ENGINES FOR ALTERNATIVE FUELS

1 Introduction

Engines function by converting one form of energy, i.e., heat from fuel, to another form of energy, i.e., work in the form of power. This mechanical system depends on the existence of fuel. Since Japan pledged to achieve carbon neutrality by 2050, discussions and studies aiming to decarbonize the transportation sector have progressed rapidly. Vehicles 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 is now reaching a critical point on the road to zero-emission mobility. This article summarizes the current trends in generally available LP gas and natural gas vehicles and in the development of their engines. It also introduces the progress of research and development on hydrogen reciprocating and dimethyl ether (DME) engines, which represent potential future automotive fuels.

2 LPG Engines

The number of LPG vehicles registered in Japan was 181,990 as of the end of December 2021. In April 2018, this number exceeded 200,000 and reached 209,423 vehicles. Since then, registrations have gradually declined year after year, falling below the 200,000 level in June 2019. However, the slight increase that occurred in the second half of 2021 suggests that this declining trend is coming to an end.

The Toyota JPN taxi, the flagship of universal design taxis (UD taxis), which debuted in October 2017, features a hybrid engine developed exclusively for LPG based on the 1,500 cc engine of the Sienta. Despite the slight slowdown in the rise in the number of these vehicles since it passed the 20,000 mark at the end of March 2020, registrations increased again smoothly in 2021 (Fig. 1).

Although no accurate data about the number of LPG stations is publically available, it is estimated that the number remains at around 1,500 nationwide. Aiming to raise the value of LPG station businesses around the country, in 2019, the Japan LP Gas Association introduced a new system that accredits business operators with the capability to continue operations even during a power cut as "independent LP gas stations." So far, a total of 38 business operators have registered in Yamagata, Ibaraki, Saitama, Tokyo, Chiba, Kanagawa, Nagano, Yamanashi, Shizuoka, Shiga, Nara, Osaka, Hyogo, Okayama, Kagawa, Ehime, Oita, Kumamoto, and elsewhere. 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 should continue to enter more widespread use as a means of enhancing energy resilience.

In November 2020, the Japan LP Gas Association established a research institute to develop production technology for green LPG. A report of its activities and results up to March 2021 was released in June 2021. The future direction of research through this institute may be summarized as follows: to continue the responsible supply of LPG as a sustainable energy source necessary for society even beyond 2050, it will be extremely important to adopt an approach that works toward social im-

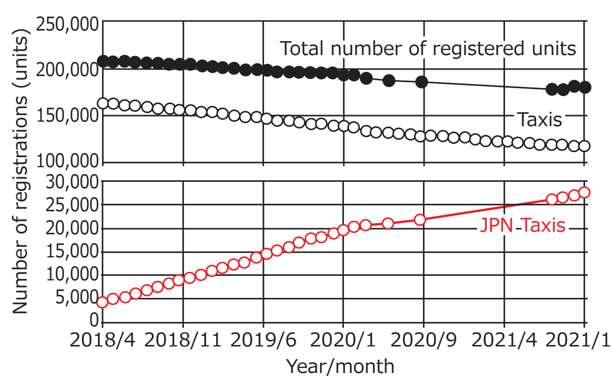

Fig. 1 Trends in LPG Vehicle Registrations

plementation in parallel with technological development by green DME and carbon-free LPG synthesis (propanation and butanation). In addition, to promote this approach, the five major companies that import and sell LPG (Astomos Energy, the ENEOS Group, Gyxis Corporation, Japan Gas Energy Corporation, and Iwatani Corporation) established the Institute of Japan Green LP Gas Promotion in October 2021. This institute plans to research and develop propanation and butanation technologies capable of producing LPG at yields close to 100% via a process that involves the synthesis of hydrogen and carbon dioxide and reformation into methanol and the like, as well as technologies to produce LPG from DME, which has properties resembling LPG. These trends are likely to attract attention in the future.

3 Natural Gas Engines

The price of crude oil is increasing due to the effects of the global COVID-19 pandemic and, from the beginning of 2022, heightened geopolitical risks. According to the Agency for Natural Resources and Energy in the Ministry of Economy, Trade and Industry (METI), the subsidy scheme to stabilize the price of fuel oil lowered the retail price of gasoline and diesel by approximately 36 yen per liter in May, keeping the price in line with the level immediately before the application of this measure (January). In contrast, although the price of automotive natural gas is also trending upward, it does not qualify for the same treatment under this scheme. However, as of May, the difference in the price of fuel per unit of calorific value (MJ) (compared with diesel) was between approximately -19 and 28% (the difference varies with the amount of fuel used). From the perspective that natural gas is mainly used by commercial vehicles, it can be concluded that natural gas and natural gas vehicles are helping to increase the resilience of logistics and the economy through fuel diversification.

As an example of research trends for natural gas engines, the 2021 Autumn Congress of the Society of Automotive Engineers of Japan (JSAE) (held online between October 13 and 15, 2021) included a presentation from Waseda University called *Combustion and Exhaust Emissions Characteristics of a Natural Gas DDF Engine by Diesel Early Injection*. This presentation described the construction of a combustion model for a dual-fuel engine using natural gas and diesel, and reported that advancing the injection timing in a two-stage injection process was an effective way of reducing emissions.

The 32nd Internal Combustion Engine Symposium held online between December 7 and 9, 2021, jointly by the JSAE and the Japan Society of Mechanical Engineers (JSME) featured a large number of presentations related to dual-fuel engines from universities and automakers, including *Influence of Difference in Natural Gas Fuel Composition on Autoignitive Propagation Velocity* (Nihon University), *Improvements in Thermal Efficiency and Methane Slip in Natural Gas Dual-Fuel Engines with Ozone Addition* (Hokkaido University), *Local Equivalence Ratio Measurement at Inhomogeneous Field in Pre-Chamber Natural Gas Engine* (Okayama University), and *A Study on Combustion Improvement in Dual-Fuel Engine for Biogas Applications* (Yanmar). Of these, the research by Yanmar reported that, even when biogas is used as fuel, equivalent performance to natural gas can be realized by combining combustion improvements involving adjusting the injection timing and quantity of the diesel used for ignition. It should be possible to realize further reductions in CO_2 emissions and contribute to the achievement of carbon neutrality in the future through the combined use of spark injection (SI) combustion type natural gas engines and biogas or, after advancements in research, introducing compression ignition (CI) combustion type dual-fuel engines with high thermal efficiency in Japan and combining these engines with biogas.

4 Hydrogen Engines

Based on its primary energy sources and material composition characteristics, hydrogen fuel is regarded as a highly feasible next-generation fuel that offers effective solutions to various 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 related to fighting climate change. In Japan, the Green Growth Strategy through Achieving Carbon Neutrality in 2050 that was formulated in 2020 under the leadership of METI was revised in June 2021. The revised strategy provides a further concrete roadmap for fuel ammonia and its manufacture, transport, and use up to 2050. In response to these measures, the New Energy and Industrial Technology Development Organization (NEDO) HySTRA pilot project involving the marine transportation of liquid hydrogen produced in Australia to Japan, 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 at the end of 2020, and global sales reached 5,600 units in 2021. 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, and are therefore seen as having a high potential for commercialization at a lower cost, making them the object of worldwide research and development. In May 2021, Toyota Motor Corporation entered a 24-hour endurance race at Fuji Speedway with a vehicle equipped with a 1.6-liter 3-cylinder engine using hydrogen as a fuel, completing 358 laps. This vehicle subsequently completed 478 laps in June 2022. As this demonstrates, the characteristics of research and development into hydrogen engines were a prominent feature in reports related to the actions of Japanese automakers and parts suppliers in 2021.

Research and development into hydrogen engine combustion systems is advancing focusing on direct injection systems, which are capable of resolving issues such as backfire and the low power generated particularly by gas engines. As injection technologies advance, the combination of high-pressure injection with turbocharging that aims to further boost power is becoming more frequent. A wide range of engines are being used, including those using technologies researched and developed under the Strategic Innovation Promotion (SIP) Program implemented mainly under the leadership of the Cabinet Office since 2014, Toyota's hydrogen engine described above, and those covered by the research papers mentioned below. Research and development trends related to hydrogen engines in each field and technical papers related to the effectiveness of these engines in mitigating global warming and the like were presented by AVL, Bosch, IAV, and other parties at the 2021 JSAE Annual Spring Congress and the JSAE Gasoline Engine Symposium, introducing these initiatives to Europe and the U.S.

In addition, many of the research and development papers on hydrogen engines published in Japan in 2021 concerned the direct injection systems described above. Tokyo City University has been carrying out research using a high output near-zero emission hydrogen engine. This research found that 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 chamber and adopting a high 20:1 compression ratio achieved an indicated thermal efficiency of 52.4% with NO_x emissions in the single figure ppm. Other research has identified the knocking characteristics of hydrogen engines when high compression ratios are adopted with lean air-fuel mixtures of hydrogen fuel, which is susceptible to knocking. The effectiveness of turbocharging in raising the thermal efficiency of this engine was also reported. Other papers described the mixed combustion of hydrogen produced from renewable energy sources and research related to cyclical closed-cycle hydrogen engines using argon.

5 Dimethyl Ether (DME) Engines

International standardization (ISO) work for vehicles fueled by DME continues. Items being discussed in the ISO working group (ISO/TC 22/SC 41/WG 8, DME) include the New Work Item Proposal (NP) previously made by Japan about a standard for a refueling connector with pressure equalization port and four other items about fuel systems (85% stop valve, level indicator, PRV, and PRD). Unfortunately, discussions have been delayed by the impact of the COVID-19 pandemic.

With the aim of reducing transportation-related carbon emissions in Germany, SHV Energy (an LPG supply company from the Netherlands) and Primagas (a gas supply company from Germany) are participating in the German-government funded C3-Mobility project and the DME-Plus-X projects for the supply and delivery of renewable DME (rDME). SHV Energy is synthesizing rDME from waste products using technology supplied by KEW Technology (UK) and plans to produce 300,000 tons of rDME annually by 2017 to be blended with LPG for sale. The C3-Mobility project aims to develop CO_2-neutral fuels for transportation. Participants in the project include 30 parties from industry and academia. The DME-Plus-X projects are scheduled to run from 2021 to 2024. Primagas is building refueling stations capable of supplying rDME fuel and delivering this fuel to vehicles.

Vehicle development is being carried out by Ford, which is converting Mondeos and Transit vans.

In Switzerland, FPT Motorenforschung is carrying out a project related to the use of alternative e-fuels to help reduce CO_2 in the future. The project is co-financed by the Swiss Federal Office of Energy (SFOE), and is using DME produced from renewable feedstock in tests of an 11-liter diesel engine. This project involves the development of common rail technology suitable for DME and a highly efficient selective catalyst reduction (Hi-SCR) system.

Oberon Fuels has begun the first commercial-scale production of rDME in the U.S. The company is synthesizing rDME from biogas produced from feedstock including waste methanol, waste dairy products, waste foodstuffs, and waste agricultural products, as well as from hydrogen and CO_2 using surplus electricity. The carbon intensity (CI) of these processes has been estimated as -278. The CI achieved by blending propane (CI: 83) with 20% rDME is estimated as 11. This could play a major role in the decarbonization of the transportation sector.

Suburban Propane Partners (a U.S. company that sells propane gas) and Empresas Lipigas (a company that sells liquefied gas in countries such as Chili, Columbia, and Peru) announced a project to asses and verify the material compatibility, safety, and performance characteristics of a blended rDME/LPG fuel for domestic, commercial, heating, and cooking applications in South America. This blended rDME fuel is produced and supplied by the U.S. company Oberon Fuels. A blended rDME/LPG fuel can be stored and transported using the existing LPG infrastructure, and should be compatible with a wide range of applications including transportation, cooking, heating, forklifts, and power generation.

References

- M. Oikawa, et al.: Int. J. of Hydrogen Energy, Vol. 47, No. 2, 5 January 2022, p. 1319 — 1327
- https://www.shvenergy.com/our-impact/impact-stories/sustaining-the-environment/primagas-pioneering-projects-to-reduce-germany-s-transport-related-carbon-emissions
- https://www.fptindustrial.com/global/Documents/PRESS_release/2021/DME/FPT_Industrial_DME_English.pdf
- https://oberonfuels.com/2021/06/10/oberon-fuels-starts-commercial-production-of-renewable-dimethyl-ether-rdme-a-pivotal-step-towards-a-net-zero-future/
- https://www.lipigas.com/en/noticias-y-enventos/empresas-lipigas-announce-collaboration-to-evaluate-renewable-dimethyl-ether-propane-blends-in-latin-america/