ENGINES FOR ALTERNATIVE FUELS

1 Introduction

Engines configured for alternative fuels are unlikely to come into widespread use unless incentives are introduced or they can markedly distinguish themselves in terms of fuel cost, refueling infrastructure, cleanliness of emissions, or being free of CO_2. Table 1 compares alternative fuel vehicles (methanol and CNG vehicles (CNGVs)), hybrid vehicles, electric vehicles (EVs), and fuel cell vehicles (FCVs) commercially-produced in Japan. Of the alternative fuel vehicles, CNGVs have gained a certain amount of traction in part due to the incentive of natural gas not being subject to the fuel tax.

One reason for the slow spread of alternative fuel vehicles is the balance with crude oil prices. This is the result of the shale oil revolution and other factors causing crude oil and liquefied natural gas (LNG) prices to level off in the last few years. The price of crude oil, which plunged to approximately 20 yen/L in the spring of 2016, is currently recovering, but is still approximately 40 yen/L. It remains difficult to see advantages to alternative fuel vehicles in terms of cost[1].

Looking further ahead, the United States and Europe have increasingly been focusing on dimethyl ether as an alternative to diesel due to the possibility of manufacturing it from shale gas or biomethanol. Other alternatives are also exhibiting their strengths in niche applications, as in the case of Stirling engines serving as an air-independent propulsion power plant in submarines, which require quietness. This article summarizes the current trends in engines configured for alternative fuels.

2 LPG Engines

The global LPG market has changed greatly in recent years. Triggered by the 2007 shale gas revolution, the amount of LP gas exported by sea by the U.S. increased from 5 million tons/year to 10 million tons/year in 2013, and exceeded 20 million tons/year in 2015, making the U.S. the largest producer and exporter of LP gas in the world. With the completion of the Panama Canal expansion in 2016, Saudi Arabia stopped exporting LPG to regions west of the Suez Canal, and its exports that used to reach 13 million tons/year have fallen as low as 7 million tons/year. Japan has also reduced imports from Saudi Arabia from 7 million tons/year to 1.04 million tons/year, and increased imports from the U.S.[2].

The number of LPG vehicle registrations in Japan at the end of March 2016 was 226,288, a decrease of 7,948 vehicles compared to the same period in the previous year[3]. The reasons behind this decline include the introduction of lower fuel consumption hybrid vehicles, and a drop in the number of corporate taxis, which account for approximately 85% of LPG vehicles. The number of LPG stations is also decreasing. Given these circumstances, the related industry associations are engaging in activities to popularize LPG vehicles. Such activities include increasing the number of LPG vehicle models, installing LPG stations at roadside stations or other locations for disaster response purposes, and harmonizing standards with European regulations.

Globally, the number of LPG vehicles had reached approximately 25.15 million vehicles as of 2014, with approximately 17.35 million in Europe (Turkey: 4.08 million, Russia: 3 million, Poland: 2.85 million, Italy: 1.97 million, Ukraine: 1.6 million), 6.53 million in Asia (South Korea: 2.36 million, India: 2.15 million, Thailand: 1.07 million), 0.87 million in the North, Central and South America, and 0.33 million in Africa[3].

3 Natural Gas Engines

In January 2017, U.S.-produced LNG was delivered to Japan[4]. Not counting imports of conventional natural gas produced in Alaska, this was the first time shale gas produced in the U.S. entered Japan, marking the start of the import of shale gas. The gas was procured by JERA Co., Inc., a joint venture between Tokyo Electric Fuel and

Table 1 Comparison of alternative fuel, hybrid, and electric vehicles

Vehicle Type	Methanol	CNG	Hybrid	EV	FCV	Vehicle Registration
Passenger vehicles	0	1 591	5 558 725	62 134	630	39 506 932
Light, mid, and heavy-duty trucks	576	5 928 19 723	14 026	1 270	0	5 868 283
Buses	0	1 577	1 089	39	0	232 169
Special vehicles	0	3 988	7 729	37	0	1 712 158
Small Vehicles	0	10 416	239 962	17 031	0	Not available
Total	576	43 223	5 821 531	80 511	630	Not available

Power and Chubu Electric, for use in power generation. However, as the diversification of natural gas procurement has stabilized prices and supply, the use of shale gas is expected to spread to vehicles.

Recent research on natural gas engines in Japan include research on low emissions of diesel dual fuel (DDF) engines (Mitsubishi Heavy Industries)[5], on wall heat loss(Waseda University)[6], and thermal efficiency using an engine with a swirl combustion chamber (Chiba University)[6]. In addition, government-industry-academia research and development initiatives to further reduce emissions, improve thermal efficiency, and decrease CO_2 are underway. One example involves the development and conducting of demonstration tests for heavy-duty trucks that use LNG, carried out under the auspices of the Ministry of the Environment's Low Carbon Technology Research, Development and Demonstration Program[7].

Outside Japan, Ecomotive Solutions has used a diesel vehicle manufactured by DAF of the Netherlands to develop a diesel and natural gas-based DDF engine compliant with the Euro VI European emissions regulations. This Italian DDF engine is the first to comply with the Euro VI regulations[8].

The DDF engine uses the same CI combustion system as a diesel engine, resulting in high thermal efficiency and improved fuel efficiency compared to the SI combustion natural gas engines currently used in the market. Since it uses the same CI combustion system as diesel engines, the DDF engine has equivalent thermal efficiency and is considered to benefit directly from the 27% difference in the CO_2 emission rate per unit energy of natural gas compared to diesel (diesel fuel/natural gas (13 A): 68.6/49.9 kg-CO_2/GJ)[9]. The difference (assuming the vehicle runs primarily on natural gas) is effective not only in terms of CO_2 reduction, but also at contributing to the diversification of fuel due to the use natural gas and the improvement of energy security.

In addition, full-scale sales of the Isuzu Motors heavy-duty natural gas truck announced as a completed vehicle have started, and it is being introduced in the transportation business and coming into use for long distance transportation operations.

There is hope that this year's introduction of shale gas, in conjunction with DDF engine technology, will impart momentum to the popularization of natural gas vehicles in Japan.

4 Hydrogen Engines

Depending on the selected primary energy source, hydrogen, which does not emit CO_2, is strongly expected to be a next-generation fuel that effectively contributes to resolving the issues of global warming, environmental pollution, and energy resource depletion faced by the planet. The development of technology to use hydrogen as fuel for automotive power units has been pursued in various countries and sectors since the early 1990s. This resulted, in December 2014, in Japan take the global lead in the commercial production of fuel-based vehicles that use hydrogen as fuel[10], which were continued later also in the U.S.

In contrast, hydrogen engines can leverage well-established technologies while using existing materials and production equipment. Therefore, they are seen as having a high potential for commercialization at a lower cost, making them the object of worldwide research and development. Currently, the use of a combustion system based on direct injection into the combustion chamber has largely solved past issues such as backfiring or the low output that is typical of gas-based engines, and the combustion system to apply in high output engines is gradually taking shape. The current issues that have to be solved to commercialize hydrogen engines are suppressing formation of NO_x under high load operating conditions and further improving thermal efficiency.

In 2016, both in and outside Japan, reports concerning the research and development of hydrogen engines focusing on the above further improvements in thermal efficiency and suppression of NO_x production stood out. In Japan, Tokyo City University has presented research on the use a rich mixture combustion system that significantly reduces NO_x emissions through ignition and combustion of the jet during or immediately after injection by optimizing injection timing and jet shape, as well as improve thermal efficiency by reducing cooling loss, an issue described as inescapable in hydrogen engines[11]. Results from related research concerning core technologies, such as the numerical calculation of the jet and the measurement of thermal flux[12]–[14] have also been reported. Outside Japan, Okayama University presented the results of measuring hydrogen concentration in the rich mixture combustion system mentioned above[15], which shows that the course of the research and development of hydrogen engines has essentially been determined. In contrast, research on engine performance when hydrogen is mixed into the natural gas has also been presented[16], providing an example of the expanding scope of the application of hydrogen energy.

5 Dimethyl Ether (DME) Engines

The International Organization for Standardization (ISO) established a working group (ISO/TC22/SC41/WG8) to examine the standardization of fuel supply systems and refueling port for DME vehicles, excluding the on-board tank. Its first meeting was held in Japan in June 2016. A pressure-equalizing refueling port developed in Japan has been proposed.

In Japan, the Society of Automotive Engineers of Japan established a subcommittee for DME under the Environment Technical Committee, and a DME Vehicles Technical Committee is scheduled to be set up in 2017 to address these issues.

At the meeting of the automotive DME fuel standardization working groups (ISO/TC28/SC4/WG13 and WG14, on the topic of the quality of DME fuel and methods of analyzing it) held in September 2016, members evaluated the conducting of round robin tests in preparation for the periodic review of the standards established from 2014 to 2015. The ASTM DME task force convened by the American Society for Testing and Materials (ASTM) in December 2016 reported on the progress of the lifecycle evaluation, as well as projects by Ford and Volvo.

One example of technical initiative on DME vehicles undertaken outside Japan is the evaluation of the possibility of synthesizing renewable DME alternative fuel for diesel engines from municipal waste conducted by Mack Trucks in collaboration with the New York City Department of Sanitation and Oberon Fuels[17].

6 Stirling Engines

Commercially available Stirling engines are used in compact combined heat and power (CHP) systems, power generation achieved through ligneous biomass combustion or the combustion of low-grade biogas generated by waste from sewage, excrement or landfill processing plants, and solar power generation relying on sunlight concentrated through parabolic mirrors as a source of high temperature heat. The generators used for those applications are the 1 kW-class free piston engine by Microgen (MEC) of the Netherlands, 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 75 kW-class 4-cylinder double-acting engine (power generation output: 60 kW) for submarines by Kockums of Sweden. They are produced from knockdown kits by Kawasaki Heavy Industries Ltd., and four engines were commissioned for, and refitted to, the Jinryu Soryu-class submarine.

ÖkoFEN of Austria started sales of wood pellet boilers fitted with generators from MEC and Qnergy that provide 0.6 kW of electric power and 9 kW (maximum 13 kW) of thermal power, as well as of wood pellet combustion-based CHP systems that provide 4.5 kW of electric power and 55 kW of thermal power. These systems will also be made available in Japan. In addition, sales of the MEC 1 kW engine and Qnergy 7.5 kW engine have begun.

Examples of original engines being developed in Japan include an e-stir Co., Ltd. generator that uses relatively low-temperature waste heat from plants, a Suction Gas Engine Mfg. Co., Ltd. generator that uses ligneous biomass combustion, and a Momose Kikai Sekkei KK generator that uses combustion heat from wood stoves. Those engines have an output ranging from 0.2 to 10 kW or so, and are still only available on a made-to-order basis.

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