Engines for Alternative Fuels

1 Introduction

Until this year, the Year Book included a chapter called New Powerplant Systems. This chapter described engines that run on fuels other than gasoline and diesel, i.e., liquid petroleum gas (LPG) engines, natural gas engines, hydrogen engines, dimethyl ether (DME) engines, and Stirling engines, in addition to biofuels. However, since fuels are also partially covered in the Conservation of Resources in the Automobile Industry chapter, a review of the categories covered by the Year Book decided to move the biofuels section to that chapter. As a result this chapter has been renamed Engines for Alternative Fuels and now focuses on the specific trends of alternative fuel engine technologies.

2 LPG Engines

The number of registered vehicles in Japan that run on LPG has been decreasing steadily since reaching a peak of 319,000 in 1991. In 2013, this figure was 236,000, a decrease of around 8,000 vehicles from 2012. The reasons behind this decline are the long-term rise in LPG prices and the erosion of the relative cost merit of LPG vehicles as gasoline vehicles become more fuel efficient.

Most of the LPG imported into Japan is produced in the Middle-East, and the import price is strongly influenced by the contract price (CP) published by the Saudi Arabian Oil Company (also known as Saudi Aramco), a national petroleum company in Saudi Arabia. However, the production of natural gas is dramatically increasing in North America, resulting in higher production of LPG derived from this source. The LPG market price in this region (called the Mont Belvieu price) is lower than the CP. It has been pointed out that, if Japan imported LPG from North America, the CP might cease to be the dominating force in the market, causing the price of LPG to fall. It currently takes 35 to 45 days to transport gas from North America to Japan, from ports of loading on the eastern or southern coasts, across the Atlantic Ocean, and through the Suez Canal or around the Cape of Good Hope. However, once expansion work of the Panama Canal is completed (scheduled date of completion: 2016), the transportation time will be halved to 20 days, which should make it easier to import cheaper LPG from North America.

Focusing on technological developments, two reports were published in 2013 describing research to accurately measure the octane number, one of the fundamental properties of fuel. The octane number of a conventional liquid fuel can be measured using Cooperative Fuel Research (CFR) engines. However, these engines are not designed to handle gaseous fuels. Morganti, Dryer, et al. added a supply system capable of independently adjusting the flow rates of the four main components of LPG (propane, propylene, n-butane, and i-butane) into a conventional CFR engine to measure the octane number of LPG. This method was used to measure the research octane number (RON) and motor octane number (MON) of each element separately and as a mixed gas. The octane numbers obtained using this method matched those measured in accordance with the test method defined by the American Society for Testing and Materials (ASTM) from the 1940s to 1960s and currently expired.

Genchi et al. measured the MON of a mixed fuel containing LPG (MON: 92.6) and commercially available gasoline (MON: 84.1) by changing the fuel supply method from a carburetor to an injector based on a CFR engine. Based on this result, an empirical formula was obtained for obtaining the MON of a mixed fuel with respect to the LPG content in the mixture. According to this method, a fuel with a LPG content of 30% has a MON of 88.1, and a fuel with a LPG content of 40% has a MON of 90, which is equivalent to premium gasoline. Therefore, mixing LPG into gasoline may be regarded as a way of increasing the octane number of the fuel.

The Hyundai research group reported on the particle

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number (PN) of emissions from gasoline direct injection (DI) and LPG direct injection (LPDI) engines. In the case of LPDI, most PM emissions are nucleation mode particles with a size of 23 mm or less. In the Federal Test Procedure of the U.S. Environmental Protection Agency (commonly known as the EPA Federal Test Procedure or FTP-75), the PN of LPDI emissions was 60% lower than that of gasoline DI.

Other notable reports described the emissions performance of large LPG engines for buses, improvements to the injection performance of a lean-burn LPDI engine, and safety evaluations of LPG tanks for passenger vehicles.

3 Natural Gas Engines

On May 17, 2012, the U.S. Department of Energy announced that it would permit the export of liquid natural gas (LNG) to countries such as Japan that had yet to sign a free trade agreement (FTA) with the U.S. As a result, exports of LNG to Japan are due to start in or around 2017. The resulting diversification of LNG procurement should help to lower the price of natural gas in Japan.

In December 2012, the Japanese government announced the Basic Act for National Resilience Contributing to Preventing and Mitigating Disasters. This Act calls for activities to promote the popularization of compressed natural gas (CNG) vehicles to help improve energy security in the fields of transportation and logistics. As a result, the use of natural gas vehicles (NGV) is gaining momentum in Japan.

At the end of 2013, there were roughly 19.9 million NGVs on the road worldwide, an increase of around 2.7 million from 2012. Of this total, there were 46,603 NGVs on the roads in Japan as of the end of March 2014.

In June 2012, Isuzu Motors Ltd. announced that it would launch a large CNG vehicle (gross vehicle weight (GVW) class: 25 t), start monitored test drives of LNG vehicles, and develop an ultra-high efficiency natural gas engine using a technique called dual fuel compression ignition. In addition, Mazda Motor Corporation unveiled the Mazda3 SKYACTIV-CNG Concept (Fig. 1) at the Tokyo Motor Show in January 2012. This vehicle uses a dual-fuel system that enables it to switch between running on gasoline or CNG.

Outside Japan, in June 2012, the Swedish automaker Scania AB delivered the world's first natural gas truck that complies with the Euro 6 emissions regulations to a delivery company in Sweden. Scania has designed two Euro 6-compliant engines with the same performance as a diesel engine. The power ratings of these engines are 280 hp (torque: 1,350 Nm) and 340 hp (1,600 Nm).

Basic research for natural gas engines is mainly being carried out by Universities. Waseda University is running a trial of an auxiliary ignition method using diesel injection to control combustion, including homogeneous charge compression ignition (HCCI) in a natural gas engine. This research has confirmed that stable ignition and combustion can be achieved by adjusting the supply proportion of diesel, even with high rates of exhaust gas recirculation (EGR), which conventionally make it difficult

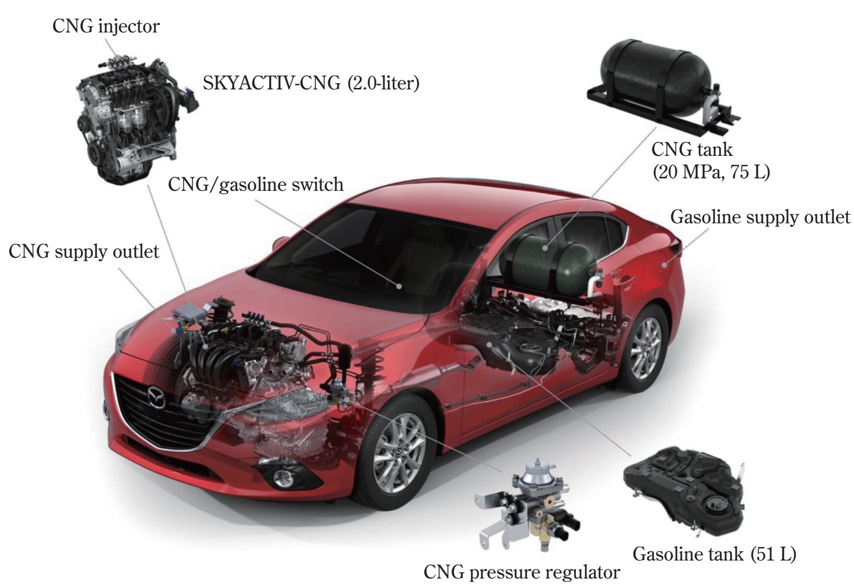

Fig. 1 Mazda3 SKYACTIV-CNG Concept.

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to ignite the fuel. Honda R&D Co., Ltd. is working on identifying the effects of the combustion chamber shape in a high-compression ratio natural gas engine. By comparing two prototype engines with the same displacement but different stroke/bore ratios of 1.0 and 2.1, this research has confirmed that brake thermal efficiency can be increased by 9.1% with a stroke/bore ratio of 2.1 (39.0%) compared to a stroke/bore ratio of 1.0 (29.9%).

As a result of this research, it is hoped that several automakers will launch natural gas vehicles powered by highly efficient engines in Japan in the near future.

4 Hydrogen Engines

Hydrogen is regarded as having a critical role to play in the future to help improve energy security and address global warming. Hydrogen engines use the same power source as fuel cell electric vehicles (FCEVs) but can be realized at a lower cost by using existing production equipment and auxiliary equipment based on well-established technology. Universities, research institutions, and automakers inside and outside Japan are currently researching these engines. The issues of hydrogen engines include restricting abnormal combustion caused by the high ignitability of hydrogen, measures to counter the large quantities of NOx generated in high power regions, and improving thermal efficiency. In recent years, research has started to focus on DI as a way to help resolve these issues.

In 2013, several research papers were published both inside and outside Japan. Published research in Japan included papers by the Tokyo City University and the National Traffic Safety and Environmental Laboratory (NTSEL) group, Mazda, and Toyota.

The Tokyo City University and NTSEL group proposed a combustion concept that ignites a rich mixture plume during the injection period or directly after the completion of injection (called the Plume Ignition Combustion Concept (PCC)). Shadowgraph analysis was carried out to identify why thermal efficiency in partial load operation improved in comparison with pre-mixed combustion. This analysis found that this method increased combustion speed, reduced unburned hydrogen, and lowered cooling loss. However, the issue of increased NOx remains.

Mazda is developing a low-pressure DI hydrogen rotary engine, taking advantage of the suitability of rotary engines for low-pressure DI. Computer aided engineering (CAE) analysis of the mixture distribution suggested potential improvements in thermal efficiency by optimizing the direction and timing of injection. Furthermore, a vehicle equipped with a hydrogen rotary engine as a range extender had NOx emissions substantially below super ultra-low emission vehicle (SULEV) standards in the JC08 test cycle when used in combination with lean-burn and a NOx storage catalyst.

Toyota is researching a NOx-free argon circulated hydrogen engine with high thermal efficiency. This engine uses an argon circulation method in which oxygen is supplied to an argon-filled intake manifold, hydrogen is directly injected and combusted, and the water vapor combustion by-product is separated from the exhaust gas by condensation. This research has confirmed the auto-ignition performance of this method, the combustion chamber shape, injector nozzle position, oxygen concentration, and number of injector nozzle holes. As a result, this engine achieved an indicated thermal efficiency of 60.9% by improving the degree of constant volume and reducing cooling loss.

Outside Japan, the University of Michigan and Ford Motor Company group has developed a dual zone combustion system in which hydrogen is injected to the left and right of the cylinder head center and one spark plug is provided on each side. This engine achieved an indicated thermal efficiency of 47.7% and NOx emissions of 51 ppm.

5 DME Engines

After the so-called shale gas revolution, research in North America has begun to study DME as a way of making use of the abundant natural gas resources in the region. In a press release on June 6, 2013, Oberon Fuels announced that it would start North America's first production of fuel-grade DME at a mini plant starting in 2015. The company has also started standardization of DME fuel quality at the ASTM. In addition, Volvo issued a press release on June 7, 2013 stating that it would start mass production of a DME truck in North America from 2015.

The standardization of DME fuel is being promoted through discussions in the International Organization for Standardization (ISO)/TC 28/SC 4/WG 13. Draft international standard (DIS) balloting has been completed with respect to DME quality as a base fuel including for vehicles (ISO DIS 16861), and four analytic methods

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under discussion by WG 14 in the same organization (determination of total sulfur by the ultraviolet fluorescence method (DIS 17198), determination of evaporation residues (DIS 17786), determination of water content (DIS 17197), and determination of impurities by the gas chromatographic method (DIS 17196)). Various technical comments were received so these DIS are still waiting for registration as final draft international standards (FDIS). If a majority in favor is obtained by FDIS balloting within two months, it is planned to issue these as ISO standards in 2014. Gradual studies of DME fuel quality for vehicles is also due to start.

6 Stirling Engines

Stirling engines have mainly been practically adopted for combined heat and power (CHP) systems for ordinary households, solar power generation, and as a closed-cycle engine for propulsion and power generation on submarines. Commercial projects using these applications, in addition to engines and engine systems in or close to mass production are as follows. Infinia Corporation in the U.S. has developed a 3.5 kW class solar power generation system using a free-piston Stirling engine. A solar farm consisting of 429 dishes (1.5 MW) using this system has been installed at the Tooele U.S. Army Base. At the end of last year, Qnergy acquired the assets of Infinia Corporation and started preparing to mass-produce 3.5 and 7.5 kW-class free-piston engines developed by Infinia. The main applications for these engines are CHP systems for ordinary households and solar power generation.

In addition, a CHP unit for ordinary households fueled by utility gas (power generation capacity: 1 kW, heating capacity range: 3 to 24 kW) has already been commercialized. MEC in the UK and the Netherlands are mass-producing a 1 kW-class free-piston engine generator in China. Production last year reached 5,000 units.

Other Stirling engine-based CHP units include a 1 kW-class 4-cylinder double-acting engine generator developed by Whisper Tech Ltd. in New Zealand (power generation capacity: 1 kW, heating capacity range: 7.5 to 14.5 kW) and a 10 kW-class single acting alpha-type V-cylinder arrangement engine developed by Cleanergy in Sweden (power generation capacity: 2 to 9 kW, heating capacity range: 8 to 26 kW).

Units under development in Japan include 0.2 kW to 10 kW-class engines for relatively low-temperature waste heat and biomass combustion power generation using waste heat from vehicle engines, marine diesel engines, and factories. However, these are either still in the development phase or are only available on a made-to-order basis.

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