Study on Hydrogen Engines for Carbon Neutrality

Kawasaki Heavy Industries Group is developing a hydrogen supply chain in response to the accelerating worldwide movement toward carbon neutrality to prevent global warming. Within the Group, Kawasaki Motors is conducting experiments and simulations to analyze hydrogen jet flows within engines, with the aim of commercializing new mobility solutions based on hydrogen-fueled combustion engines. The research engine has also been mounted on four-wheeled and two-wheeled vehicles to explore practical applications.

Introduction

To prevent global warming, the worldwide movement toward carbon neutrality is accelerating and expectations for mobility solutions are also rising. One way considered necessary for promptly reducing CO_2 emissions is a multi-pathway approach in which various types of systems that each have different advantages, such as battery vehicles, fuel cell vehicles, and alternative fuel engine vehicles (e.g., alcohol-, synthetic fuel-, or hydrogen-fueled), are combined in an optimal way based on the application purpose. Among such vehicles, vehicles with hydrogen-fueled engines (hereinafter, "hydrogen vehicles") are gaining attention as a means to achieving carbon neutrality while further utilizing the advantages of conventional small power-sport vehicles.

1 Background

The Kawasaki Heavy Industries Group is working to establish a supply chain throughout the processes of production, storage, transportation, and use of hydrogen. Focusing on the use of hydrogen, Kawasaki Motors, Ltd. is working to commercialize small vehicles with hydrogen-fueled engines to make them carbon-neutral.

(1) Characteristics and problems of hydrogen engines

The by-product of hydrogen combustion is water, and thereby hydrogen combustion releases no CO_2. In addition, compared with gasoline, hydrogen has the characteristics of a faster combustion rate and wider combustion range. Therefore, because hydrogen engines can offer the quick response required in small power-sport vehicles, they are expected to both achieve carbon neutrality and provide a new driving feel. Furthermore, the combustion period is shortened and is closer to the theoretical cycle, which is expected to deliver higher efficiency.

Meanwhile, although the ignition temperature is high, the ignition energy is low. Consequently, there are concerns that minute hot spots may ignite, causing abnormal combustion (preignition and engine knocking) and backfires, where flames flow back to the intake pipes, may occur. There are also concerns of an increase in the heat loss and burning of engine oil due to the short quenching distance, as well as generation of nitrogen oxides caused by high-temperature combustion gas; however, the mechanisms of such phenomena have not been clarified in detail.

In addition, because the hydrogen fuel is gas at room temperature, various technologies are required for filling small vehicles with gas and to prevent, detect, and stop fuel leaks.

(2) Hydrogen Small Mobility & Engine Technology Association (HySE)

Although the issues described in the previous section need to be resolved in order to commercialize hydrogen engines, various companies studying basic technologies to control the physical properties of hydrogen at the same time is an inefficient way to do it. Accordingly, a technology association was set up for member organizations to work together to solve the problems. Regular members of HySE, which was established in May 2023, are Kawasaki Motors, Ltd., Suzuki Motor Corporation, Honda Motor Co., Ltd., and Yamaha Motor Co., Ltd., while special members are Kawasaki Heavy Industries, Ltd. and Toyota Motor Corporation. HySE's main tasks are to research and discuss common problems related to hydrogen engines (establishment of a hydrogen engine model based on element research and studies using actual engines/vehicles) and storage (tanks and peripheral equipment). In addition, as another major policy, HySE is working to make hydrogen engines a world-standard technology in cooperation with companies around the world, instead of allowing the technology to be peculiar to Japan.

2 Study of hydrogen engines

(1) Deciding on the fuel supply system

There are two fuel supply systems: the port injection (PI) system, in which fuel is injected into intake ports to produce an air-fuel mixture so as to supply it into the cylinders; and the in-cylinder direct injection (DI) system, where fuel is directly injected into cylinders to produce an air-fuel mixture.

Regarding the PI system, the volume of fuel in an air-fuel mixture in a state with the theoretical air fuel ratio is approximately 2% for gasoline, while it is approximately 30% for hydrogen. Because the volume of air that can be taken in decreases for the volume of hydrogen, the calorific value per cylinder capacity decreases by approximately 16%. In addition, at high loads, a backfire (where a flame that ignites in the cylinder during the intake process reaches the intake port) may occur, which poses a problem in high-load operations.

With regard to the DI system, the intake air volume does not decrease and backfires can be avoided, so this system is optimal for small engines requiring high power. Accordingly, this study targeted the DI system.

(2) Deciding on the air-supply system

It is known that when the combustion temperature in hydrogen combustion is high, nitrogen oxides (NOx) form and lean-burn is effective to suppress this. However, lean-burn reduces the output, and adopting a supercharging system is an effective way to supplement the power loss. To expand the air volume selection range, in this study we selected a supercharging system. The test engine was prepared based on supercharging engines for the Ninja H2[1),2)]. **Table 1** lists the main specifications.

Table 1 Specifications

Engine type	Inline 4
Displacement [cm^3]	998
Bore×stroke [mm]	76. 0×55. 0
Stroke/bore	0. 72
Compression ratio	8. 5

(3) Deciding on the fuel supply pressure

For the DI system, to secure a sufficient intake air volume and prevent hydrogen from flowing back to intake ports, the hydrogen supply start (SOI) timing was determined to be after intake valve closure (IVC). In addition, injection needs to finish by the ignition timing (IgT). The crank angle is approximately 100CA, so when the engine speed is 6,000 min^{-1}, the actual time is approximately 4 ms while when the engine speed is 12,000 min^{-1}, the actual time is only approximately 2 ms. To achieve the theoretical mixture ratio, hydrogen of approximately 100 Ncm^3 needs to be supplied into cylinders within this time period, so the fuel supply pressure needs to be set to high at 2 to 10 MPa or higher.

(4) Optimizing the air-fuel mixture formation

Regarding the supply of hydrogen, in addition to the appropriate volume, it is necessary to form an air-fuel mixture in optimal concentration distribution and guide the flammable air-fuel mixture close to the ignition plug at the ignition timing. We performed 3D CFD simulation to understand the phenomenon and discussed the design of improved engines. **Figure 1** illustrates the simulation results. When the injection directions are as shown in the figure on the lower left, the simulation results indicate imbalance in the fuel concentration, etc., and in evaluations using actual engines, abnormal combustion, such as preignition and engine knocking, was observed. After the fuel injection directions were changed to downward as shown in the figure on the lower right, the air-fuel mixture distribution was improved and in operations using actual engines, less abnormal combustion was seen. As described above, it is crucial to understand the behavior of hydrogen gas in the cylinders of hydrogen engines[3)].

3 Understanding the behavior of hydrogen jet flows

(1) Experiments

As the molecular weight of hydrogen (2) greatly differs from that of air (30), understanding the phenomenon of

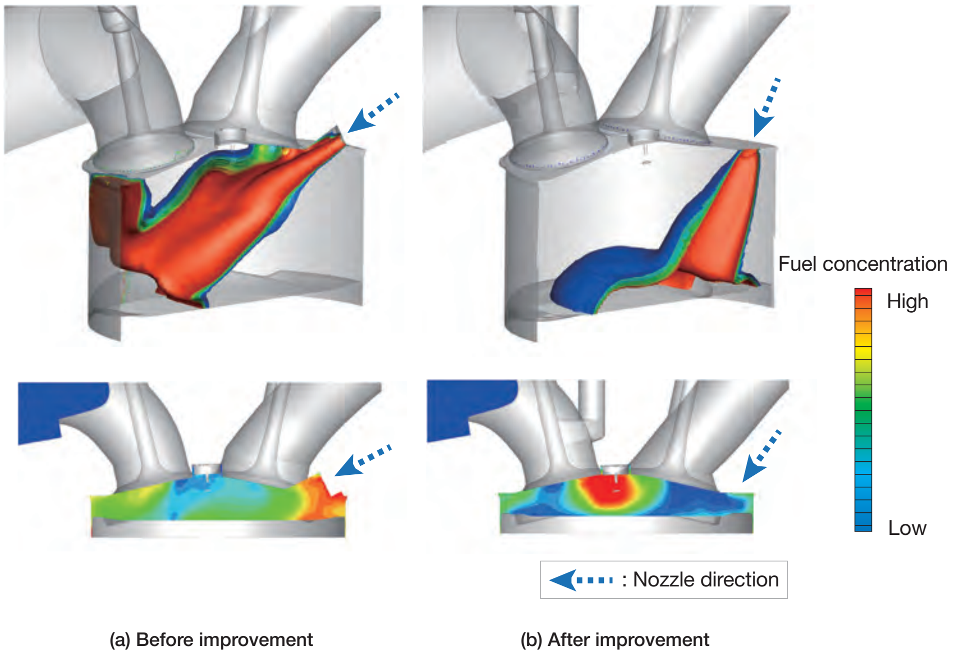


Fig. 1 Improved mixture through simulation of mixed air and fuel (Upper figures: After injection; lower figures: before ignition)

their mixing is crucial when considering abnormal combustion and the generation of nitrogen oxides. This chapter introduces cases in which hydrogen was injected into constant-volume vessels to measure the mixing of the hydrogen and air.

Regarding the DI system, to supply hydrogen into engine cylinders, hydrogen needs to be injected at pressure sufficiently higher than the in-cylinder pressure. If the pressure close to the injector nozzle outlet is two times or more of the back pressure (in-cylinder pressure), an under-expansion jet flow involving a shock wave occurs and the jet flow structure becomes complicated.

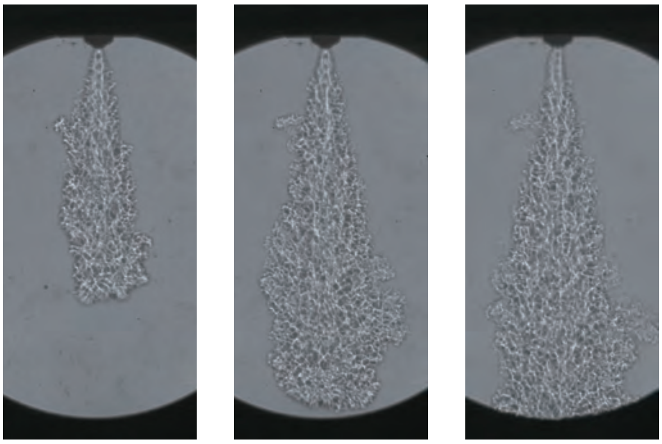
Accordingly, to understand the behavior of hydrogen jet flows and their spreading phenomena, the behavior of hydrogen jet flows when the pressure in constant-volume vessels and the hydrogen injection pressure were changed was photographed using the Schlieren method. In the injection tests, hydrogen was jetted from the injectors into constant-volume vessels for predetermined times and a high-speed camera (Phantom V2512 manufactured by Vision Research Inc.) was used to photograph the behavior of the hydrogen jet flows through a glass window installed in each vessel.

Table 2 lists the test conditions. Assuming injection in the compression process, the pressure in the vessels was set to 0.2 to 1.0 MPa and changes in the behavior of hydrogen jet flows according to the changes in the injection pressure were observed. **Figure 2(a)** shows the behavior of a hydrogen jet flow assuming injection in the first period of the compression process (near the IVC). The pressure in the vessel was set to be equivalent to in-cylinder pressure in a low-pressure atmosphere (0.2 MPa) and the hydrogen was injected at the injection pressure of 2 MPa. The photographs show that the hydrogen in the vessel starts spreading within 2.0 ms after injection,.

Figures 2(b) and **2(c)** show the behavior of hydrogen jet flows when the injection pressure was changed, assuming injection in the middle of the compression process. When the injection pressure is high, the jet flow distance at the front end increases and the hydrogen starts spreading after injection. The photographs also show that when compared with injection in a low-pressure atmosphere, the hydrogen jet flow gathers and remains at

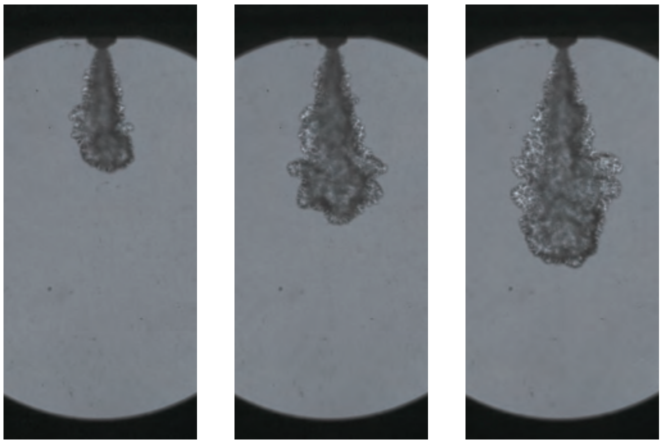
Table 2 Conditions for Schlieren photography of hydrogen jet flows

Fuel	Hydrogen
Fuel injection pressure [MPa]	2. 0–10. 0
Fuel temperature [K]	300
Injection time [ms]	1. 0
In-vessel pressure [MPa]	0. 2–1. 0
Gas in the vessel	Nitrogen
Frame rate [fps]	39000



In 1.0 ms In 1.5 ms In 2.0 ms

(a) Injection pressure of 2 MPa and in-vessel pressure of 0.2 MPa



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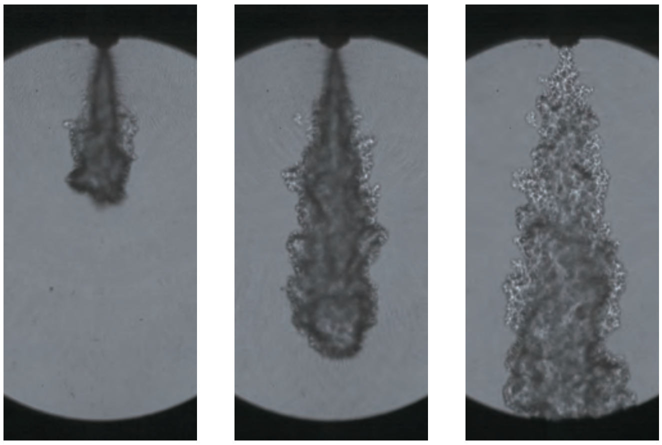
(b) Injection pressure of 2 MPa and in-vessel pressure of 1 MPa



In 1.0 ms In 1.5 ms In 2.0 ms

(c) Injection pressure of 10 MPa and in-vessel pressure of 1 MPa

Fig. 2 Schlieren images of hydrogen jet flows that place. Through such characteristic results from observing the hydrogen jet flows, we will gain a clearer understanding of the behavior of hydrogen jet flows and hydrogen mixing phenomena, which will contribute to optimizing the air-fuel mixture concentration distribution in engine cylinders.

(2) Numerical simulations

Understanding the process of forming an air-fuel mixture as a result of a hydrogen jet flow is important, so CFD numerical simulation is considered to be effective for ① considering hydrogen injection on a parametric basis and, ② evaluating the state in the mixing process.

As described above, high-pressure hydrogen jet flows generally become supersonic flows, causing very high-turbulence flows. Accordingly, spreading phenomena of turbulent flows of hydrogen and air are important to know, so a turbulent flow model needs to be selected for conducting numerical simulations. There are two simulation types: Reynolds averaged numerical simulation (RANS), in which turbulent flows are smoothed to create a model, and large eddy simulation (LES), in which eddy scales equal to or larger than the designated mesh size are directly subjected to numerical calculation and eddy scales smaller than the designated size are subjected to modeling.

In addition, as the hydrogen injection modeling method, the motions of the lifting parts in an injector were simulated and an injection pressure boundary was given to the upstream side of the lifting parts. The pressure in the cylinders of direct-injection hydrogen engines changes moment by moment, so establishing an injection model that includes the motion of the lifting parts was determined to be necessary. However, the details inside injectors are not known, so the approximate diameter of the resting position was tentatively determined from the appearance of the injector, and the time history of the injector curtain area (opening) was adjusted such that it matches the state of the injection signal history and hydrogen injection volume per cycle.

Figure 3 compares the numerical simulation results with the test results of the visualization of hydrogen jet flows in constant-volume vessels within 1 ms after injection starts when the injection pressure was set to 6 MPa and the in-vessel pressure was set to 1 MPa under the testing conditions listed in **Table 2**. The images of the Schlieren test and LES show projections and depressions of the eddy structures of the turbulent flows at the jet flow interfaces, while the RANS image shows the jet flow in a teardrop shape without projections and depressions at the jet flow interface because the turbulent flow is smoothed. In other words, these results show that the area of the jet flow interface varies from the turbulent flow model to the model, which may make the degree of mixed diffusion different to some extent. Next, **Fig. 4** compares the jet flow distances and injection angles between the test and simulation models. The jet flow distance is an important index for observing the momentum of jet flows and mixing behavior after collision in cylinders. The jet flow distance obtained in the test closely matches the numerical simulation (LES/RANS) results, and these results show that all turbulent flow models can reproduce the test results. Meanwhile, the injection angle is an important index for evaluating the spread of jet flows; although the injection angles in the latter half of the injection differ slightly between the test and simulations, the LES angles are almost the same as the RANS angles. Note that the calculation time varies greatly between RANS and LES; it is approximately 1.5 days for RANS but around 14 days for LES.

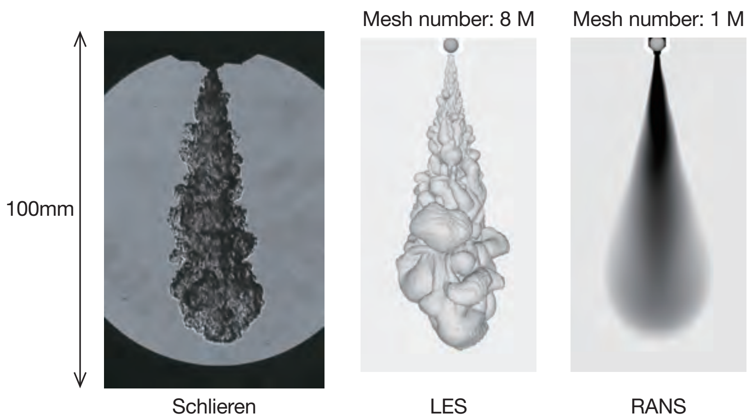


Fig. 3 Comparison of visualized hydrogen jet flow within a constant-volume vessel with simulated images (Within 1 ms after injection start, injection pressure of 6 MPa and in-vessel pressure of 1 MPa)

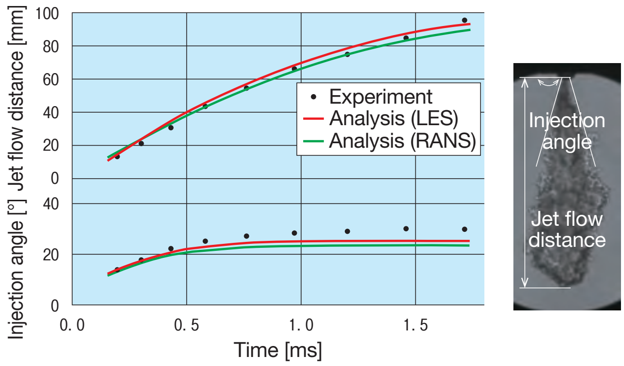


Fig. 4 Comparison of jet flow distances and angles in tests and simulations

Through verification with the test results above, a technology for numerically simulating hydrogen jet flows has been successfully established. It may be appropriate to use optimal turbulent flow models for different situations: LES to evaluate phenomena in the mixing process of hydrogen and air in detail, and RANS for globally discussing many design parameters (e.g., injection positions, directions, and pressure).

4 Evaluating actual hydrogen engines

(1) Study of hydrogen engines in environments involving actual machines

Before applying hydrogen engines to two-wheeled vehicles and other small vehicles, as well as conducting desktop tests, we need to extract problems that may arise during actual driving and develop measures against them. In actual driving, engines need to have transient characteristics to cope with changes in conditions, such as user-initiated acceleration and deceleration, road gradients, slippery surfaces, and influences from surrounding vehicles. In addition, influences on abnormal combustion, exhaust gas, driving feel, and other factors also need to be considered.

Furthermore, a fuel supply system is required and the vehicles need to be equipped with various other systems: a hydrogen storage system (e.g., hydrogen tanks, filling ports, and pressure regulating valves), a hydrogen storage control system that recognizes the state of the storage system and controls it, and a hydrogen safety system that prevents, detects, and stops hydrogen leaks.

We produced a test hydrogen vehicle based on Kawasaki Motors' TERYX KRX1000 off-road four-wheeled vehicle as a mobile laboratory equipped with the aforementioned systems and is in use for research. A driver and a vehicle status monitor ride the test vehicle, and control adaptations can be done in real-time. For the engine, a four-cylinder DI system was adopted.

Because we worked in cooperation with the other HySE members to build the laboratory vehicle, driving tests could be done in a short period of time with safety secured. In pursuing the common goal of carbon neutrality, we have been able to build an inter-company friendship that we could never have imagined in the past (**Fig. 5**).

(2) Study of hydrogen engines in harsh environments

To accelerate the establishment of fundamental technologies for hydrogen engines, the HySE team participated in the Dakar Rally, one of the world's toughest motorsport events, as part of our study of hydrogen engines so we could promptly extract unknown problems we could not easily foresee. The 2024 Dakar Rally's Mission 1000 (from January 3 to 19, 2024 in Saudi Arabia) is a new category established in 2024 to encourage the development of next-generation power trains, such as hydrogen vehicles, bio-fuel vehicles, fuel-cell electric vehicles, electric motor vehicles, and hybrids of them, toward carbon neutrality. The machines travel approximately 1,000 km in total within 11 days. The route consists of 11 stages that include desert terrain, sandhills, and wastelands, so the road conditions vary; the elevation height is 0 to 1,700 m or so and the difference in temperature between daytime and nighttime is drastic. These conditions make it possible to test machines in various harsh environments in a short time. The organizer provided a mobile hydrogen station, which made it possible for our team to participate in the rally. In addition, it is said that the number of TV viewers of the Dakar Rally is the second largest in the world, so HySE aimed to showcase our work and hydrogen engines as an option to the world, and spread awareness of us beyond Japan.

The HySE team used an all-terrain vehicle (HySE-X1) to participate in Mission 1000 (**Fig. 6**), and the engine was a four-cylinder DI system. The engine adaptation was carried

Fig. 5 The unveiling of the hydrogen vehicle at a racetrack

Fig. 6 HySE members with the HySE-X1

out near the stoichiometry (theoretical air fuel ratio) for the entire range by prioritizing the output, and the team's policy was, by enhancing the driving characteristics on various road surfaces and elevation heights, to travel as far as possible to collect data.

Although the preparatory period was short at just four months, thanks to the experience described in the previous section and the support of people with a rally background, the team could travel 830 km of the 11 stages' 922 km. In the stages whose distance exceeded 100 km, the team drove the machine with a focus on fuel economy while in the stages whose distance was 50 km or so, they drove it at high loads. Therefore, by changing the load conditions during driving (**Fig. 7**), the team could observe multiple abnormal combustion occurrences during the event. In addition, many media (TV and online news and live streaming during the 2024 Dakar Rally) picked up on our team and machine, so HySE could present its efforts to the world and contribute to attracting partners in the future. HySE will use the outcomes and experience gained through the rally to develop hydrogen engine technologies from now on.

(3) Study of hydrogen engines for two-wheeled vehicles

The space for installing components in two-wheeled vehicles is limited compared with four-wheeled vehicles, and because two-wheeled vehicles need to be picked up and pushed, there is a strict limit on the weight as well. In addition, there is a risk of two-wheeled vehicles falling, we need to extract problems specific to these vehicles (e.g., protection of equipment in case of a fall) promptly to solve them. Furthermore, at present the legal framework for these vehicles is not well developed, so test vehicles for technological demonstration are needed to bring the law up to date with the technology. If test driving on public roads is allowed, studies can be done across a wider scope, such as checking the relationship with existing vehicles in actual environments and extract problems associated with using hydrogen stations in urban environments.

With these factors as the background, we decided to produce and study a two-wheeled vehicle with a hydrogen engine (**Fig. 8**). The engine is a four-cylinder DI system. The machine is equipped with two hydrogen tanks on both sides at the rear. The tanks are surrounded with piping materials to protect them, they are fixed in place with suitable fasteners, and the outsides are covered with CFRP (carbon-fiber reinforced plastic) covers. This structure prevents third parties from directly touching the hydrogen tanks even when the vehicle falls over or is involved in a collision. This structure was subjected to FEM analysis to check the behavior of the hydrogen tanks when the machine experiences a crash. The tank capacity was set to 50 L (2 kg) because this is the minimum size that can be filled at urban hydrogen stations that have been set up according to the JPEC-S0003 Compressed hydrogen filling technical standard. However, regarding the

Fig. 7 HySE-X1 racing across sandy terrain

Fig. 8 Hydrogen-powered motorcycle

size of tanks for two-wheeled vehicles, UN Regulation 146 (UNR146) specifies up to 23 L, so we will use this test vehicle to appeal to related organizations to expand the tank size according to the vehicle category.

With regard to exhaust gas, NOx emissions could be reduced by adopting the lean-burn method.

To promote the appeal of hydrogen engines, we ran a public driving event at the Suzuka Circuit during the Suzuka 8 Hours Endurance Race held on July 20 and 21, 2024. We also hosted a public driving event in France, which highlighted the potential for hydrogen engines to the world.

Conclusion

In addition to technological development, related laws and regulations and the supply infrastructure need to be developed in order to popularize hydrogen vehicles. In addition, the Japan Automobile Manufacturers Association is proposing a multi-pathway approach, and public activities are important for raising awareness of hydrogen engines among the general public. We drove the test hydrogen vehicle during an event at the racetrack and at an exhibition of zero-emission vehicles held by the Tokyo metropolitan government and asked the Governor of Tokyo to test-ride it, which has helped make hydrogen vehicles better known to society at large.

Although hydrogen engines have been studied since long ago, they are now nearing commercialization due to rapid advances in equipment, such as storages and injectors, in recent years and gaining attention worldwide as a way to achieve carbon neutrality. We are focus on small vehicles in particular, and will work to commercialize them through various measures such as demonstration, the spread of our association, appeal to public opinion, and helping with the development of laws and regulations, in addition to research.

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