ENGINES FOR ALTERNATIVE FUELS

1 Introduction

Automobiles that use alternative fuels are unlikely to come into widespread use unless they can markedly distinguish themselves in terms of fuel cost, refueling infrastructure, cleanliness of emissions, or CO_2 reduction. This article summarizes the current trends in generally available LP gas and natural gas vehicles and in the development of their engines. The progress of research and development on hydrogen reciprocating and DME engines, which represent potential future automobile fuels, is also introduced.

2 LPG Engines

The number of LPG vehicles registered in Japan[1] was 195,918 as of the end of December 2019. Those registrations break down into a total of 165,376 units for taxis, private, cargo, special purpose, and shared vehicles, 18,253 JPN taxis, 8,147 bi-fuel vehicles, and 4,142 mini-vehicles.

Universal design taxis (UD taxis)[2] came out in October 2017. Among those, the Toyota JPN taxi[3] is equipped with a hybrid engine developed exclusively for LPG based on the 1,500 cc engine of the Sienta. The number of such taxis exceeded 20,000 units as of the end of March 2020, and they can be seen in Tokyo and many other parts of Japan. The development concept of such taxis is explained in detail in the January 2020 issue of the *Journal of Society of Automotive Engineers of Japan* under the title of "What should JPN TAXI aim of?"[4]. Another UD taxi is the NV200 taxi LP gas bi-fuel engine vehicle by Nissan[5]. Since taxis have a short service life, these UD taxis are expected to spread rapidly in the near future.

As LPG hybrid vehicles, the JPN Taxi is reported to be approximately twice as fuel efficient as a conventional LPG vehicle. This has led to a drop the consumption of LP gas fuel, and deteriorating business conditions is said to have shut down some LP gas stations. In contrast, simpler autogas refueling stations[6], which mitigate equipment investment and maintenance costs and target taxi companies and driving schools, have emerged.

There are many examples of LPG vehicles that consist of remodeled existing gasoline vehicles. The LPG Vehicle Promoting Association in Japan reviewed its LPG vehicle structural handling standard and interpretation document[7] (May 29, 2019). Six years have passed since this standard was revised in January 2013, and the structural handling standard was reviewed since the structure of LPG vehicles is now more sophisticated than it was at the time. The standard was revised at a meeting on LPG vehicle security measures attended by committee members and observers from related industries and government agencies.

3 Natural Gas Engines

According to the latest information available as of the end of December 2019, there are about 28.54 million[8] natural gas vehicles (NGVs) in the world. By area, as shown in Table 1, NGVs are most widespread in the Asia-Pacific region. By country, they are most common in China (about 6.76 million units), Iran (about 4.95 million units), and India (about 3.31 million units)[9] which each reach the millions of units level. Similarly, there are approximately 33,000 natural gas stations in the world. The 2016 yearbook edition of this Journal reported that there were about 3.99 million NGVs in China (as of April 2016), which means that over three and a half years, a further 2.77 million units have spread in the Chinese market, a

Table 1 Global Spread of NGVs and Stations[8] (As of December 31, 2019)

Area	NGVs	Stations
Asia-Pacific	20,473,673	19,606
Europe	2,062,621	5,116
North America	224,500	1,856
Latin America	5,484,676	5,789
Africa	295,349	210

remarkable pace of increase.

Among trends in research on natural gas engines (April 2019 and later), the papers *A Study of Ignition Method for Gas Engine using Low Temperature Plasma* (Chiba University) and *A Study on Flame Extinction in the Gap of Natural Gas Engines* (Waseda University), which were presented at the Annual Spring Congress held by the Society of Automotive Engineers of Japan (May 22 to 24, 2019, in Yokohama). In addition, the Autumn Congress (October 9 to 11, in Sendai), featured the presentation of various papers, including one entitled *Environmental Impact Assessment on Traveling of Natural Gas Vehicle*—LCA of "Well to Tank" and "Tank to Wheel"— (Kanto Gakuin University). Research on plasma-based ignition has confirmed that it can expand the lean burn limit compared to current spark plug-based ignition. The phenomenon leading to flame extinguishing at the gap was found to be influenced by the relationship between the CO production concentration, the flame zone thickness and the vortex scale. Further investigation revealed that controlling these factors makes it possible to suppress flame extinguishing and HC emissions. In all countries, LCA evaluations of NGVs estimate that tank-to-wheel CO_2 emissions are lower for CNG or LNG than for diesel, while in Japan LNG, diesel, and CNG rank lowest to highest in well-to-wheel CO_2 emissions.

Also, research presented at the 30th Internal Combustion Engine Symposium held by the Society of Automotive Engineers of Japan and the Japan Society of Mechanical Engineers (December 10 to 12, 2019 in Hiroshima) included *Visualization of End Gas Region Auto-Ignition in Dual Fuel Gas Engines*, *Numerical Simulation of Natural Gas Auto-Ignition in the End Gas Region* (Okayama University) and *Building a Combustion Control Model for Dual Fuel Engines* (University of Tokyo). The dual fuel engine presented at that symposium has a complex system due to the need to load two types of fuel, making higher costs, more intensive maintenance, and other cost performance factors a concern. Nevertheless the diesel ignition natural gas engine has high thermal efficiency because it uses the same compression ignition combustion as a conventional diesel engine. Also, since natural gas emits about 25% less CO_2 per unit energy[(10)] than diesel, dual fuel engines using natural gas are viewed as an effective approach to reducing CO_2 in the transportation sector, and are expected to be introduced in Japan in the future.

4 Hydrogen Engines

Based on primary energy sources and structural composition characteristics, hydrogen fuel is strongly expected to become a next generation fuel that offers effective solutions to various issues such as global warming, air pollution and energy resource depletion. The technical development of various power sources has been pursued in various countries and sectors since the early 1990s. In December 2014, Japan took the global lead in the commercial production of vehicles that use hydrogen as a fuel. In March 2019, Japan revised its hydrogen and fuel cell strategy roadmap and revealed a clear plan to introduce a complete supply chain of hydrogen production, transportation, and storage to be put to practical use around 2030. In that context, 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. In current research, the use of a combustion system based on direct injection into the cylinders has largely solved past issues such as backfiring or the low output unique to gas-based engines. The remaining issues of suppressing NO_x generation under high load operating conditions and the further improvement of thermal efficiency are being tackled. Similarly, there is a significant amount of research on the blending of hydrogen and natural gas.

Announcements on the research and development of hydrogen engines made in Japan in 2019 include studies on the above further improvement of thermal efficiency and control of NO_x production under high load driving. Research by Tokyo City University[(11)] reported results for a highly efficient high output near-zero emission hydrogen engine. A large bore unit is used to optimize the injection timing and jet shape using a lean burn combustion system that ignites and burns the air-fuel mixture mass immediately after injection completes. Thermal efficiency is improved by reducing cooling loss, an issue described as inescapable in hydrogen engines, thereby achieving an indicated thermal efficiency of over 49% while reducing NO_x generation to a single digit ppm in the high load region. Following the same concept, research by the National Institute of Advanced Industrial Science and Technology reduced NO_x via EGR, and achieved an indicated efficiency of 50% or higher[(12)]. Basic research on engines aiming for high thermal efficiency while eliminating NO*x* generation through an argon-based closed cycle[13]. One research paper presented outside Japan, which focuses instead on intake port injection, described the development of technology that enhances the viability of a 4-cylinder engine achieving improved thermal efficiency through turbocharging and EGR, while reducing NO*x* and boosting output. Other papers looked at improving engine performance using a blended natural gas and hydrogen fuel[15].

5 Dimethyl Ether (DME) Engines

Discussions on ISO standards for DME automobile related component (ISO/TC22/SC41/WG8, DME) are being held. At an international conference held in Cleveland, USA in May 2019, Japan once again proposed its standard for a pressure-equalizing port. In addition, the *Dimethyl Ether (DME) refuelling connector* (ISO 21058) standard, as well as *Part 1: General requirements and definitions* (ISO 22760-1) and *Part 2: Performance and general test methods* (ISO 22760-2) of the standard on DME fuel system components, were officially issued in December 2019. Also, four new fuel system items (85% stop valve, level indicator, PRV, and PRD) were proposed and approved.

A DME Automotive Subcommittee was established under the Environmental Technical Committee at the Society of Automotive Engineers of Japan. This subcommittee discusses the ISO standards. The ISO standard on refueling connectors mentioned above covers pressurized refueling, a method that must contend with the issues of slow refueling or the inability to refuel in use environments such as hot regions. The pressure equalizing refueling port takes advantage of the monomolecular characteristic of DME to solve the above issues.

The DME Sustainable Mobility Workshop[16] was held in Berlin in May 2019. The workshop presented the results of the xME (DME, OME) project led by Ford and the Forschungsvereinigung Verbrennungskraftmaschinen e. V. (FVV), and featured a demonstration of a DME vehicle based on the Ford Mondeo. Prins Autogassystemen BV, a Westport Fuel Systems company is studying a retrofitting system that adapts an LPG direct injection engine conversion kit. It is described as a dual fuel system that can switch between diesel and DME. Ford is evaluating a lightweight commercial DME vehicle equipped with this conversion kit installed as its next step.

The Netherlands Organization for Applied Scientific Research (TNO) announced that, in the context of the EU's ALIGN-CCUS carbon recycling project[17] it would build a pilot plant to synthesize DME from the CO_2 emitted from renewable power and plants for use in automobiles and power generation.

On a different note, an initiative to use propane with 20% renewable DME (rDME) made from biogas has been announced in North America[18]. SVH Energy (Netherlands), a distributor of propane gas, will use rDME supplied by Oberon Fuel to work on reduce the carbon content of propane. SVH Energy is also considering switching all of its LPG to BioLPG by 2040[19]. Oberon Fuel has received a 2.9 million dollar grant from the California state government and announced a target rDME production of 1.6 million gallons per year (4,000 tons/year).

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