

Effects of Low-viscosity Engine Oil on Fuel Economy and Wear

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ABSTRACT

The effects of lower engine oil viscosity on fuel economy and engine reliability were investigated, unhampered by the SAE viscosity standard, with the aim of enhancing fuel economy. The fuel economy effects were predicted by using low-viscosity engine oil and measuring the friction torque. The results showed that lowering the engine oil viscosity provides favorable prospects for enhancing fuel economy.

Engine reliability was investigated by confirming the effects on sliding wear at high temperature, which is the greatest issue for low-viscosity engine oil. These effects were confirmed through CAE analysis and engine endurance tests. The results provided prospects for wear resistance of sliding parts at high temperature, even when using engine oil with a lower viscosity than specified in the SAE viscosity standard in the tested mass-production engine.

In addition, a number of prototype engine oils with a lower viscosity than specified in the SAE viscosity standard were created, and the property values and positioning of these prototype engine oils relative to the SAE viscosity standard were confirmed.

Engine oil with a lower viscosity than specified in the current SAE viscosity standard can be expected to further enhance fuel economy, so the establishment of further low-viscosity standards is desired.

1. Introduction

Suppression of global warming and other recent issues are increasing demands for enhanced automobile fuel economy to reduce CO₂ emissions. Lowering the engine oil viscosity is known to be an effective method of enhancing fuel economy^{(1), (2)}. However, lowering the viscosity by too much has the opposite effect of reducing fuel economy for some engine mechanisms^{(3), (4)}. In addition, there are concerns that simply lowering the engine oil viscosity may result in increased wear at high temperature, lower operating performance of hydraulic devices, and increased oil consumption⁽⁵⁾.

Engine oil is a general-purpose part with the highest replacement frequency and market availability, so a number of standards have been established, as typified by the Society of Automotive Engineers (SAE) viscosity standard (SAE-J300), which guarantees fuel economy and sliding wear at high temperature. For this reason, many papers concerning the impact of engine oil on fuel economy and

sliding wear report with the premise of compliance with the current SAE viscosity standard⁽²⁾⁻⁽⁵⁾.

Therefore, this study first predicted the fuel-saving effects of using low-viscosity engine oil, unhampered by the current SAE viscosity standard. Next, the wear resistance of sliding parts at high temperature was verified, which is the greatest issue for low-viscosity engine oil. A number of prototype low-viscosity engine oils were then created based on these results, and their position relative to the SAE viscosity standard was confirmed.

2. Course of This Study

Engine oil has characteristics such that the viscosity falls at high temperature, and rises at low temperature. When the viscosity is high at normal temperature, there are concerns that viscosity resistance may lower fuel economy. On the other hand, when the viscosity falls by too much at high temperature, sliding wear becomes a concern. Recently, there have been demands to develop fuel-economy engine

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Table 1 SAE viscosity standard

	Viscosity grade	CCS viscosity		MRV viscosity		Kinematic viscosity (100 °C) (mm ² /s)		HTHS viscosity (150 °C) (mPa·s)
		mPa·s	°C	mPa·s	°C	Min.	Max.	
Winter grade	0 W	6200	-35	60000	-40	3.8		
	5 W	6600	-30	60000	-35	3.8		
	10 W	7000	-25	60000	-30	4.1		
	15 W	7000	-20	60000	-25	5.6		
	20 W	9500	-15	60000	-20	5.6		
	25 W	10000	-10	60000	-15	9.3		
	20					5.6	9.3	2.6
	30					9.3	12.5	2.9
	40 (0 W, 5 W, 10 W)					12.5	16.3	2.9
	40 (15 W, 20 W, 25 W)					12.5	16.3	3.7
	50					16.3	21.9	3.7
	60					21.9	26.1	3.7

oil with further reduced viscosity at normal temperature, and that maintains viscosity at high temperature⁽⁶⁾.

To meet these needs, polymer components called viscosity index improvers are often added to engine oil. Engine oil with viscosity index improvers added is known to become a non-Newtonian fluid⁽⁷⁾.

The viscosity of engine oil that has become a non-Newtonian fluid drops temporarily under shear conditions such as engine operation. This temporary drop in viscosity is produced by the polymer orientation⁽⁸⁾. In particular, the ratio of this drop in viscosity is known to increase under high-speed shear conditions. On the other hand, Newtonian fluids do not have polymer components added, so there is no temporary drop in viscosity due to shear.

Engine tests using Newtonian fluids that do not experience changes in viscosity due to shear are better from the standpoint of more accurately understanding the correlations between viscosity and fuel economy, and between viscosity and sliding wear. Therefore, it was thought that engine tests can be performed using Newtonian fluids, by dividing normal temperature (approximately 80°C) and high temperature (approximately 130°C) into separate cases, and adjusting the viscosity using separate oils.

That is to say, one case adjusted the Newtonian fluid oil focusing on only the viscosity at normal temperature, to understand the relationship between fuel economy and viscosity. Verification used friction torque measurement (motoring friction torque on an engine bench tester), and estimated the correlation between fuel economy and viscosity.

The other case adjusted the Newtonian fluid oil focusing on only the viscosity at high temperature, to understand the relationship between sliding wear at high temperature and viscosity. Verification used bearing oil film analysis

by CAE and engine endurance tests (firing endurance on an engine bench tester), and confirmed the feasibility of application of low-viscosity oil. Note that the viscosity of the Newtonian fluid was calculated by multiplying the kinematic viscosity with the density⁽⁹⁾.

The test results using Newtonian fluid oils were used to create a number of prototype low-viscosity engine oils with an emphasis on fuel economy. Viscosity index improver polymer components were added, so the finally created prototype fuel-economy engine oils were non-Newtonian fluids. As previously mentioned, Newtonian fluids and non-Newtonian fluids exhibit different viscous behavior under shear conditions. To minimize this difference in effects, the viscosity of the prototype fuel-economy engine oils was evaluated by measuring the high-temperature high-shear (HTHS, ASTM D4624) viscosity, which lowers the viscosity of non-Newtonian fluids more than that of Newtonian fluids.

3. SAE Viscosity Standard and Positioning of Commercially Available Oils

Table 1 gives an overview of the current SAE viscosity standard. As shown in Table 1, the SAE viscosity specifies the viscosity at high temperature, but there is no specification for viscosity at normal temperature. However, if the aim is to enhance the fuel economy of engine oil, it is important to understand the viscosity at normal temperature.

Therefore, the viscosity at normal temperature of commercial oils that comply with the SAE viscosity standard was investigated, and this information was used to help set the viscosity of the test oils used in this study. As described in the previous chapter, recent multi-grade engine oils are non-Newtonian fluids, so the viscosity was

organized according to the HTHS viscosity. Figure 1 shows the HTHS viscosity of commercial oils at each temperature. The HTHS viscosity is measured at 100°C and 150°C, and values calculated based on those measured values are used for the HTHS viscosity at other temperatures⁽⁹⁾.

The results of investigating commercial oils confirmed that of the oils complying with the SAE viscosity standard, Honda 0W-20 oil occupies the position with the lowest HTHS viscosity, in any temperature range.

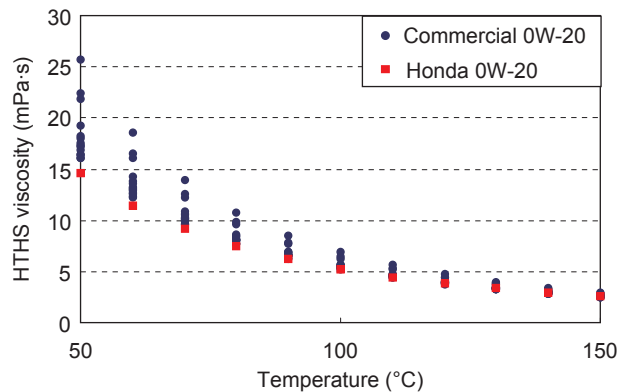


Fig. 1 Market data for commercial oil (HTHS viscosity)

4. Fuel-saving Effects of Low-viscosity Engine Oil

4.1. Determination of Friction Loss Reduction Effects of Low-viscosity Engine Oil

The Stribeck curve is well known as a friction theory⁽⁸⁾. Figure 2 shows a Stribeck curve. Assuming constant load and velocity conditions, the friction coefficient decreases together with the engine oil viscosity under hydrodynamic lubrication (III in Fig. 2). Therefore, when considering the contribution to fuel economy of engine oil under hydrodynamic lubrication, a lower viscosity is effective. However, it is said that when the engine oil viscosity is lowered by too much, mixed lubrication and boundary lubrication that result in metal contact eventually occur, and the friction coefficient increases^{(3), (4)}.

Therefore, it is important to determine the limit of the effects of lowering engine oil viscosity on reducing friction loss.

4.2. Friction Torque Measurement Conditions

The friction torque was measured, which is a typical method of confirming the friction loss reduction effects of engine oil⁽¹⁾. Figure 3 shows the test apparatus used to measure friction torque, and Fig. 4 shows the viscous properties of the test oils used to measure friction torque. The viscosity of the test oils was set based on the results of investigating commercial oils complaint with the

SAE viscosity standard. To understand the fuel-saving effects of simply lowering the viscosity, the friction torque was measured using Newtonian fluid oil (only the base oil) without any additives. Table 2 lists the engine specifications and test conditions used. In consideration of 10-15 mode, which represents typical driving conditions,

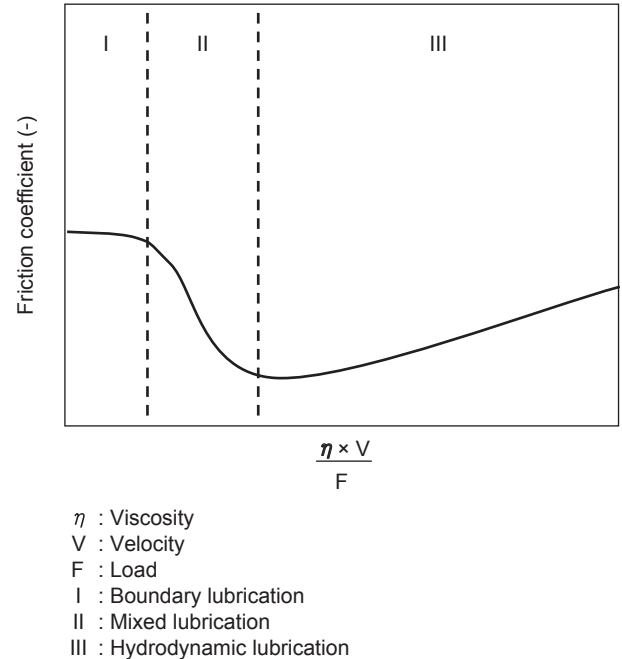


Fig. 2 Stribeck curve

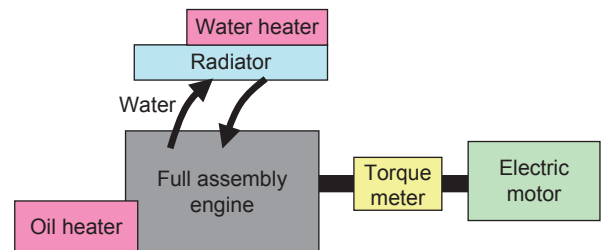


Fig. 3 Schematic diagram of engine motoring tester

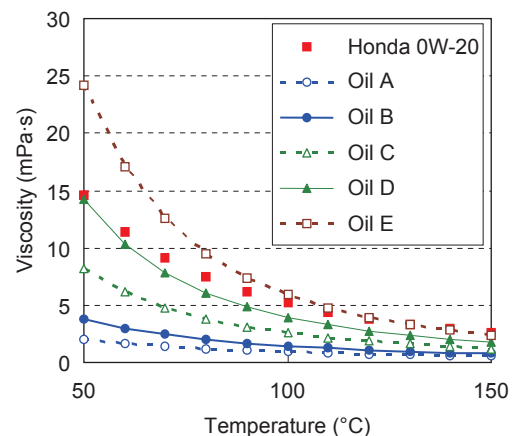


Fig. 4 Viscosity of test oils with engine motoring tester

Table 2 Engine specifications (friction torque tests)

Engine	L13
Number of cylinders and configuration	Inline 4
Valve train	SOHC 4-valve, Roller follower
Displacement (cm ³)	1,339
Bore × Stroke (mm)	73.0 × 80.0
Compression ratio	10.5

the test conditions were an oil temperature of 80°C and engine speeds between 700 and 3500 rpm^{(2),(6)}.

4.3. Friction Torque Measurement Results and Analysis

Figure 5 shows the correlation between viscosity (80°C) and friction torque at each engine speed. The friction torque decreases together with the viscosity at almost all engine speeds, and enhancement of friction torque was confirmed even for engine oil with a viscosity lower than that reported in 1995 by Nagashima et al.⁽⁴⁾ This is thought to be because advances in engine technology such as roller-follower valve trains and reduced surface roughness of each sliding part resulted in lower overall engine friction.

On the other hand, a slight increase in friction torque was confirmed under low engine speed, low-viscosity conditions. This is thought to be because, according to the Stribeck curve theory, the circumferential velocity and viscosity dropped excessively, and the mixed lubrication and boundary lubrication ranges were reached.

4.4. Prediction of Fuel-saving Effects

The results of friction torque measurement were used to predict the fuel economy enhancement effects of the test oils A to E. Equation (1) shows the base formula of the arithmetic algorithm used to predict fuel economy⁽¹⁰⁾.

$$\Sigma G_{fuel} = \Sigma \{BSFC \times Pse \times Hr\} \quad (1)$$

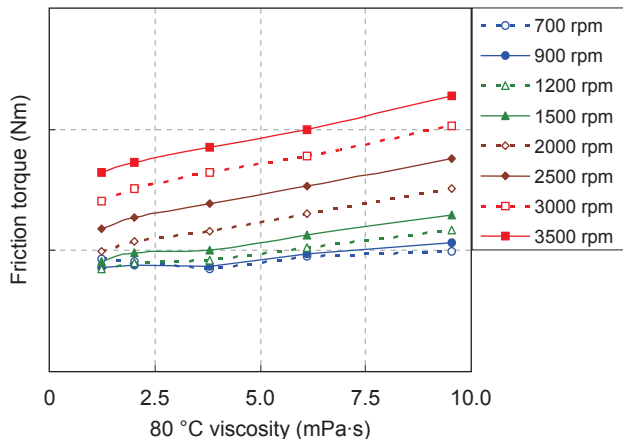


Fig. 5 Friction measured in fully assembled engine

G_{fuel} : Fuel consumption amount
 $BSFC$: Net fuel consumption rate
 Pse : Net output power
 Hr : Time

Equation (2) shows the formula used to calculate G_{fuel} when the test oil is changed, relative to Eq. (1).

$$\Sigma G_{fuel}' = \Sigma \{BSFC' \times Pse \times Hr\} \quad (2)$$

$$BSFC' = \{(Pse + Psf') \times BSFC\} / (Pse + Psf) \quad (3)$$

G_{fuel}' : Fuel consumption amount after changing the test oil

$BSFC'$: Net fuel consumption rate after changing the test oil

Psf : Engine (friction) loss

Psf' : Engine (friction) loss after changing the test oil

Figure 6 shows a concept drawing of the method used to predict the fuel-saving effects. As shown in Eq. (1) to Eq. (3) and Fig. 6, when vehicle characteristics and mode data are present and the net fuel consumption rate, net output power and engine loss (friction torque) have been measured using a standard oil, the fuel-saving effects can be predicted simply by measuring the friction torque of the test oil to be evaluated.

Therefore, Honda 0W-20 oil was used as the standard oil, and the net fuel consumption rate, net output power and friction torque in a Honda L13 engine were measured.

The fuel economy enhancement effects were predicted using these measurement data and the friction torque measurement results shown in Fig. 7. The fuel consumption mode used to predict the fuel economy enhancement effects was the typical 10-15 mode. Figure 7 shows the results of predicting the fuel-saving effects. Figure 7 shows that when the typical actual cruising mode is taken into account, fuel economy enhancement effects are seen even with low-viscosity oil that was confirmed to increase the friction torque slightly under lower engine speed conditions. That

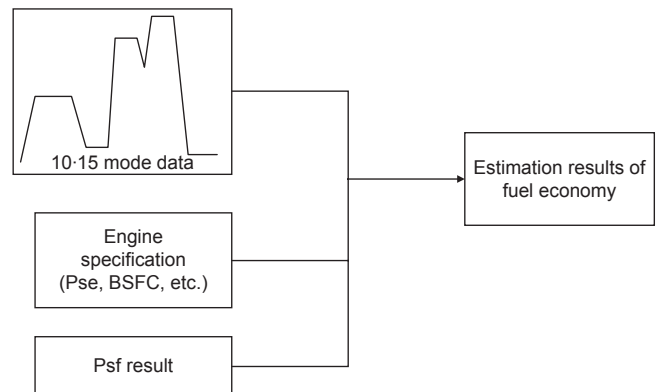


Fig. 6 Simulation model structure

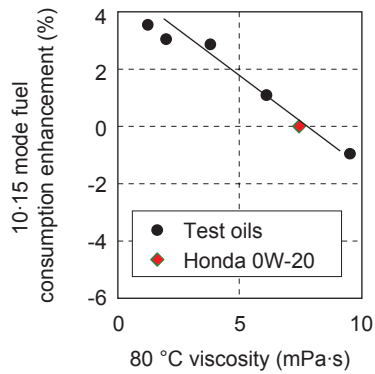


Fig. 7 Relationship between 80 °C viscosity and estimated fuel economy enhancement

is to say, in consideration of fuel economy during actual cruising, the fuel economy performance increases as the viscosity at normal temperature decreases.

5. Effect on Sliding Part Wear

5.1. Concerns of Sliding Wear at High Temperature due to Lower Viscosity

Under high-speed high-load conditions, the engine oil temperature increases and the viscosity decreases, making wear resistance for sliding parts an issue. In particular, the connecting rod big end bearing is given as one of the engine sliding parts most affected by wear due to explosive load and inertia load⁽¹¹⁾. Therefore, the effects of lower viscosity on bearing wear were confirmed using the following two approaches.

- (1) Oil film calculations by CAE
- (2) Engine endurance tests

5.2. Test Oils Used

Table 3 lists the test oils used for the CAE and engine endurance tests. The test oil viscosity was set based on the investigation results of commercial oils compliant with the SAE viscosity standard. In addition, the oil I in the position with the highest viscosity was adjusted so that the viscosity at high temperature is approximately equal to that of Honda 0W-20 oil. Figure 8 shows the viscosity data for the test oils. To understand the effects on sliding wear of simply lowering the viscosity, engine endurance tests were performed using Newtonian fluid oil (only the base oil) without any additives. In addition, oil film analysis using CAE also treated the oil as a Newtonian fluid.

5.3. Oil Film Calculation Method and Conditions

Oil film calculations were performed by elastohydrodynamic (EHD) calculations to take into account the elastic deformation of the connecting rod big end. The oil film characteristics were calculated by calculating the oil film thickness and oil film pressure based on the report by Sato et al.⁽¹²⁾

Table 3 CAE and engine bench test oils

Oil name	CAE	Engine bench
F	✓	
G	✓	
H	✓	✓
I	✓	✓

The connecting rod model and various data used in the calculations were the engine data used in the engine endurance tests described hereafter. The calculation conditions used the same high-speed high-load operation mode as the endurance conditions.

5.4. Results of Oil Film Calculation Using CAE, and Observations

Reducing the minimum oil film thickness raises concerns about metal contact in locations with coarse surface roughness, and increasing the maximum oil film pressure raises concerns about fatigue delamination of sliding parts and other issues. Figure 9 shows the minimum oil film thickness and maximum oil film pressure for each

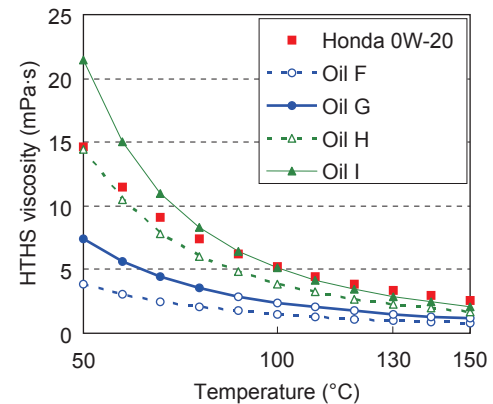


Fig. 8 HTHS viscosity of CAE and engine bench test oils

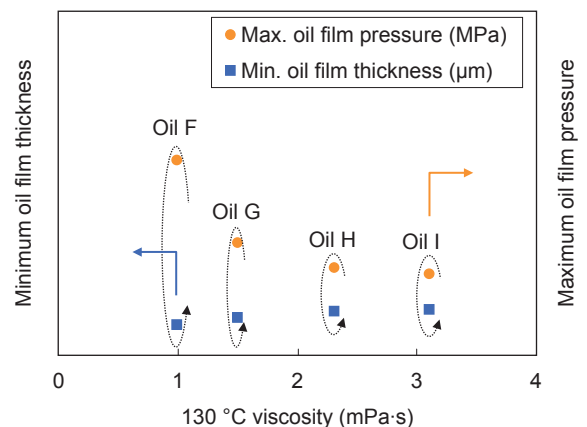


Fig. 9 CAE results of oil film on conrod bearing

Table 4 Engine bench test conditions

Engine	L13
Engine speed	High
Throttle	Wide open
Engine oil temperature	About 130 °C

viscosity, as the result of oil film calculations. Figure 9 confirms that as the engine oil viscosity decreases, the minimum oil film thickness tends to decrease slightly, and the maximum oil film pressure tends to increase noticeably.

The reason for this is thought to be that when the oil film thickness is thin enough, even a slight additional decrease in the thickness produces a considerable reaction effect to try and maintain the oil film. Therefore, when applying low-viscosity engine oil, wear originating in fatigue delamination as the oil film pressure increases is thought to be a greater issue than wear due to metal contact.

When performing engine bench tests using an actual engine, attention was given to this point, and the test oil viscosity was adjusted so that the oil film pressure was almost equal to that of current SAE viscosity standard compliant oil.

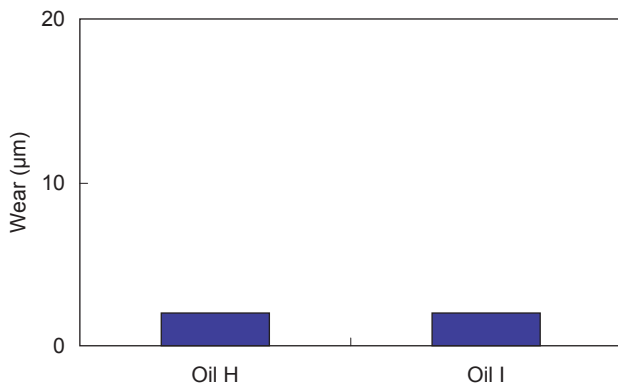


Fig. 10 Average bearing wear results

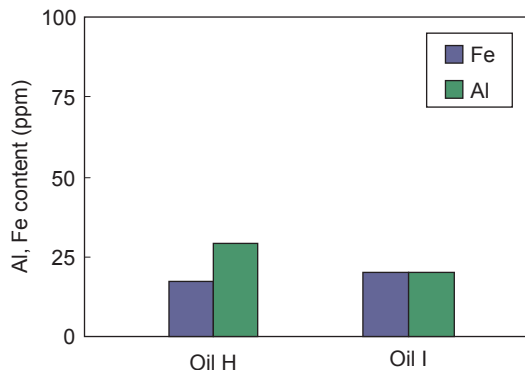


Fig. 11 Metal contents in engine oil after endurance tests

5.5. Engine Durability Test Conditions

Table 4 lists the engine endurance test conditions. To coordinate with CAE, an L13 engine was used, and the test was conducted in the high-speed high-load operation endurance mode. In addition, based on results of calculating the oil film pressure using CAE, the test oils H and I were used in the engine endurance tests.

5.6. Engine Durability Test Results

Figure 10 shows the amount of wear to the connecting rod big end bearing after the engine endurance tests. Figure 11 shows the Fe and Al contents obtained by ICP analysis (ASTM D5185) of the engine oils before and after the engine endurance tests.

The oil I viscosity at high temperature is approximately the same as that of Honda 0W-20 oil, so it is thought that lowering the viscosity would not tend to result in much noticeable wear (Fig. 10). In addition, no noticeable wear due to lower viscosity was confirmed in sliding parts other than the connecting rod big end bearing. As corroborating data, no noticeable increase was confirmed in the Fe and Al contents in the engine oil at lower viscosities (Fig. 11).

These results are thought to indicate that even when the high-temperature viscosity is lower than current SAE viscosity, as long as the generated oil film pressure can be kept to the same approximate level as that of current SAE viscosity standard compliant oil, sliding wear is not an issue.

6. Approach toward Oil Formulation

6.1. Approach toward Oil Formulation of Low-viscosity Oils

Verification was performed using Newtonian fluid oil to understand the relationship between fuel economy and viscosity, and between sliding wear and viscosity. This is because the tests performed as parameter studies were divided into normal-temperature viscosity and high-temperature viscosity. However, in the course of the development, both lower viscosity at normal temperature and maintenance of viscosity at high temperature are demanded, so viscosity index improvers are required. Based on the test results thus far, prototype low-viscosity engine oil was created with the aim of optimizing the viscosity index from the following two standpoints.

- Fuel economy is enhanced as the viscosity at normal temperature decreases.
- To secure resistance to sliding wear at high temperatures, the viscosity should be set so that the oil film pressure does not increase.

Table 5 gives an overview of the prototype oil formulation. A blend of Gr. III, IV and V were used as the base oils to aim for better temperature-viscosity characteristics. Polymethacrylate (PMA), which is highly effective at enhancing the viscosity index, was used as the viscosity index improver to transform the oil into a non-

Table 5 Prototype engine oil formulation

Base oil	Viscosity index improver	Other additives
Gr. III Gr. IV Gr. V	PMA-1 PMA-2	Commercial additive pack (GF-4)

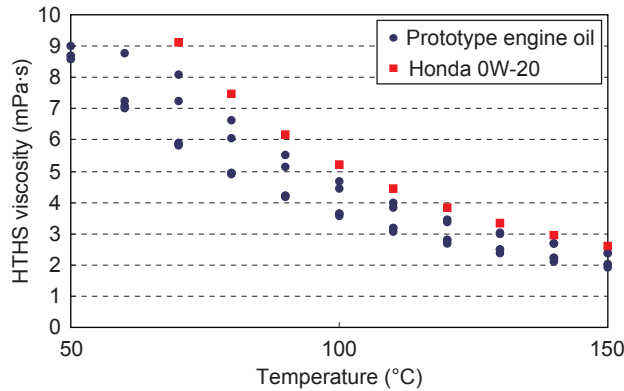


Fig. 12 HTS viscosity of prototype engine oil

Newtonian fluid⁽⁸⁾. Other additives consisted of an additive package equivalent to ILSAC GF-4, which was used to formulate a number of low-viscosity engine oils.

6.2. Prototype Oil Viscosity and Position relative to the SAE Viscosity Standard

Figure 1 shows that of the various 0W-20 oils, Honda 0W-20 oil is positioned with the lowest HTS viscosity at normal temperature. Therefore, when an attempt is made to further lower the HTS viscosity at normal temperature, it is a challenge for the high-temperature viscosity to comply with the current SAE viscosity standard, as seen with the prototype oils in Fig. 12.

7. Conclusions

Fuel-saving effects and sliding wear at high temperature were investigated using low-viscosity engine oil in the tested mass-production engine. The results yielded the following information.

- (1) Even when the viscosity at normal temperature is reduced, almost no effect to increase friction due to boundary lubrication or mixed lubrication was confirmed, indicating that reducing viscosity is an effective means of creating fuel-economy engine oil.
- (2) The effects on sliding wear at high temperature were verified, and the results provided prospects for wear resistance even at viscosities lower than specified in the current SAE viscosity standard.
- (3) When viscosity at normal temperature is reduced to a certain level or less, it is a challenge to comply with the high-temperature viscosity prescribed by the SAE viscosity standard.

These results indicate that to pursue further fuel

economy by lowering the engine oil viscosity, additional low-viscosity standards should be established in the SAE viscosity standard.

8. Future Prospects

This study presented the effects of low-viscosity engine oil, and prospects for wear resistance of sliding parts at high temperature, which is one of the greatest issues. However, it is thought that attention should be given to the following points in order to actually apply engine oils with a lower viscosity than specified in the current SAE viscosity standard to mass production.

- Consideration for hydraulic mechanisms due to a predicted drop in oil pressure.
- Consideration for engine oil evaporation and other items in standards such as those prescribed by the International Lubricant Standardization and Approval Committee (ILSAC).
- Consideration for engine reliability related to phenomena thought to be the boundary lubrication and mixed lubrication at low engine speeds confirmed as a result of friction torque measurements.

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