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear-Rate</td>
<td>0.1 sec^-1</td>
</tr>
<tr>
<td>Dia. of the Pipe</td>
<td>82.9 mm (2in pipe)</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>100 cc/min</td>
</tr>
<tr>
<td>Length of the Line</td>
<td>100 m</td>
</tr>
</tbody>
</table>

Condition 1 corresponds to that of long-line industrial lubricating systems such as for steel rolling mills, and condition 2 corresponds to that of short-line small-scale systems such as for an automotive chassis lubrication or the dispensing at service stations.

Pressure drops were calculated from apparent viscosity data using Hagen-Poiseuille's equation, and the results are shown in Fig. 6. These results show that lubricating grease like A is suitable for the system operated at such a condition as 1, while grease like C is suitable for the system operated at such a condition as 2.

Thus, distinctive features of greases expected from the flow curves and flow constants were confirmed by the calculated pressure drop value.

Slumpability in Reservoir

Meaning of "Slumpability"

There are two difficulties in the flow of grease in
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Fig. 6 Calculated Pressure Drop in Hypothetical Pipe Lines

a reservoir at low temperatures. In one case, the pressure drop developed in the reservoir is so high that greases cannot be pumped out. In the other case, a lot of grease remains on the wall and the bottom of the reservoir after channeling had occurred.

In the former case, the degree of difficulty may be estimated by the pressure drop as mentioned above on the presumption that reservoir is a part of a pipe and the flow condition in the pipe line is generally more severe than in the reservoir, so that the lower limit of temperature to be dispensed effectively is determined mainly by the pressure drop in the pipe line. Consequently, the slumpability is discussed mostly in relation to the latter difficulty. Such a slumpability may be evaluated by the ratio of the amount of discharged grease to the capacity of a reservoir.

Experimental

The observation of the flow of lubricating greases in a reservoir and the measurement of the discharge ratio of greases were carried out on an actual small-scale dispensing system. The inner diameter of the reservoir was 60 mm and the height was 150 mm. Grease was discharged at a rate of 0.33 cm²/strokes by a stroke pump driven by a 24 V.D.C. motor.

Three lubricating greases were used in this experiment. Principal properties and the composition of these greases are given in Table 4.

Pumping tests were carried out at 25, 0, -15, -25 and -35°C after overnight standing at testing temperature. Numbers of strokes of the pump per min., i.e. the rates of discharge decreased with the lowering of temperature in all cases, but the relation of discharge ratio to the temperature was very characteristic to each grease as shown in Fig. 7. In the case of grease D, discharge ratio decreased with the lowering of temperature, while it increased in the case of grease E. Curve of grease F had a minimum point at a temperature of -15°C.

Table 4. Properties and the Composition of Grease D, E and F

<table>
<thead>
<tr>
<th></th>
<th>Grease D</th>
<th>Grease E</th>
<th>Grease F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worked Penetration</td>
<td>362</td>
<td>388</td>
<td>419</td>
</tr>
<tr>
<td>Dropping pt. °C</td>
<td>93</td>
<td>193</td>
<td>188</td>
</tr>
<tr>
<td>Thickener</td>
<td>Ca-Soap</td>
<td>Li-Soap</td>
<td>Li-Soap</td>
</tr>
<tr>
<td>Base Oil</td>
<td>V.1</td>
<td>V.1</td>
<td>V.1</td>
</tr>
<tr>
<td>Viscosity, cst @37.8°C</td>
<td>145.7</td>
<td>107.9</td>
<td>50.5</td>
</tr>
<tr>
<td>@68.9°C</td>
<td>9.04</td>
<td>10.39</td>
<td>5.67</td>
</tr>
</tbody>
</table>

Fig. 7 Change of the Discharge Ratio with Temperature

Flow Mechanism in the Reservoir

In order to explain these peculiarities, the following flow mechanism in the reservoir was considered.

Because of very low shear-rate (=10^{-3} sec^{-1}) in the reservoir, the grease is supposed to behave similarly as the Bingham plastic body in it. If the flow equation of the grease is \( \dot{\gamma} = \frac{1}{\eta_p} (\tau - \tau_c) \), where \( \eta_p \) is the plastic viscosity and \( \tau_c \) is the yield value, the velocity profile of the grease

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distant from the bottom has such a shape as shown in Fig. 8 (a), including core I in which the grease moves as a solid plug. The radius of the core, I, \( r_0 \), is equal to \( 2l/\Delta p \), where \( l \) is the length of the pipe and \( \Delta p \) is the pressure difference. If each portion of the grease flows down holding a constant speed, the profile of the upper surface changes in the manner as shown in Fig. 8 (b) and (c) with the lapse of time. However, the part of the grease remained on the wall does not receive the kinetic energy from the neighboring layer, so that its velocity decreases rapidly as the result of internal friction and the core II is formed which adheres to the wall and does not flow. On the other hand, near the bottom the core III is formed by the effect of the sudden reduction of the diameter and flow lines gather toward the center (Fig. 8 (d)). When the upper surface approaches to the bottom, the surface slumps along the core III, and finally the grease remains in the reservoir in the manner as shown in Fig. 8 (e) combining the core II and III.

According to the above discussion, it may be concluded that as the radius of the core I, \( r_0 \), approaches to the radius of the reservoir, \( R \), the core II becomes thinner and as the result, the height of the core III decreases, which brings about the improvement of the discharge ratio of the grease.

**Calculation of the Adhesion Limit of the Grease to the Wall**

In order to clarify the effects of flow properties of greases and dimensions of the reservoir on the adhesion of the grease to the wall, \( r_0/R \) was calculated according to the McMillen's method (6), as shown in Fig. 9, supposing several values of \( \sigma_\text{o} \) and \( \eta_\text{pl} \). Correlations of \( r_0/R \) versus \( \tau_e \) calculated at the condition of \( R=3.0 \text{ cm} \), \( \eta_\text{pl}=10^8 \) and \( 10^4 \) poises and the discharge rate \( v=0.14 \text{ cc/sec} \) (the nominal rate of the pump).

As we saw in the above discussion, thickness of core II cannot be less than \( R-r_0 \), so the inner radius of the core II, \( r_{II} \), must be in the left side of the curves COB or DO'B. On the other hand, because the weight of the grease adhering per unit area of the wall surface cannot exceed \( \tau_e \), \( r_{II} \) is limited also by the following relation.

\[
\left( \frac{\pi R^2}{2\pi R} - \frac{\pi r_{III}^2}{2\pi R} \right) \frac{\rho g}{\rho g} \leq \tau_e
\]

Critical \( r_e \) is given by

\[
r_e = \sqrt{R^2 - \frac{2\pi \tau_e \rho g}{\rho g}}
\]

Introducing to (3) \( R=3.0 \), \( \rho=0.95 \text{ g/cm}^3 \), \( g=980 \text{ cm/sec}^2 \), \( r_e/R \) versus \( \tau_e \) curve is given as AO'O'E shown in Fig. 9. Consequently, \( r_{II}/R \) must be in the region above AOB or AO'B.

Effects of the radius of the reservoir \( R \) on \( r_0/R \) and \( r_{II}/R \) are shown in Fig. 10. Curve A is the relation of \( r_{II}/R \) versus \( R \) at \( v=0.14 \text{ cm}^2/\text{sec} \) similarly in Fig. 9, and curve B is that in the case \( v \) changes proportionally to the sectional area of the reservoir holding a constant value of the linear velocity. The limit by the yield value is

**Fig. 8 Flow Mechanism in the Reservoir when the Grease is assumed to be a Bingham Plastic Body**
shown by the curve C. When R is small, the adhesion to the wall is prominent and mainly governed by the radius of the core I. As R increases, the absolute value of the thickness gradually increases but it becomes negligible compared with the capacity of the reservoir and finally reaches a constant value $\tau_c/p_c$ at $R \rightarrow \infty$.

Dimensions of the core III formed on the bottom of the reservoir cannot be determined because the flow pattern around here is very complex. Evans et al. investigated the suction of the grease from a 400 lb drum and reported that the depth of the grease layer remained on the bottom is linearly proportional to $\dot{\gamma}$. However, in this investigation the depth of the core III rather decreased as $\dot{\gamma}$ increased. It may be considered that in a small reservoir the formation of the core III is affected very much by the core II, and the increase of the thickness of the core II results the growth of the core III, which makes worse the discharge ratio.

Comparison with the Measured Flow Properties of Grease

Flow properties of greases were measured by the conic cylindrical rotating viscometer at 25, 0 and -25°C. Flow properties of the base oils were also measured in the same manner to confirm the wax deposition in them. The results were shown in Fig. 11, 12 and 13. $\tau_c$ and $\eta_{pl}$ were determined from these results. $\tau_c$ was taken for the shear stress at which log $\dot{\gamma}$ versus log $\tau$ curve becomes very steep in the manner as shown in Figure and $\eta_{pl}$ was taken for the viscosity of the base oil $\dot{\gamma} \rightarrow \infty$. Obtained values of $\tau_c$ and $\eta_{pl}$ are shown in Fig. 14. At grease D, $\eta_{pl}$ increases rapidly with the lowering of temperature but the increase of $\tau_c$ is small. As the result, the discharge ratio decreases with the lowering of temperature. On the other hand, $\tau_c$ of grease E increases steeply at lower temperatures. It may be attributed to the deposition of wax in the grease. Highly non-Newtonian character of the base oil at -25°C also indicate this fact.
In this way observed peculiarity of the change of the discharge ratio with the lowering of temperature can be explained by the values of $\tau_0$ and $\eta_{pl}$ considering the Bingham plastic flow mechanism in the reservoir.

**Conclusion**

1. Pressure drop in a pipe line is governed mainly by the viscosity of the base oil at low temperatures and at high shear-rates, but at relatively high temperature and at low shear-rates the effect of the content of thickener becomes predominant.

2. These effects of the component on the flow properties of greases are evaluated by the values of constants of an empirical flow equation and they offer the criteria for the selection of a suitable grease at the given condition.

3. Slumpability evaluated by the discharge ratio of the grease from a reservoir, varies with the temperature very peculiarly to each grease in the case of a small reservoir. This peculiarity is due to the concurrence between the effect of the base oil viscosity and that of the yield value on the thickness of the grease adhered on the wall, and can be explained by applying the Bingham plastic flow model on the flow in the reservoir.

4. In a small scale reservoir a good slumpability is expected when the yield value of the grease is relatively high and the viscosity of the base oil is low at the application temperature. Consequently, for the lubricating grease for small-scale systems, it is suitable to use a low viscosity and high VI base oil as far as the circumstance of lubricating parts permits.

**Literatures**