ENGINES FOR ALTERNATIVE FUELS

1 Introduction

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 liquid petroleum gas (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 dimethyl ether (DME) engines, which represent potential future automotive fuels.

2 LPG Engines

Figure 1 shows the trends for the number of registered LPG vehicles in Japan, as well as the number of ordinary taxis and JPN Taxi models powered by LPG. In 2018, the number of registered LPG vehicles exceeded 200,000. This figure has gradually declined year by year, falling below 200,000 in June 2019, and reaching 174,291 at the end of December 2022.

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. After exceeding 20,000 at the end of March 2020, the number of JPN Taxis on the road has steadily increased to more than 30,000 vehicles in September 2022.

Table 1 lists the number of LPG stations in each Prefecture, metropolitan area, and territory in Japan. At the end of September, there were 1,679 LPG stations in Japan, mostly in major cities.

The Institute of Japan Green LP Gas Promotion, which was established in October 2021, was selected alongside the National Institute of Advanced Industrial Science and Technology, and N.E. CHEMCAT Corporation to conduct research and development as part of a program (Development of Technologies for Carbon Recycling and Next-Generation Thermal Power Generation, Project for Promotion of Next Generation Thermal Power Generation, Development of Common Fundamental Technologies for Carbon Recycling) organized by the New Energy and Industrial Technology Development Organization (NEDO). Starting in the 2022 fiscal year, the three institu-

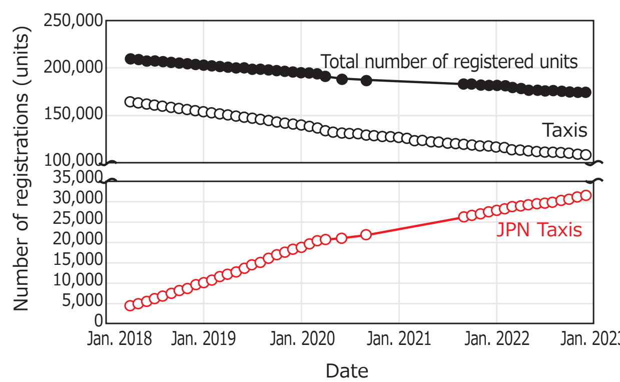

Fig. 1 Trends in LPG Vehicle Registrations

Table 1 Number of LPG Stations in each Prefecture, Metropolitan Area, and Territory in Japan (as of End of September 2021)

Area	Stations	Area	Stations	Area	Stations
Hokkaido	79	Yamanashi	18	Shimane	22
Aomori	26	Shizuoka	48	Hiroshima	38
Akita	14	Aichi	83	Yamaguchi	36
Iwate	29	Mie	25	Tokushima	22
Yamagata	22	Gifu	32	Kagawa	28
Miyagi	34	Toyama	23	Kochi	20
Fukushima	38	Ishikawa	21	Ehime	35
Ibaraki	43	Fukui	10	Fukuoka	51
Tochigi	25	Shiga	24	Saga	15
Gunma	29	Kyoto	23	Nagasaki	22
Saitama	98	Nara	19	Oita	31
Chiba	89	Wakayama	13	Kumamoto	30
Tokyo	77	Osaka	54	Miyazaki	23
Kanagawa	69	Hyogo	42	Kagoshima	55
Niigata	39	Tottori	10	Okinawa	24
Nagano	39	Okayama	32	Nationwide total	1,679

tions launched a project entitled, "Research and Development of LP Gas Synthesis Technology through Carbon Recycling." More specifically, this project aims to establish an optimized process to produce carbon-neutral propane and butane at high yields by catalytic reactions from dimethyl ether (DME) that can be produced from renewable hydrogen and CO_2 recovered from power plants and other sites.

3 Natural Gas Engines

In November 2022, The Japan Gas Association announced the decision made by the Methanation Promotion Public-Private Council (which consists of gas companies and other suppliers, automakers and other companies on the demand side, as well as representatives from the supply chain, research institutes, financial organizations, and government, as well as prominent scholars) to unify the various names for synthetic methane under the term "e-methane." This term is to be used for synthetic methane produced from non-fossil energy sources such as green hydrogen. Also in November, Mitsubishi Corporation and Air Water Incorporated announced the start of a project involving the mixing of LNG with livestock manure-based liquefied biomethane with the aim of reducing carbon in LNG truck fuel as part of a project organized by the Ministry of the Environment to demonstrate the feasibility of methods to decarbonize heavy-duty truck logistics by building a network of compact LNG filling stations. Both e-methane and biomethane are alternative fuels that can help to achieve carbon neutrality and diversify fuel use in the transportation sector. Technical development toward mass production and the types of market trials described above remain ongoing.

As an example of research trends for natural gas engines, the 2022 Autumn Congress of the Society of Automotive Engineers of Japan (JSAE) (held at the Grand Cube Osaka and online between October 12 and 14, 2022) included a presentation from Tokai University called Effects of Hydrogen Addition to Pre-Chamber Gas Engines on Engine Performance and one from Doshisha University called A Study for High Efficiency of Gas Engine by Hydrogen Addition. The latter of these presentations reported that forming a hydrogen-rich mixture around the spark plug by the port injection of hydrogen shortened the combustion period, reduced cooling losses by decreasing the heat loss at wall surfaces, and lowered emissions of unburned hydrocarbons and H_2.

At the 33rd Internal Combustion Engine Symposium held jointly by the Society of Automotive Engineers of Japan (JSAE) and the Japan Society of Mechanical Engineers (JSME) between November 11 and 24 at the Kokusai Fashion Center in Tokyo and online, notable presentations included ones called Study of Combustion Timing Control in Hydrogen Mixed Gas Engine (by Hitachi, Ltd.), The Effect of Hydrogen Addition to a Natural-Gas Engine Ignited with Diesel Fuel on the GHG-Emission (The University of Shiga Prefecture), and Premier Combustion of Natural Gas Ignited with Diesel Fuel in a Dual Fuel Engine: Effect of EGR on End-Gas Auto Ignition (Okayama University).

A total of ten presentations about natural gas engines were made at Technical Sessions such as these, seven of which involved research into dual fuels formed by adding hydrogen to natural gas. Research and commercialization efforts are already underway focusing on dual fuel engines involving diesel combustion combining natural gas and diesel, which realizes a higher thermal efficiency than conventional natural gas stratified injection (SI) engines. Research using natural gas and hydrogen is under way to examine the impact on thermal efficiency using conventional SI engines, the effects on greenhouse gas (GHG) emissions, changes in combustion characteristics, and so on.

Research into natural gas engines is diversifying due to potential combinations with biomethane, diesel, hydrogen, and other fuels. It is hoped that further advances in this research can contribute to measures for both saving energy and achieving carbon neutrality.

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 planet-wide issues such as global warming, air pollution, and energy resource depletion. Hydrogen has been identified by many countries as a means of meeting targets set by the Paris Agreement relating to 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. In June 2022, the first ship loaded with liquid hydrogen produced in Australia docked in Japan.

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. Building on the launch of the second-generation model at the end of 2020, 2022 saw significant progress made in the planning and development of light-duty fuel cell (FC) trucks. In addition, 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 long-term worldwide research and development. In May 2021, Toyota Motor Corporation entered a 24-hour endurance race with a vehicle equipped with a 3-cylinder 1.6-liter hydrogen engine. Recent research and development is also aiming to utilize hydrogen engines in various fields such as heavy-duty trucks and marine vessels, as well as passenger vehicles.

The combustion methods used by hydrogen engines can be broadly divided into comparatively simple premixed fuel supply and in-cylinder direct injection, which is 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 were presented by AVL and other parties at the 2022 JSAE Annual Spring Congress. In addition, many research and development presentations and research papers on hydrogen engines were made and published in Japan. Toyota announced research into the particular abnormal combustion mechanism of hydrogen and technologies capable of mitigating it. Tokyo City University has been carrying out research using a high-power near-zero emission hydrogen engine. This research found that optimizing the injection timing and jet shape significantly increased thermal efficiency while also considerably reducing NOx 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 NOx emissions in the single figure ppm. This research also included numerical analysis by computational fluid dynamics (CFD) into the effects of the combustion chamber shape on mixture formation. Other research related to natural gas engines involving the addition of hydrogen was also reported.

5 DME Engines

Discussions by the International Organization for Standardization into the creation of an ISO related to automotive fuel systems using DME restarted after being temporarily halted by the COVID-19 pandemic. Items currently 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). In addition, the World LP Gas Association (WLPGA) is examining the commercialization of LPG containing 20% DME derived from sustainable sources (called renewable DME or rDME) to help realize a low-carbon society and to achieve decarbonization. The working group involved in this project also held discussions about standardizing automotive fuel systems using rDME blends, but these efforts have been declared as premature and have stalled.

In April 2022, Suburban Propane Partners (a nationwide distributor of propane, renewable energy, and related products and services in the U.S.) announced the launch of a commercially available blend of propane and rDME. This blend combines rDME produced by Oberon Fuels with propane to lower the carbon intensity (CI) of the fuel and help create a pathway for reducing carbon.

In addition, Suburban Propane Partners and Iwatani Corporation of America (a partner of Iwatani Corporation) agreed to collaborate in advancing the adoption of low-carbon alternative energy solutions in the propane market, including propane blended with rDME. Suburban Propane Partners and Iwatani also announced partnerships with original equipment manufacturers (OEMs) and suppliers to evaluate material compatibility, equipment performance, and emissions of forklifts, on-road vehicles, and residential appliances at varying blend levels of propane and rDME.

At the 2022 North American International Auto Show (also known as the Detroit Auto Show), the U.S. company Stanadyne unveiled a new alternative fuel injector for medium- and heavy-duty commercial vehicle powertrains. This was developed as a multipurpose port injector capable of delivering hydrogen, compressed natural gas, DME, and other fuels into the engine. Due to its history of use on existing hydrocarbon fuel engines, it is capable of a high flow capacity that delivers the same energy and enables fuel injection with the same energy density as conventional fuels.

In May 2022, Dimeta, a joint venture between SHV Energy and UGI International, announced plans to construct a plant capable of annual commercial production of 50,000 tons of rDME from general waste at its Teesworks facility in the UK. There is an urgent need in the UK for low-carbon heating solutions. The blending of rDME into LPG or the use of 100% rDME can reduce carbon emissions while also boosting employment. Although this venture originally intends to supply low-carbon energy to the UK market, it is also aiming to supply rDME to Europe and the U.S. in 2024.

References

- M. Oikawa, et al.: Int. J. of Engine Research, https://doi.org/10.1177/14680874221135277 (2022)
- Y. Mogi, et al.: Int. J. of Hydrogen Energy, Vol. 47, Issue73, 26 August 2022, pp. 31459 — 31467
- https://investor.suburbanpropane.com/2022-04-27-Suburban-Propane-Announces-the-Commercial-Launch-of-Propane-rDME,-a-Revolutionary-Low-Carbon-Fuel/
- https://www.lpgasmagazine.com/suburban-propane-iwatani-team-on-propanerdme-test-projects
- https://www.stanadyne.com/stanadyne-unveils-new-hydrogen-fuel-injector-at-the-detroit-auto-show/
- https://www.ugi-international.com/news/dimeta-announces-intended-location-its-first-commercial-scale-rdme-production-plant-teesworks