# FUEL, LUBRICANT AND GREASE

## 1 Introduction

West Texas Intermediate (WTI) crude oil is a benchmark for pricing all crude oil and the price of WTI rose to around $50 USD per barrel during the first half of 2016 to recover from the decline it suffered during the second half of 2015 when it had fallen to a price of $30 USD per barrel. However, by the latter half of 2016 it had once again fallen to around $40 USD per barrel in early August before rising again and then it remained in a relatively narrow range of about $50 USD per barrel ± $5 USD(1).

The amount of crude oil imported into Japan in 2016 was 192.72 million kL, a decrease of 1.6% from the previous year, while the amount of crude oil processed in Japan was 190.87 million kL, a 1.0% increase over the previous year(2) (Fig. 1).

Figure 2 shows the changes in the Japanese fuel oil sales volume(2). The total fuel oil sales volume in 2016 was 178.19 million kL (a decrease of 2% from the previous year) and the sales volume of both gasoline at 52.84 million kL (0.5% decrease) and diesel at 33.41 million kL (0.8% decrease) were less than the previous year.

On April 3, 2017 the 4th Petroleum Market Trend Survey Working Group of the Japanese Ministry of Economy, Trade and Industry (METI) met to forecast future demand for petroleum products, and deliberated on and approved the FY 2017 to FY 2021 Petroleum Product Demand Forecast (proposal)(3). This forecast reported that the average demand from 2017 to 2021 for total fuel oil (excluding C heavy oil for generating electric power) would decrease by 1.5% per year, demand for gasoline would decrease by 2.2%, and demand for diesel oil would remain almost flat. The forecast noted that the main causes of the decrease in demand for gasoline are the decrease in the total number of miles that gasoline vehicles are being driven and the improved fuel economy of modern vehicles promoted via the popularization of environmentally-friendly vehicles and advances in low-fuel consumption technologies.

## 2 Fuels

### 2. 1. Fuel Trends

According to the Second Notice of the Act on Promotion of Use of Non-Fossil Energy Sources and Effective Use of Fossil Energy Material by Energy Supply Operators (the Act on Sophisticated Methods of Energy Supply Structures), petroleum refiners in Japan shall examine "Measures for optimizing facilities and equipment (improving the installation ratio of residual oil processing equipment)" and "Policies for business restructuring" by March 31, 2017. The results of these efforts were announced on April 6, 2017, and Table 1 shows the residual oil processing equipment installation ratio of each compa-

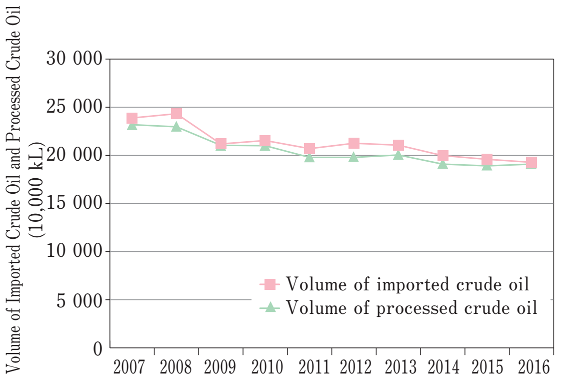

Fig. 1 Volume of Imported Crude Oil and Processed Crude Oil in Japan

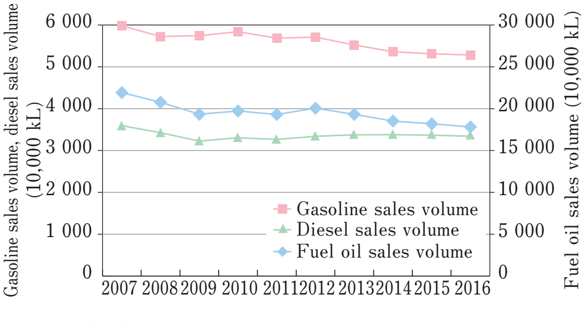

Fig. 2 Changes in Japanese Fuel Oil Sales Volume

**Table 1 Residual Oil Processing Equipment Installation Ratio of Each Company**

| | Installation ratio on March 31, 2014 (*4) | Targeted percentage improvement in installation ratio | Installation ratio on March 31, 2017 (*4) | Remarks |
|---|---|---|---|---|
| JX Energy (*2) | 46.2 % | at least 11 % | 51.2 % | |
| TonenGeneral Sekiyu (*2) | 35.9 % | at least 13 % | 40.6 % | |
| Idemitsu Kosan | 51.5 % | at least 11 % | 57.2 % | |
| Cosmo Oil Company | 43.4 % | at least 13 % | 49.0 % | |
| Showa Shell Sekiyu (*3) | 59.4 % | at least 9 % | 64.8 % | |
| Fuji Oil Company | 48.3 % | at least 11 % | 52.4 % | (*5) |
| Taiyo Oil Co., Ltd. | 24.6 % | at least 13 % | 23.2 % | (*5) |

*1: Residual oil processing equipment installation ratio = processing capacity of residual oil processing equipment ÷ capacity of normal pressure distillation equipment

*2: JX Energy includes Kashima Oil Co., Ltd. and Osaka International Refining Co., Ltd. TonenGeneral Sekiyu includes the former Kyokuto Petroleum Industries, Ltd. JX Energy and TonenGeneral Sekiyu merged their companies on April 1, 2017 and changed the name to JXTG Energy.

*3: Showa Shell Sekiyu includes Toa Oil Co., Ltd., Showa Yokkaichi Sekiyu Co., Ltd., and Seibu Oil Co., Ltd.

*4: The installation ratio is based on notifications from each company (figures rounded up from the second decimal place). The calculation of the installation ratio as of March 31, 2014 included the changes in capabilities that were implemented to comply with the judgment criteria established in 2010.

*5: Efforts to implement measures to improve the residual oil processing equipment installation ratio based on Note (1) viii) of the judgment criteria.

ny(5). Furthermore, the installation ratio of residual oil processing equipment in Japan reached 50.5%, reaching the target (approximately 50%) specified in the judgment criteria of the Notice.

The Act on Sophisticated Methods of Energy Supply Structures also set targets for the introduction of biofuels into the Japanese market and these targets were 440,000 kL of crude oil equivalent in 2016 and 500,000 kL of crude oil equivalent in 2017.

The Act on Sophisticated Methods of Energy Supply Structures stipulated an increase in the installation ratio of residual oil processing equipment and as a result it has now become more important than ever before to expand the use of cracked distillates. Consequently, the petroleum industry and automotive industry conducted a joint research project called JATOP II (Japan Auto-Oil Program II) to evaluate automobiles and fuels for the three years from 2012 to 2014. JATOP II consisted of two working groups, the Diesel Vehicles Future Fuel Working Group and the Atmospheric Research Working Group. The Diesel Vehicles Future Fuel Working Group examined the impacts of the use of fuels made from cracked diesel oil distillates on the various performance aspects of a diesel vehicle. The purpose of these examinations was to identify and understand the practical problems of using these fuels, as well as obtain technical knowledge that would allow the eventual introduction of these fuels to the market.

In 2015 the JATOP III (Japan Auto-Oil Program III) program was begun, and it will conclude in 2017.

### 2. 2. Gasoline for Automobiles

In the above-mentioned JATOP III program, participants assumed that the use of cracked gasoline distillates will increase, and the impact of using such fuels, which have increased levels of olefin components and heavy aromatic content, on vehicle emissions is being researched(6).

Other research into gasoline fuels has reported on the relationship between the fuel octane number and knock generation in a high compression-ratio engine(7). That research compared the knock characteristics obtained from engine experiments and those obtained using the Livengood-Wu integral, which is widely used to predict the knocking occurrence timing. It also found that the prediction accuracy of the Livengood-Wu integral decreased when low-RON fuel is used and the engine operates at a high rotation speed, and clarified the need to consider the cycle fluctuations and negative temperature range (NTC: negative temperature coefficient) in the temperature dependence of the ignition delay to improve prediction accuracy.

Fundamental combustion characteristics, such as the ignition delay and laminar burning velocity of gasoline, as well as the detailed chemical reaction mechanisms to reproduce them, have been studied for a long time with several reports on these topics published in 2016(8)-(10). One particularity of the reports published in 2016 was that the reported results came from research carried out as part of the Innovative Combustion Technology program within the Cross-ministerial Strategic Innovation Promotion Program (SIP) of the Cabinet Office in Japan[8]. In this research, the ignition delay of SIP common gasoline (equivalent to commercial gasoline) and SIP common surrogate fuel (fuel that simulated SIP common gasoline using isooctane, n-heptane, toluene, diisobutylene, and methylcyclohexane) were measured with a rapid compression machine, and these measurements were compared to a detailed chemical reaction model of the SIP common surrogate fuel. Although the ignition delay calculated from the detailed chemical reaction model was longer than the experimental value, it was reported that the trends in the experiment were largely reproduced.

In addition, the results of evaluating the hardness of the deposits produced in the combustion chamber using a nanoindenter were also reported[11]. In this research the deposits were analyzed by categorizing them based on source and hardness according to whether they were produced from fuel or oil, and whether adjusting operating conditions made them hard or soft. The maximum hardness of the deposits derived from oil was about 30 GPa, while the maximum hardness of deposits derived from fuel was relatively soft at about 9 GPa. The amount of accumulation of the deposits was also examined and reported to reach the point of saturation at a thickness of approximately 0.4 mm.

### 2. 3. Diesel Fuel for Automobiles

One of the problems that remained to be solved at the completion of JATOP II was the increase in load on DPF regeneration when a low-cetane number diesel fuel with high aromatic content was used. Consequently, in JATOP III the effects of the various measures implemented in both the vehicle and the fuel to address this problem were evaluated[6].

Other research into diesel fuels examined the effects of the properties of low cetane number fuel on the combustion and exhaust characteristics of diesel engines[12]. In that research, testing was carried out using fuels with cetane numbers that varied from 40 to 55, as well as fuels with different compositions (saturation component, aromatic content), but a fixed cetane number of 45. In the fuels with a fixed cetane number but different compositions, a difference in the ignition delay under high-EGR conditions and more sluggish combustion were observed at high aromatic content. In addition, the results indicated that the use of pilot injection for low cetane number diesel fuel made it possible to suppress the amount of $NO_x$ and soot emissions. It was also revealed that the net fuel consumption rate and noise of a low cetane number fuel could be improved in comparison to the conventional approach by increasing the pilot injection ratio and performing split injection to divide combustion into two phases.

Other research investigated the influence of the distillation properties and cetane number of diesel fuel on ignition characteristics[13]. In that research the influence of the distillation properties and cetane number were examined using normal diesel fuel, high-cetane number diesel fuel (approximately 80), and hydrogenated bio-diesel fuel with light distillation properties (T90 ≒ 240℃). The results indicated that the distillation properties affected premixed and diffusive combustion, while the cetane number affected the time required to go from cool flame to hot flame in the high-temperature region.

Diesel fuel has a larger number of carbon atoms and its structure is more complicated than gasoline so the chemical reaction mechanisms of diesel fuel are often studied using a simulated surrogate fuel with lighter hydrocarbons. A simplified reaction model that could predict ignition delay with adequate precision over a wide operating range in diesel engines has been developed. In this model, the reactive portion of isooctane was removed from the elementary reaction model of heptane-isooctane mixed fuel and a reaction mechanism with a hydroxyl-based reaction was used[14].

## 3 Lubricants

### 3. 1. Automotive Lubricant Oil Standards

### 3. 1. 1. Gasoline Engine Oil

The next generation of the gasoline engine oil standard will be ILSAC GF-6, but the introduction of this standard has been postponed due to a delay in the development of the new test methods, with the fourth quarter of 2018 now considered the earliest time it could be introduced.

The main goals of the new GF-6 standard compared to the existing GF-5 standard are to improve vehicle fuel economy and sustainability, improve compatibility with the exhaust system, improve the robustness of the engine oil to better protect the engine, improve the ability to prevent low-speed pre-ignition (LSPI), and improve the wear resistance of various engine components, such as the timing chain valve train system.

Many of the current engine tests in the existing ILSAC GF-5 standard will be changed in the new ILSAC

GF-6 standard, and there are also plans to add a chain wear test and an LSPI prevention performance test. The development of Sequence III H, a high temperature oxidation stability test, has been completed and can now be registered based on the ACC Code of Practice. Although the standard values are still under discussion, the evaluation items in Sequence III H are a viscosity increase and high temperature deposits. Furthermore, the average wear of the cam and lifter required in the existing Sequence III G will no longer be required. The development of Sequence VI E, a fuel economy performance test for engine oils with a viscosity grade of 0W-20 or higher, was completed and approved as a test method by ASTM. Other engine tests are under development, with tests to confirm precision either already implemented or in the process of having their results confirmed.

Engine oils with the current viscosity grades of 0W-20 and higher in ILSAC GF-5 are expected to fall under the ILSAC GF-6A standard, while the XW-16 viscosity grade oils will fall under ILSAC GF-6B standard due to the difference in viscosity grades. Evaluations of the fuel economy performance shall be stipulated to use the Sequence VI F test in ILSAC GF-6A and the Sequence VI E test in ILSACGF-6B(15)(16).

Oils with a viscosity grade of XW-16 are becoming more widespread. In terms of standards, these oils were only recognized under the API SN category in the past, but as of March 16, 2016 it became possible for them to be certified as API SN/Resource Conserving (RC). Fuel economy performance is stipulated to be FEI SUM 2.8% or higher and FEI2 1.3% or higher in the Sequence VI D test, but otherwise the performance requirements are the same as those for other viscosity grade oils.

In Europe the ACEA 2016 standard was issued on December 1, 2016. In addition to the changes made to the piston detergency test, the standard values were set in the CEC L-104 test for engines using bio-fuels, and the CEC L-109 test, an on-bench test for engines using bio-fuels, was added. Furthermore, the A1/B1 category was eliminated from the A/B class. In the C class, the C5 category was introduced for XW-20 oils and it became possible to register low-viscosity oils, such as 0W-20.

### 3. 1. 2. Diesel Engine Oil

In Japan a revision of the automotive diesel engine oil standard (JASO M355) is scheduled for April 2017. The revision will introduce JASO DH-2F, which adds fuel economy performance to the existing JASO DH-2, and JASO DL-0, which addresses Euro 4-compliant fuels (with a sulfur content of 500 ppm or less), are planned to be added(17).

The fuel economy performance of JASO DH-2F shall be stipulated in accordance with the N04C fuel economy test. In the U.S. and Europe the fuel economy of heavy-duty diesel engine oil is specified by the HTHS viscosity at 150℃, whereas in JASO DH-2F it is evaluated via an engine test.

The N04C fuel economy test was developed by the JASO diesel engine oil standard revision task force set up in April 2012. It is the world's first public fuel economy test method for heavy-duty diesel engine oil using an engine test. This test uses the same engine that is used for the piston detergency and the valve train wear tests, and evaluates the fuel economy performance of both new oil and degraded oil assumed to have been used in a vehicle that has traveled for tens of thousands of kilometers. The test considers the fact that heavy-duty vehicles are used in a wide variety of ways, so the testing of the new oil and degraded oil is conducted using two test oil temperature conditions: 60℃ and 90℃. The average of these results is then used as the standard value. The JASO DH-2F standard is expected to stipulate fuel economy performance requirements representing an improvement rate of 3.7% or more for new oil in comparison to the reference oil (SAE 30), and a total improvement rate of 6.8% or more relative to the reference oil for the new oil and degraded oil combined(18).

JASO DL-0 is a standard for Asian regions where exhaust emissions regulations at Euro 4 or lower levels are in force. In these regions, many API CF-4 engine oils from the 1990s are still used as the recommended engine oil in the market, but standards for those oils expired in 2008. Consequently, JASO DL-0 is being considered to maintain the quality of the oils in those markets. In comparison to the JASO DL-1 standard, the JASO DL-0 standard does not have fuel economy performance requirements, and the amount of sulfated ash has been relaxed to 1.6% of mass, while the base number is required to be 8.0 mg-KOH/g or higher.

In the U.S. the API CK-4 and FA-4 standards were introduced in December 2016. In comparison to the existing API CJ-4 standard, these new standards have stricter requirements for high-temperature oxidation stability, shear stability, and oil aeration performance. One of the major differences between these new standards is the

HTHS viscosity at 150℃. In API CK-4 the viscosity is set at 3.5 mPa·s or higher, which is the same as in API CJ-4, but in API FA-4 it is set to a range of 2.9 to 3.2 mPa·s. While API CK-4 can be used for existing vehicles, API FA-4 is designed only for vehicles that meet 2017 model year on-highway greenhouse gas emission standards(19).

In Europe, as previously mentioned, the ACEA 2016 standard was issued in December 2016. In the E Class for heavy-duty vehicles, the CEC L-109 bench test using biofuels was added to all categories, and the CEC L-104 engine test using biofuels was added to ACEA E6 and E9. Consequently, the engine tests and bench tests were changed, but the categories were not.

#### 3. 1. 3. Four-Cycle Engine Oils For Motorcycles

JASO T903, which is a 4-cycle engine oil standard for motorcycles that is widely used in Japan and overseas, was revised in March 2016. The main points of the 2016 revisions were to ensure correlation between the classifications in JASO T903-2006 and to review the friction characteristics test method. Reviewing the friction materials and standard oils used in the test, the test conditions and methods of calculating the indices, and the classification thresholds established a proper correlation with the JASO T903-2006 standard, and appropriate classification became possible(20).

### 3. 2. Automotive Lubricant Technology Trends

#### 3. 2. 1. Gasoline Engine Oil

The growing demand for gasoline engine oils to provide better fuel economy performance is making technologies that reduce oil viscosity and improve viscosity characteristics more important. It has now become possible for 0W-16 oils to receive API SN certification, and examples of the development of these fuel-efficient API SN 0W-16 oils have been reported(21). 0W-16 is the lowest viscosity standard for API certified oils, but to further improve fuel economy, the performance of even lower viscosity oils such as 0W-8 and 0W-4 oils, which are currently being examined under the SAE J300 standard, is being investigated. While engine oils with lower viscosities are expected to improve fuel economy performance, they also involve several issues, such as decreases in oil pressure retention, decreases in oil film thickness, and a worsening of evaporation characteristics.(22)

#### 3. 2. 2. Diesel Engine Oil

Fuel economy regulations for heavy-duty diesel engine vehicles are beginning to be introduced in many countries, leading to growing demand for diesel engine oils to provide better fuel economy performance. Low-viscosity oils are now being used as these more fuel-efficient diesel engine oils, and a new oil that not only has lower viscosity, but also helps cope with fuel dilution through improved viscosity characteristics, has been developed(23). Reducing the viscosity of diesel engine oils and improving additives, such as viscosity index improvers, have proven effective at improving fuel economy performance, but there are concerns that this will lead to poorer wear resistance and piston detergency. It has been reported that an evaluation of low-viscosity diesel engine oil used in a fleet test found no problems with wear and oil deterioration(24). Furthermore, it was also reported that the detergency of the piston underside could be improved by blending an additive that contains boron(25).

#### 3. 2. 3. Gear Oils

In addition to good fuel economy performance, high reliability and a long service life are also being demanded of environmentally-friendly technologies. The application of Group III and Group IV base oils is desirable for high reliability and long service life. However, taking availability in various countries around the world into consideration, gear oil with a long-service life has been developed from Group I and Group II base oils(26).

## 4 Grease

As fuel economy regulations for automobiles continue to become more stringent, various automobile parts are being made smaller and lighter and also becoming electrified. Consequently, there is growing demand for the development of low-torque grease for use with these parts. The development of low-torque grease is being carried out on a wide scale, and one case involving the development of low-torque grease for the worm reduction gear in an electric power steering unit has been reported(27).

In addition to low torque, various other functions are required of modern greases. For example, decreasing the size of an electric motor increases the amount of heat generated within that motor. This subjects grease to a more severe usage environment, and requires a long service life in a high-temperature region. Although lithium-soap-based grease is widely used as a thickener, it has insufficient service life in a high-temperature environment, and the adoption of urea as a thickener is anticipated to become more frequent(28).

The growing trend in the automotive industry toward more electric-powered vehicles such as full electric vehicles (EVs) and hybrids (HEVs) also has important implications for grease. Until now the driving sounds of various vehicle motors have been drowned out by the louder sounds coming from the engine and other sources. However, as more vehicles switch to running on electric power alone, it will become impossible to ignore the noise generated by grease in the electric motors. Therefore, demand for grease that can provide quiet motor operation is rising. Improving manufacturing processes was reported to enhance acoustic characteristics(28). Grease retention performance is a critical in raising the speed of EVs and HEVs. Consequently, several cases involving adapting grease to high-speed motors by applying synthetic oil, optimizing the base oil viscosity, and lowering grease consistency have been reported(29).

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