ENGINES FOR ALTERNATIVE FUELS

1 Introduction

In his policy speech at the 203rd session of the Diet, Prime Minister Suga declared that Japan would aim to achieve a carbon neutral, decarbonized society by 2050. Automobiles that use alternative fuels cannot become widespread, despite their superior emissions cleanliness or low CO_2 emissions, while issues such as fuel cost and refueling infrastructure remain unresolved. However, in conjunction with the electrification of power sources, the shift to low and carbon-neutral fuels has now reached a critical point if the objectives of that declaration are to be achieved.

This article summarizes the current trends in generally available LPG and natural gas vehicles and in the development of their engines. It also introduces the progress of research and development on hydrogen reciprocating and DME engines, which represent potential future automobile fuels.

2 LPG Engines

The number of LPG vehicles registered in Japan was 186,374 as of the end of September 2020 (an 11,500 decrease compared to the same month in the previous year). Those registrations break down into a total of 152,339 units for taxis, private, cargo, special purpose, and shared vehicles, 21,758 JPN taxis, 8,135 bi-fuel vehicles, and 4,142 mini-vehicles (unchanged since the end of March 2017).

The Toyota JPN taxi, the flagship of universal design taxis (UD taxis) registered since October 2017, features a hybrid engine developed exclusively for LPG using the 1,500 cc engine of the Sienta as a base. A slight slowdown of the rise in the number of vehicles has been observed since it passed the 20,000 mark at the end of March 2020 (Fig. 1).

In addition to the decrease in the number of LPG vehicle registrations, the consumption of LPG fuel—perhaps due in part to the emergence of highly fuel-efficient LPG hybrid vehicles such as the JPN taxi—has also dropped, as has the number of LPG stations, which are now found at approximately 1,500 locations nationwide. In contrast, simpler LPG stations that mitigate equipment investment and maintenance costs have expanded beyond taxi companies and driving schools to also target the private sector in general. As a distributed energy resource that can be supplied to consumers individually, LPG has a relatively rapid recovery time in the event of a disaster, and the expansion is attributed to businesses seeking to enhance their resilience by introducing simpler LPG stations in conjunction with the switch to LPG vehicles.

Given the benefit of LPG as a distributed energy resource, the Japan LP Gas Association established a study group to develop production technology for green LPG in November 2020 with the aim of having that fuel contribute to achieving a carbon neutral society.

3 Natural Gas Engines

Natural gas emits approximately 26 or 27% less CO_2 per unit calorific value than gasoline or diesel, and will eventually be producible from renewable energy sources. It is therefore viewed as a crucial alternative fuel to achieve carbon neutrality in the transportation sector. Typical natural gas is a fossil fuel, and its use will have

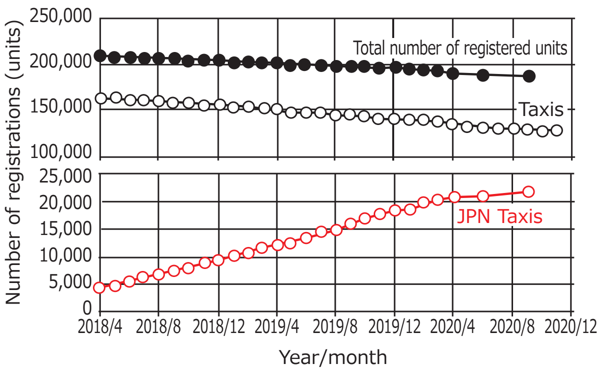

Fig. 1 Trends in LPG vehicles registrations[1]

to be reduced in the long term. However, it will undoubtedly become a fuel enabling the achievement of carbon neutrality when natural gas using a synthetic gas (methane) produced from hydrogen and CO_2 using bio-methane and green electricity is introduced as a complement to already available carbon neutral natural gas. In particular, high expectations are placed on its use, in conjunction with the hydrogen used in fuel cells, as a source of energy in heavy-duty vehicles, a segment where electrification is challenging.

The high octane number of natural gas makes it appropriate for SI engines, and recent technological breakthroughs have also made its use in CI engines possible. Research to improve thermal efficiency and reduce emissions in both types of engine is underway.

The JSAE Spring Annual Congress (Yokohama, May 20 and 21, 2020), featured presentations such as *Numerical Study on Ignition Process of Micro Pilot Fuel Spray in CH4-Air Mixture using 1D Diesel Jet Model* (National Institute of Maritime, Port, and Aviation Technology) and *Premier Combustion of Dual Fuel Gas Engine Ignited with Diesel Fuel* (Okayama University).

At the 31st Internal Combustion Engine Symposium held jointly by the Society of Automotive Engineers of Japan (JSAE) and the Japan Society of Mechanical Engineers (JSME), notable presentations included *Combustion Characteristic of Dual Fuel Engine by Fuel-Energy-Ratio of Biogas and Biodiesel* (Muroran Institute of Technology) and *Measurement of Instantaneous Heat Flux on Combustion Chamber Wall in Gas Engine with Pre-Chamber* (Yanmar).

The Fifty-Eighth Symposium (Japanese) on Combustion held by the Combustion Society of Japan (online, December 2 to 4, 2020) offered presentations such as *Study on Combustion Using Biogas* (Nihon University), *NO_x Formation in Mild Combustion of Gasified-Gas of Woody Biomass* (Osaka University), and *Study on OH Chemiluminescence and OH Concentration of Methane - Hydrogen Mixture Flame* (Toho Gas).

Outside Japan, the *Heavy Duty Vehicle Performance Evaluation* project conducted by the Advanced Motor Fuel (AMF) Technology Collaboration Programme (TCP) of the International Energy Agency (IEA) presents data on reducing heavy-duty vehicle CO_2 emissions on both a tailpipe and well-to-wheel basis for the EU 2025 (−15%) and 2030 (−30%)CO_2 reduction targets. Among the several types of heavy-duty vehicle powertrains (e.g., diesel, SI natural gas (fossil fuel, biogas)), CI natural gas (diesel dual fuel), FCV, and battery EV), the project demonstrates that, on a well-to-wheel basis, those using renewable energy (making use of biogas in SI natural gas or dual fuel, for example) or a battery EV (EU 2030 electric power mix forecast) are anticipated to achieve the 2030 EU CO_2 emissions reduction target.

The above AMF project underscores the necessity of a well-to-wheel-based evaluation of automotive CO_2 emissions reductions, as well as the importance of using renewable energy. Expanded utilization of renewable natural gas also shows promise in initiatives to achieve carbon neutrality in Japan.

4 Hydrogen Engines

Hydrogen is drawing attention as a next-generation form of energy that will play a key role in measures to solve various environmental issues such as global warming, air pollution, and energy resource depletion. Various countries are placing high expectations on its potential to help achieve the goals of the Paris Agreement. In October 2020, Japan formulated the Green Growth Strategy through Achieving Carbon Neutrality in 2050 under the leadership of the Ministry of Economy, Trade and Industry (METI). The strategy updates the roadmap for the manufacturing, transport, and use of hydrogen fuel up to 2050. In response to such actions, the NEDO HySTRA pilot project involving the marine transportation of liquid hydrogen produced in Australia to Japan, and unloading it there, was initiated in May 2021 as part of the activities of the CO_2-free Hydrogen Energy Supply-chain Technology Research Association.

On a different note, technical development of engines powered by hydrogen has been pursued in various countries and sectors since the early 1990s, and in December 2014, Japan took the global lead in mass producing and selling hydrogen-powered fuel cell vehicles. The second generation model was launched in 2020, and sales have been increasing rapidly. Similarly, the NEDO Advancement of Hydrogen Technologies and Utilization Project is conducting research and development aimed at commercializing hydrogen gas turbine-based electricity generation by 2030.

Hydrogen engines can leverage well-established internal combustion engine technologies. Therefore, they are seen as having a high potential for commercialization at a lower cost, making them the object of worldwide research and development. Activity in the Japanese industrial sector in 2020 featured the announcement of joint research on a single-cylinder hydrogen engine with a 5-liter stroke volume aimed at large engines conducted by Mitsubishi Heavy Industries Engine & Turbocharger (MHIET) of the Mitsubishi Heavy Industries Group and the National Institute of Advanced Industrial Science and Technology (AIST). This engine is similar to the high-pressure cylinder direct injection combustion system using supercharging researched and developed since 2014 in the context of the Cabinet Office-led Strategic Innovation Promotion Program (SIP). In other news, Toyota Motor Corporation entered the 24-hour endurance race in May 2021 with a vehicle equipped with a 3-cylinder 6-liter engine using hydrogen as a fuel, completing all 358 laps. That engine also uses a combustion system relying on supercharging and direct cylinder injection. Current research and development on hydrogen engines, as shown by the above as well as the papers noted below, has centered on direct cylinder injection systems that solve issues such as backfiring or the low output unique to gas-based engines. Suppressing the production of NO_x under high load operating conditions and further improving thermal efficiency is the next issue to tackle.

Many of the research and development papers on hydrogens engine published in Japan in 2020 concerned the above direct injection systems. Tokyo City University announced the results it obtained using a highly efficient high output near-zero emission hydrogen engine. Optimizing the injection timing and jet shape in a large bore engine significantly increased thermal efficiency while also considerably reducing NO_x generation in the high load region. In addition, refining the shape of the combustion changer achieved an indicated thermal efficiency of almost 50%. Other research is focusing on further raising thermal efficiency at high compression ratios, as well as on elucidating the characteristics of knock generation. In other news, the AIST has published a paper on the role of hydrogen among future carbon-free fuels, including ammonia.

5 Dimethyl Ether (DME) Engines

Discussions on ISO standards for DME automobile related component (ISO/TC22/SC41/WG8, DME) are being held. The New Work Item Proposal (NP) from Japan on a standard for a refueling connector with pressure equalization port was approved in March 2020, and is currently being discussed as ISO WD 24605. Other proposed standards concerning four refueling devices (85% stop valve, level indicator, PRV and PRD) are under discussion, with drafts being prepared by working group members. Due to the impact of COVID-19, face-to-face discussions have been postponed.

In the DME Briefing Series hosted by the International DME Association, Ford provided an update on the performance tests of the single cylinder engine based on a 2-liter engine conducted as part of the C^3-Mobility project. Tests of a multi-cylinder engine and vehicle demonstrators (two light CVs) are in preparation. A standard on DME fuels (DIN/TS 51698) is also being promoted through this project.

Empa, the Swiss Federal Laboratories for Materials Science and Technology, considers DME a promising alternative fuel candidate for future CO_2 measures and a shift to non-fossil energy. It is working with FPT Motorenforschung AG Arbon, Politecnico di Milano, the lubricant manufacturer Motorex as well as other partners to study the use of DME as a fuel for commercial vehicles. They are testing engine combustion efficiency, environmental performance, and other properties using an 11-liter engine for heavy-duty commercial vehicles. The material used for the valve seat and fuel injection pump of the engine has been changed, and researchers are aiming to make the addition of lubricant in DME fuel unnecessary. The project is co-financed by the Swiss Federal Office of Energy (SFOE), and FPT is responsible for the engine tests.

A Mitsubishi Gas Chemical Company, Mitsubishi Corporation, Mitsubishi Heavy Industries Engineering, and Caribbean Gas Chemical Limited plant in Trinidad and Tobago started commercial operation in December 2020. Fueled primarily by natural gas, the plant has an annual production capacity of 1 million tons of methanol and 20,000 tons of DME. The latter can also serve as an alternative to LPG or automotive fuel and contribute to a low-carbon society in addition to its use in chemical products.

In a bid to cut imports of LPG, the Indonesian state energy firm Pertamina has launched a program involving gasifying domestic coal to manufacture DME, blend it with 20% LPG, and make it available as a household fuel. It will eventually be possible to manufacture that fuel from bio-derived or other renewable raw materials. The nation has set a goal of having renewable energy account for 23% of its energy mix by 2025.

References
・http://www.aboutdme.org/dme-briefing-series?bid=648
・https://www.automobilsport.com/fpt-industrial-swiss-funded-project-alternative-fuel-heavy-duty-engines---218521.html
・https://theicct.org/gasifying-palm-residues-helping-indonesia-go-renewable/