Engines for Alternative Fuels

1 Introduction

The fourth Strategic Energy Plan was formulated in April 2014 (1). Adopting a long-term, comprehensive view, the Strategic Energy Plan first formulated in October 2003 based on the Basic Act on Energy Policy established in June 2002, aims to ensure the stable pursuit of energy policies. The plan is subject to revision a minimum of once every three years. The second plan was released in March 2007, and the third in June 2010. After that, the impact of events such as the Great East Japan Earthquake triggered considerable changes in the energy situation both in Japan and abroad, leading to calls for sweeping policy changes that resulted in the formulation of the fourth strategic plan.

Section 8 of that plan, "Future of the secondary energy structure such as hydrogen that contributes to stable supply and global warming countermeasures," discusses the use of technologies related to storage batteries and hydrogen. In the automotive field, the plan also notes that "that biofuels, electricity, natural gas, LP gas and hydrogen are available as energy sources, an environment is being developed where choice by consumers promotes competition not only between oil products such as gasoline and diesel oil but between a wider variety of energy sources."

This article discusses trends in engines configured for alternative fuels as well as Stirling engines.

2 LPG Engines

The number of registered vehicles in Japan that run on liquified petroleum gas (LPG) has been decreasing steadily after reaching a peak of 319,000 in 1991 (2). There were 223,630 registered vehicles at the end of 2014 (including 4,619 bi-fuel vehicles and 5,093 mini-vehicles), a decrease of approximately 8,000 vehicles from the previous year. The reasons for this decline are the long-term rise in LPG prices (3) and the erosion of the relative cost merit of LPG vehicles as gasoline vehicles become more fuel efficient. A significant impact is also attributed to the policy of reducing the number of taxis, which represented 80 percent or more of registered vehicles. LPG stations can be found at approximately 1,600 locations.

By contrast, on a global scale, LPG vehicle registrations are increasing and reached almost 5 million vehicles in 2013. Table 1 lists the number of registered LPG vehicles by region (4). In Europe, registrations in Turkey exceed 3.3 million vehicles, and the continent as a whole numbers over twice as many registered vehicles as the Asia & Oceania region, where Japan lags in fifth place behind South Korea, with more than 2.45 million registrations, India, Thailand, and Australia. With just short of 120,000 registrations, China comes across as having very few registered vehicles compared to the 3.99 million natural gas vehicles presented in the next section.

Table 1 LPG vehicle registrations in major countries

Countries by region	Number of registered vehicles
Europe	Total 13 800 151
Turkey	3 335 000
Poland	2 477 000
Italy	1 787 000
Russia	1 400 000
Ukraine	1 300 000
Germany	455 000
France	194 969
UK	170 000
Others	2 681 182
Asia & Oceania	Total 6 220 613
South Korea	2 455 112
India	1 714 440
Thailand	843 450
Australia	513 562
Japan	250 159
China	119 600
Others	324 290
U.S. & Central and South America	Total 732 768
Mexico	185 000
Dominican Republic	170 000
U.S.	134 868
Others	242 900

The 134,868 registered LPG vehicles, about half as many as Japan, along with natural gas vehicles (approximately 150, 000, as per the next section) makes the still low number of vehicles running on gaseous fuels in the U.S. another point of interest.

In an October 7, 2014 press release, Neste Oil announced plans to start production of biopropane in 2016 (5). A total production of 30,000-40,000 t/a is expected from the new NEXBTL process used to separate biopropane from several gases, which was jointly developed with Neste Jacobs.

In LPG engine research and development, studies on hydrogen-enriched LPG engines have shown that the shortened combustion duration resulting from hydrogen enrichment reduces HC emissions, but leads to higher NOx emissions (6).

3 Natural Gas Engines

As of January 2015, the number of natural gas vehicles (NGVs) worldwide had reached 22.33 million vehicles. With a global share of 17.91%, Iran took the lead with 4 million vehicles, followed by China with approximately 3.99 million and Pakistan with approximately 3.7 million (7). In the U.S., where interest in shale gas is high, there are approximately 150,000 NGVs, which represents a global share of 0.67% (7). In Japan, there are 42,590 natural gas vehicles (a 0.19% share) (7).

The countries with the highest number of natural gas stations are China (6,502 locations, a 24.49% share of the 26,552 stations worldwide), Pakistan (2,997 locations, an 11.29% share) and Iran (2,220 locations, an 8.36% share) (7). It is interesting to note that, with 1,537 natural gas stations (a 5.79% share), the U.S. ranks 6th globally in terms of the number of such stations (17th place in terms of number of vehicles).

Basic research on natural gas engines is focusing on dual fuel engines where a small amount of diesel is injected directly into the cylinder as an ignition source. Waseda University used a rapid compression machine to study combustion improvements in natural gas engines with diesel ignition and confirmed that under EGR conditions, the higher dispersion of the premixed gas resulting from the multi-injection of the diesel pilot stimulates flame propagation during the main injection and improves thermal efficiency (8). Using a natural gas and diesel dual fuel (DDF) engine based on a 4-cylinder diesel engine, intake control indicators when supercharging and EGR are changed were studied by the National Institute of Advanced Industrial Science and Technology and Denso Corporation for three load conditions ranging from light to heavy loads (9). Automotive consulting firm AVL analyzed the potential and limitations of heavy-duty commercial vehicle gas engines and noted that a stoichiometric air-fuel ratio with EGR and a three-way catalyst was optimal (10). The analysis also pointed out the limited potential of premixed dual fuel engines and concluded that despite their technical excellence, high-pressure direct injection dual fuel engines also have the downside of bringing up concerns regarding increased costs (10).

4 Hydrogen Engines

Hydrogen is seen as coming to play a critical role in terms of improving energy security and addressing global warming (1). 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. Hydrogen engines must address issues such as restricting abnormal combustion caused by the high ignitability of hydrogen, countering 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.

The dominant theme of research presented in 2014 was the move from existing hydrogen engines to methods of combustion that use fuel reforming achieved through means such as waste heat recovery to extract hydrogen (along with carbon monoxide). In Japan, a group consisting of Tokyo City University, the National Traffic Safety and Environment Laboratory, and Okayama University has issued reports on improving thermal efficiency through stratification in the axial direction in hydrogen engines with high-pressure direct injection in the cylinder (11) and measuring the local excess air ratio around the spark plug (12). Nissan Motor Co., Ltd. demonstrated the possibility of ensuring stable combustion even at high EGR ratios by adding hydrogen obtained through gasoline reforming (13). Lublin University of Technology created a simulation of a hydrogen-enriched gasoline engine compliant with Euro V (14), and University College London performed numerical modeling of mixture formation and combustion for various types of direct injection hydrogen engines (15).

5 Dimethyl Ether (DME) Engines

Following the shale gas revolution, the study of DME has begun in North America as one approach to making use of its abundant natural gas resources. ASTM standardization of DME fuels has led to the publication of ASTM D7901, Standard Specification for Dimethyl Ether for Fuel Purposes on February 3, 2014. Although Volvo was planning to begin mass producing DME trucks in North America staring in 2015 (June 7, 2013 press release), it appears to have revised those plans in favor of continuing to conduct field tests (16).

Work on DME fuel standardization started at ISO TC 28/SC 4 in 2007 has led to the publication of the following standards:

ISO 16861:2015, Petroleum products — Fuels (class F) – Specifications of dimethyl ether (DME), 2015-05-15

ISO 17196:2014, Dimethyl ether (DME) for fuels – Determination of impurities – Gas chromatographic method, 2014-11-15

ISO 17197:2014, Dimethyl ether (DME) for fuels – Determination of water content – Karl Fischer titration method, 2014-11-15

ISO 17198:2014, Dimethyl ether (DME) for fuels – Determination of total sulfur, ultraviolet fluorescence method, 2014-11-15

ISO 17786:2015, Dimethyl ether (DME) for fuels – Determination of high temperature (105° C) evaporation residues — Mass analysis method, 2015-05-01

6 Stirling Engines

The primary applications of commercially available Stirling engines are combined heat and power (CHP) systems for homes, solar power generation, and power generation achieved by burning woody biomass. The generators used for those applications are the 1 kW-class free piston engine by MEC of the Netherlands, the 1 kW-class, 4-cylinder double-acting engine by Centro Stirling of Spain, which inherits technology from WhisperTech of New Zealand, the 3.5 kW and 7.5 kW-class free piston engines by Qnergy of the U.S., and the 10 kW-class single-acting alpha-type V-cylinder arrangement engine by Cleanergy of Sweden. Production volume for these engines ranges from a few dozen units to, at most, about 1,000. One special application is the air-independent propulsion Kockums 75 kW-class 4-cylinder double-acting engine for submarines. Produced from knock-down kits by Kawasaki Heavy Industries, four such engines are used to power a single Soryu-class submarine.

Examples of units originally developed 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 marine diesel engines, and factories. However, these are either still under development, or only available on a made-to-order basis. However, with the revision of the Electricity Business Act, Stirling engine generation facilities of 10 kW or less have been designated as electric facilities for general use, removing legal restrictions other than technical standards and facilitating the installation of such engines. The regional exchange center in the Omachi district of Minamisoma, which installed and operates a 10 kW-class Stirling engine power generation system that burns woody biomass produced by Suction Gas Engine Mfg. Co., Ltd., provides an example.

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References

(1) Ministry of Economy, Trade and Industry website, Strategic Energy Plan, http://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/4th_strategic_energy_plan.pdf

(2) Website of the Tokyo Metropolitan LP Gas Stations Association, http://www.tousta.or.jp/lp_gas_car/number/ (in Japanese)

(3) Website of the Japan LP Gas Association, Price Statistics, http://www.j-lpgas.gr.jp/stat/kakaku/index.html (in Japanese)

(4) Website of the LPG Vehicle Promoting Association in Japan, http://www.lpgcar.jp/

(5) AUTOGAS UPDATES, World LPG Association, Nov. 2014, http://auto-gas.net/autogasnewslet-

ter/18/48/Autogas-Updates-11-14
(6) Kim, et al., "An Experimental Study on the Performance and Emission Characteristics with Hydrogen Enrichment at Part Load Conditions Using a LPG Engine", JSAE Annual Congress Proceedings (Spring), No. 48-14 (2014)
(7) http://www.ngvjournal.com/wp-content/uploads/pdfmags/gvr157-02-2015.pdf
(8) Miyai et al., "Use of a Rapid Compression Machine to Study Combustion Characteristics and Efficiency in Natural Gas Engines with Diesel Ignition", The 25th Internal Combustion Engine Symposium, November 2014 (in Japanese)
(9) Kojima et al., "A Strategy of Intake Gas Control for Natural Gas/Diesel Dual Fuel Engine", Proceedings of the Society of Automotive Engineers of Japan, 2014 Spring Annual Congress, No. 47-14-2014.5 (in Japanese)
(10) Figer et al., "Potential and Limitation of Heavy Duty Commercial Vehicle Gas Engine", Proceedings of the Society of Automotive Engineers of Japan, 2014 Spring Annual Congress, No. 47-14 (2014.5)
(11) Matsunaga et al., "Measurement of local air excess ratio around the spark plug by SIBS in a direct injection hydrogen engine", Proceedings of the Society of Automotive Engineers of Japan 2014 Autumn Annual Congress, No. 127-14 (in Japanese)
(12) Mori et al., "Improvement in Thermal Efficiency by Axially Charge Stratification under Part Load Operation in High Pressure Direct Injection Hydrogen engines", Proceedings of the Society of Automotive Engineers of Japan 2014 Autumn Annual Congress, No. 127-14 (in Japanese)
(13) Ashida et al., "Study of Hydrogen additive High EGR Combustion for Gasoline Engine with Fuel Reformer", Proceedings of the Society of Automotive Engineers of Japan 2014 Autumn Annual Congress, No.127-14 (in Japanese)
(14) Magryta, et al., "Simulation Studies of SI Engine that Meets the Euro5 Standard, Supply by Gasoline with the Hydrogen Addition", SAE Paper, 2014-01-2548 (2014.10)
(15) Hamzehloo, et al., "Numerical Modelling of Mixture Formation and Combustion in DISI Hydrogen Engines with Various Injection Strategies", SAE Paper, 2014-01-2577 (2014.10)
(16) International DME Association HP, http://www.aboutdme.org/index.asp?bid=564