Development and Verification of Power Generation Gas Turbine Combustors for A) Hydrogen fired and B) Ammonia fired

TAKU EGAWA*1 NAOKI ABE*2
MITSUHIRO MORISHITA*2 HIROYUKI TAKEISHI*3
TOMOAKI ISOBE*4 TOMO KAWAKAMI*5

Mitsubishi Heavy Industries, Ltd. (MHI) development of large-capacity, high-efficiency gas turbines co-firing hydrogen with DLN combustors dates back to the mid-2010s and it is expanding its carbon-free power generation system lineup with a target to achieve carbon neutrality by 2050. Following the above target, several successful verifications and demonstrations have been conducted on actual-equipment, including the latest M501JAC gas turbine (rated output: higher than 450-MW), applying natural gas-hydrogen co-firing with a hydrogen blend ratio of 30 vol%. Similar efforts are ongoing with verification of the medium-size/small gas turbine H-25 (rated output: higher than 40-MW) for 100% hydrogen firing (dry). In addition, two different concepts are being developed and verified for ammonia-usage to be applied to MHI gas turbines as soon as possible:

i) an ammonia single-fired system and

ii) a high-efficiency SCR (Selective Catalytic Reduction) system for medium-size/small gas turbines.

1. Introduction

Global electricity demand is predicted to increase substantially toward 2050 (1) and highlights the importance of energy security to counter existing deficits and the growing risks caused by supply chain dependence on several countries. These circumstances are promoting large-scale power supply investment to cover the increasing electricity demand required by new data centers, semiconductor factories supporting AI, and accelerated electrification of the transportation sector, including EVs.

Introduction of renewable energy is necessary to achieve both abundant energy supply and decarbonization, while achieving a well-balanced power supply configuration not to be overly dependent on specific power sources and fuels.

Thermal power generation is still a major power source but the associated high carbon dioxide (hereinafter referred to as CO_2) emissions increase greenhouse gas (hereinafter referred to as GHG) release to the atmosphere. On the other hand, thermal power generation plays an important role to compensate for output fluctuations caused by the increasing renewable energy sources and as an inertial and synchronizing power to maintain grid stability.

Decarbonization of thermal power generation is promoted by applying carbon-free fuels such as hydrogen and ammonia as a means of energy transition, and by utilizing CCUS (Carbon dioxide Capture, Utilization and Storage), while maintaining stable generation capacity. In recent years, research and development of hydrogen/ammonia power generation systems has moved forward, and short-time hydrogen co-firing operations at existing thermal power plants have been started for demonstration purposes in Japan and overseas (2). In the future, it is expected that initiatives toward concrete implementation of the systems in society, such as increasing the operation time and blend ratio, and enlarging the system size, will progress.

*1 Gas Turbine Engineering Department, GTCC Business Division, Energy Systems
*2 Engineering Manager, Gas Turbine Engineering Department, GTCC Business Division, Energy Systems
*3 Energy Systems Research Department, Research & Innovation Center
*4 Engineering Department, Steam Power Business Division, Energy Systems
*5 Manager, Gas Turbine Engineering Department, GTCC Business Division, Energy Systems

There are three ways to decarbonize thermal power generation: "Reduce," "Capture" and "Eliminate" CO_2. **Figure 1** shows the decarbonization roadmap that Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) is focused on. High-blend ratio biomass co-firing, a technology that has already been established for coal-fired thermal power generation, and high-blend ratio ammonia co-firing under development, can reduce the CO_2 emissions. Replacement of coal-fired thermal power generation with a high-efficiency natural gas-fired Gas Turbine Combined Cycle (hereinafter referred to as GTCC) can reduce CO_2 emissions by about 65% due to the effect of the fuel conversion and improved thermal efficiency. These efforts combined with CO_2 capture technology can result in CO_2 capture up to 90% from the exhaust of the coal-fired power plant or GTCC. Ultimately, the target aims fuel conversion to hydrogen or ammonia, which are carbon-free fuels with zero CO_2 emissions and the technology is being developed along this roadmap.

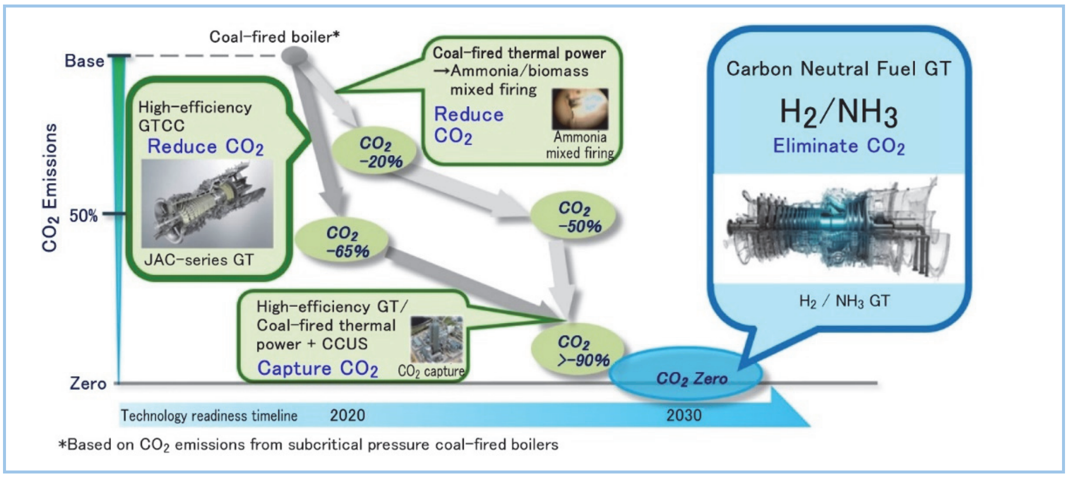

Figure 1 CO_2 Zero power generation technology roadmap

The introduction of hydrogen or ammonia to gas turbines can be achieved with relatively minor modifications:

i) replacing or modifying the existing natural gas-fired combustors in a gas turbine and

ii) modifying the fuel supply system or simply adding mixing capabilities.

The technological development for this effort will focus on the gas turbine combustors. **Figure 2** shows MHI's carbon-free gas turbine system lineup.

Compared to natural gas used in gas turbines, the calorific value and burning velocity of hydrogen (H_2) and ammonia (NH_3) are significantly different, therefore, it is necessary to either modify the existing combustors for stable combustion and low NOx emissions or develop new technologies.

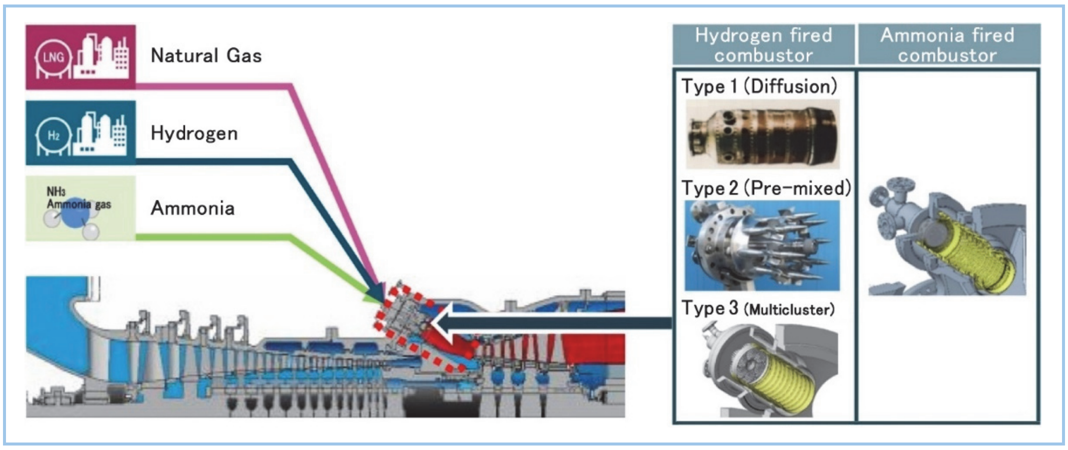

Figure 2 MHI's hydrogen or ammonia gas turbine combustor lineup

Since the mid-2010s, MHI has developed hydrogen co-fired combustors for large-capacity, high-efficiency gas turbines which use natural gas mixed with hydrogen as fuel, and hydrogen single-fired Dry Low NOx (hereinafter referred to as DLN) combustors, with a subsidy from the New Energy and Industrial Technology Development Organization (NEDO). Regarding ammonia, MHI has also developed new technology based GTCC systems. Currently, development is moving to the demonstration phase after undergoing combustor design and various tests.

This report focuses on hydrogen or ammonia-fired gas turbines and presents their development and actual-equipment verification status.

2. Verification status of hydrogen co-fired gas turbines

MHI is developing a hydrogen co-fired combustor (hereinafter referred to as Type 2 combustor) for gas turbines that enables natural gas-hydrogen co-firing. The Type 2 combustor shown in **Figure 3**, is based on a natural gas-fired DLN multi-nozzle combustor and has eight premixed fuel nozzles and one pilot flame fuel nozzle in the center to stabilize combustion. Hydrogen has a higher calorific value and burning velocity than natural gas. Therefore, when natural gas is mixed with hydrogen and burned, the flame position moves upstream compared to when only natural gas is burned, and combustion occurs at a high flame temperature before sufficient air mixing. As a result, the generation of thermal NOx, which depends on temperature, tends to increase. In addition, there is an increased risk of flashback, in which flames travel upstream of the combustor and burn the relevant parts. The nozzles are equipped with a swirler. The air passing through the swirler is mixed more uniformly with the fuel injected through the nozzle, thereby reducing NOx emissions. On the other hand, there is a low flow velocity zone, located in the center of the swirling flow (hereafter referred to as the vortex core). It is considered that flashback occurs when the flame travels upstream through this vortex core. As countermeasure, air is injected from the tip of the nozzle to increase the flow velocity in the vortex core, thereby compensating for the low flow velocity therein to prevent flashback.

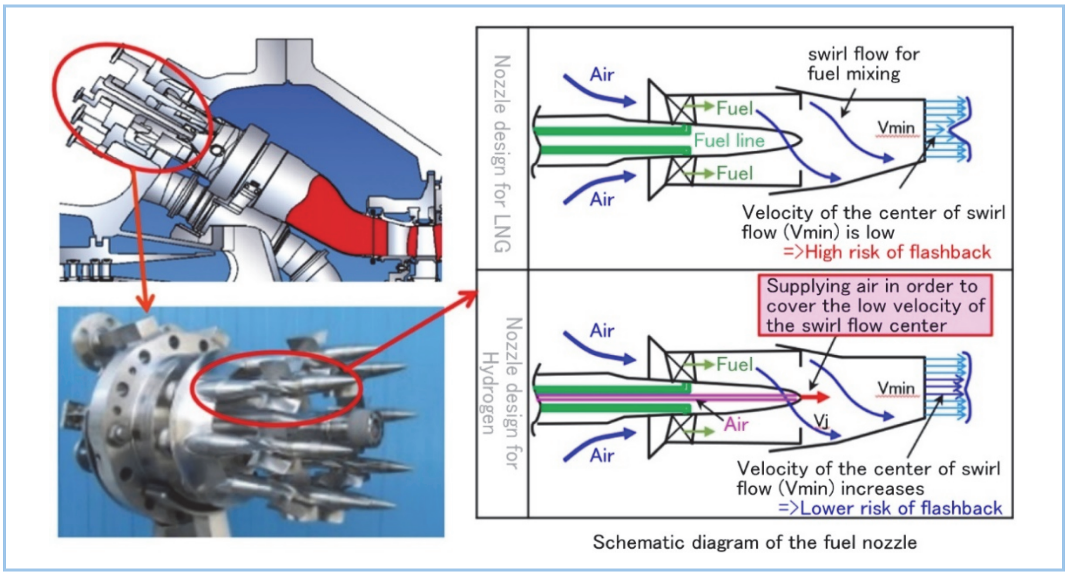

Figure 3 Hydrogen co-fired combustor (Type 2 combustor)

The Type 2 combustor was installed in a large gas turbine, and hydrogen co-firing operation was verified in autumn 2023. MHI has established the Takasago Hydrogen Park (**Figure 4**) on the premises of Takasago Plant, which is the first facility in the world capable of verifying technologies ranging from hydrogen production to power generation in an integrated manner, and began operating the facility sequentially starting in 2023.

The actual-equipment verification was conducted at the GTCC demonstration power plant located in the Takasago Hydrogen Park shown in **Figure 5**, featuring the latest M501JAC gas turbine with a Turbine inlet Temperature (hereinafter referred to TiT) of 1,650°C. The demonstration operated at partial load and 100% load using a natural gas-hydrogen mixed fuel at a hydrogen blend ratio of 30 vol%[(3)]. It was confirmed that hydrogen co-firing operation produced low NOx emissions equivalent to those of natural gas operation and that the combustion was stable as shown in **Figure 6**. Furthermore, carbon monoxide (CO) emissions from partial load operation were reduced. Compared to natural gas firing, the combustion efficiency was improved, and the minimum load at which operation in compliance with emission regulations can be maintained was lowered. In addition, it was confirmed that fuel switching from natural gas to hydrogen mixed fuel is possible during partial load and 100% load operations. As such, the operational control logic for safe operation was successfully verified.

The hydrogen used in the test was produced by equipment at the Takasago Hydrogen Park. This was the first case in the world where a large gas turbine was operated to demonstrate power generation using a 30% hydrogen mixed fuel while being connected to the local power grid with the utilization of a large amount of hydrogen produced and stored at the same site.

Actual-equipment verification at the Takasago Hydrogen Park is currently underway, with various tests being conducted using hydrogen-mixed fuel. This effort will continue to advance development to increase the hydrogen co-firing ratio.

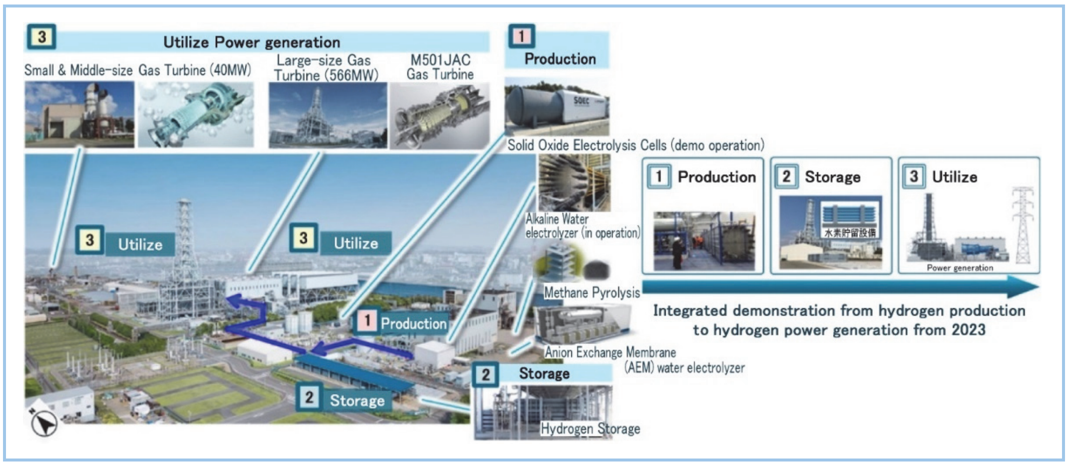

Figure 4 Takasago Hydrogen Park

Figure 5 MHI's GTCC demonstration power generation plant's latest JAC gas turbine and central control room

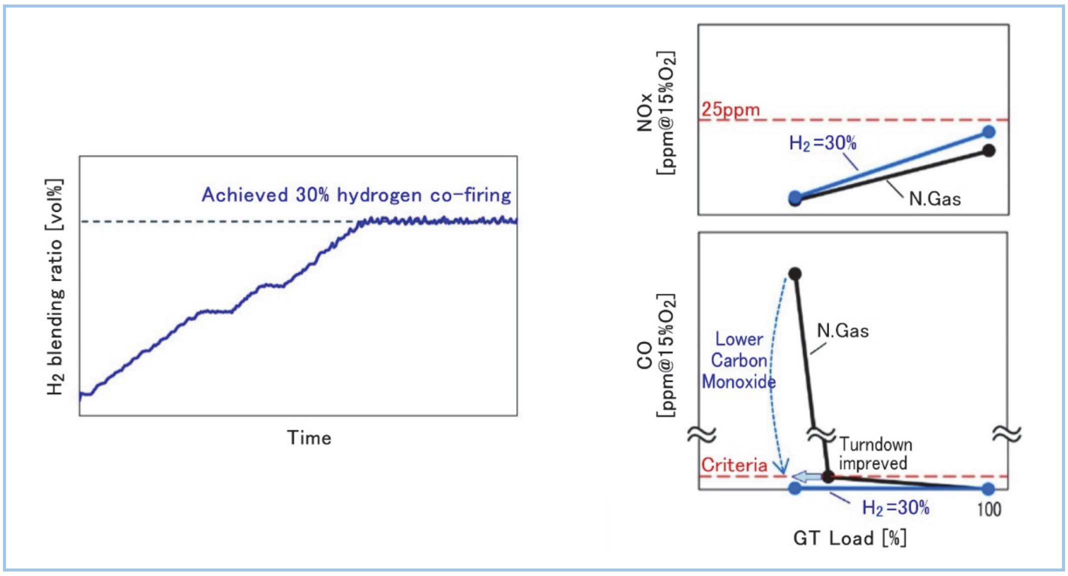

Figure 6 Results of hydrogen 30 vol% co-firing tests at MHI's GTCC demonstration power plant

In the development of the Type 2 combustor, a research aimed at increasing the hydrogen co-firing ratio from 30% to 50% is being conducted. One measure to achieve this, as shown in **Figure 7**, is to change the pilot flame fuel nozzle, which is located in the center of the combustor, from a premixed system, which mixes fuel and air in advance and then injects it into the combustor, to a diffusion system, which injects fuel and air separately into the combustor to eliminate the risk of backfire, and feed 100 vol% hydrogen fuel therefrom. By combining this with the injection of 30 vol% hydrogen fuel from the eight premixed nozzles, it is possible to increase the hydrogen co-firing ratio to 50 vol% hydrogen for the entire combustor. The increase in NOx generation in the diffusion combustion section can be suppressed by injecting water, and also conducted operational verification in single-combustor actual-pressure combustion tests.

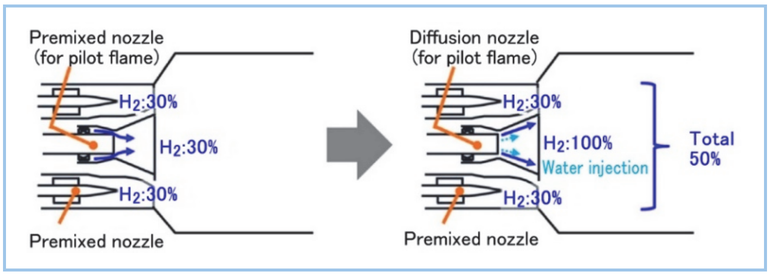

Figure 7 Measure to increase hydrogen co-firing ratio

The actual-equipment verification using this measure was conducted in 2025 at Plant McDonough-Atkinson in Georgia, USA, using an M501GAC natural gas-fired gas turbine (rated output: 283-MW class). In this verification, a successful demonstration test was conducted using 50 vol% hydrogen mixed fuel under both partial load and full load conditions [(4)]. The successful completion of this 50 vol% hydrogen co-firing test follows the successful completion of the first demonstration test using 20 vol% hydrogen co-firing conducted at the same power plant in 2022 using existing GTCC power generation equipment. It was the world's largest scale test using high-efficiency, large-scale GTCC power generation equipment. The 50 vol% hydrogen co-firing reduces CO_2 emissions by approximately 22% compared to 100 vol% natural gas firing.

30 vol% hydrogen co-firing operation of our latest M501JAC gas turbine is planned for 2025 in the Advanced Clean Energy Storage project in Utah, USA [(5)], and also hydrogen co-firing demonstration projects using large gas turbines supplied by MHI are being implemented or are underway at power plants in Japan and overseas.

3. Verification status of hydrogen single-fired gas turbines

The higher the concentration of hydrogen becomes, the risk of backfires increases. MHI is currently developing a hydrogen single-fired multicluster combustor (hereinafter referred to as Type 3), with lower risk of backfires than Type 2, as a gas turbine combustor that can be used for hydrogen single-firing combustion. The company is aiming its application to small and medium-size gas turbines (H-25). In 2024, a demonstration test of the Type 3 combustor was conducted in an H-25 gas turbine at the actual-pressure combustion test facility at Takasago Plant, and confirmed hydrogen single-firing operation. The positive experience fed the know-how gained from the combustor for small and medium-size gas turbines back into the development of a hydrogen single-fired combustor for large gas turbines, and tests are currently ongoing for verification in a single combustor.

3.1 Actual-equipment verification of hydrogen single-firing using small and medium-size H-25 gas turbine

The Type 3 combustor is based on the natural gas-fired multicluster combustor for small and medium-size H-25 gas turbines. As shown in **Figure 8**, t the combustor has many holes (premixing tubes (nozzles)), where air and fuel are rapidly mixed, to shorten the mixing distance and increase resistance to backfires. In addition, by dispersing the flame through many holes, NOx emissions can be reduced. The many premixing tubes (nozzles) are grouped into several blocks and the fuel flow ratio between the blocks is controlled, achieving fuel staging to ensure stable combustion. An ultraviolet-light reflecting image of the hydrogen flame on a model burner, which is a part of the combustor taken out, shows that the flame exists in a uniform and stable state at a short distance from the burner nozzle outlet.

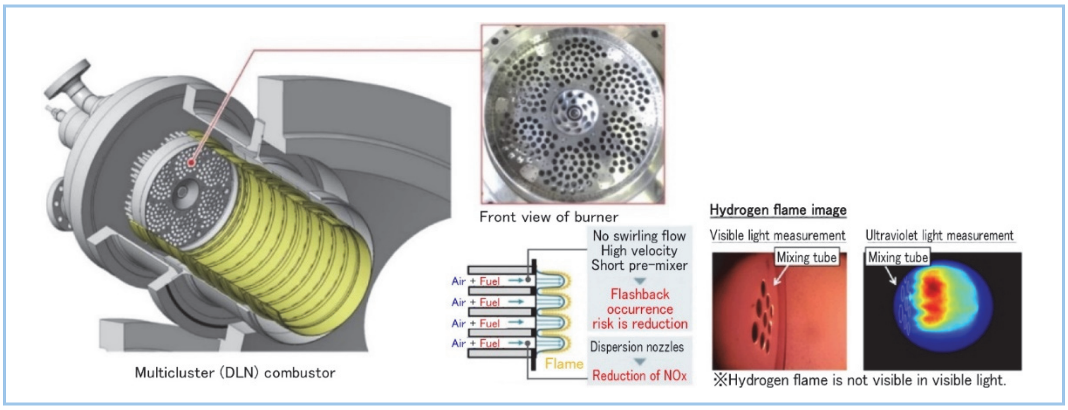

Figure 8 Hydrogen single-fired multicluster combustor (Type 3 combustor)

Up to this point, an actual-pressure combustion test has been conducted using a single prototype combustor under operating conditions (pressure and temperature) equivalent to actual-equipment operation, and had confirmed stable combustion without flashbacks in hydrogen single-firing combustion. Based on this positive results, an actual-equipment demonstration of hydrogen single-firing was conducted at the actual-pressure combustion test facility at MHI Takasago Plant in 2024. **Figure 9** shows the actual-pressure combustion test facility where an actual-pressure combustion test of the single combustor for large gas turbines was performed. Air for the combustion test was supplied from the air compressor, which is powered by an H-25 gas turbine. The actual-equipment verification was conducted using the H-25 gas turbine with Type 3 combustors fully installed. The verification test used a large volume of hydrogen, supplied from the hydrogen storage facility in the Takasago Hydrogen Park.

In the verification test, it was confirmed that the gas turbine could be operated using natural gas fuel without any problems from ignition/step-up to rated load, and then a test using hydrogen fuel was conducted. After ignition and step-up with natural gas fuel, the fuel was switched to hydrogen fuel at partial load. In the middle of this process, it was confirmed that there was no problem in operation at a 75% hydrogen co-firing ratio in the middle of this process, and then increased the hydrogen ratio to reach 100% (hydrogen single-firing), and finally confirmed that CO_2 emissions were zero during hydrogen single-firing load operation (**Figure 10**).

In this verification, combustion characteristics data for the actual gas turbine with multiple combustors installed was collected, which could not be obtained in the combustion test of a single prototype combustor. The accumulated know-how has been used to address identified issues toward the operation of the actual gas turbine. Based on these findings, verification tests will continue to improve the combustor design further.

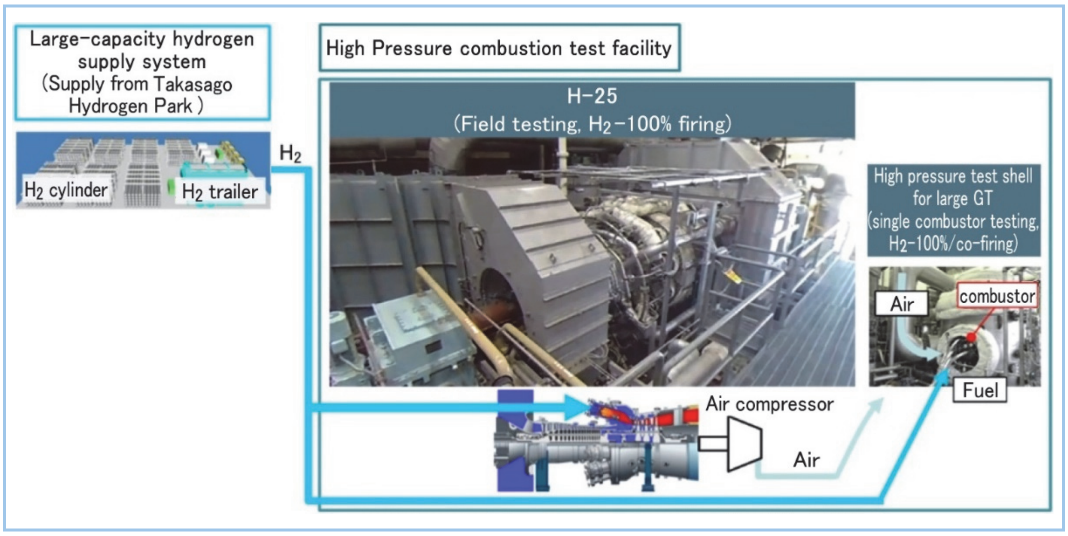

Figure 9 MHI H-25 gas turbine actual-pressure combustion test facility for hydrogen single-firing verification

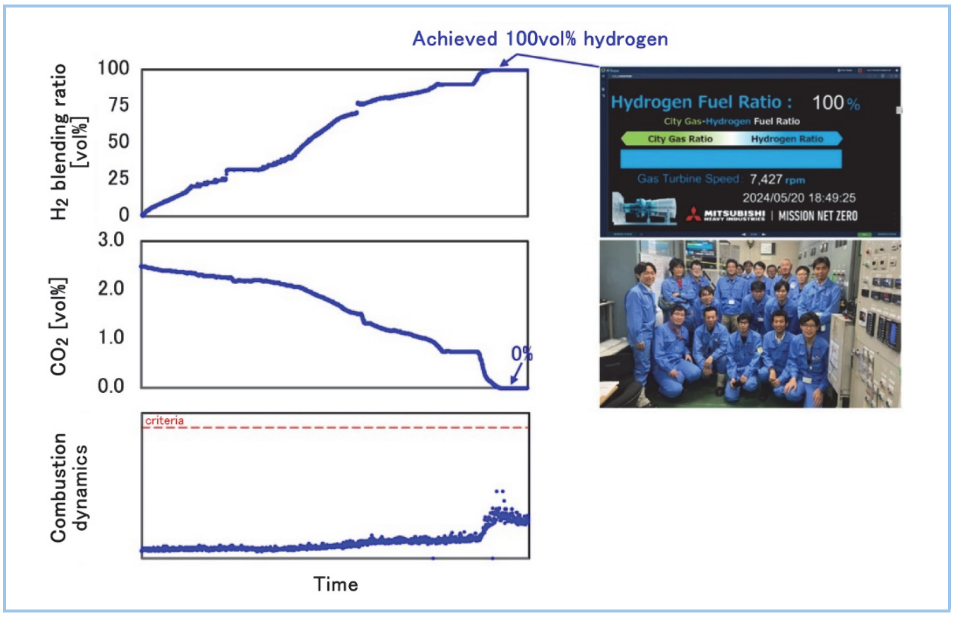

Figure 10 Verification Results of H-25 gas turbine hydrogen single-fired multicluster test

3.2 Verification status of hydrogen single-fired combustor for large JAC gas turbine

The hydrogen single-fired combustor for large gas turbines based on the Type 3 combustors for small and medium-size H-25 gas turbines is being developed by feeding back the know-how gained described above. Compared to small and medium-size gas turbines, large gas turbines have higher output and higher TiT, resulting in higher air temperatures and pressures, as well as higher air and fuel flow rates. Also, their burning velocity is higher, inducing a greater risk of backfires. In addition, they tend to be more prone to combustion pressure fluctuation. Therefore, the hydrogen single-fired combustor for large gas turbines should not be simply a larger version of a combustor for small and medium-size gas turbines, but should require further measures to ensure stable combustion.

As one of the measures to reduce the risk of backfires, metal Additive Manufacturing (AM) technology to fabricate a modified nozzle that achieves a concentration distribution of the air-fuel (hydrogen) mixture that is less likely to cause backfires has been applied.

Hydrogen single-firing combustion tests of the prototype combustor are being conducted at the blowdown combustion test facility (6) at MHI Research & Innovation Center (Takasago District), as shown in **Figure 11**. This facility is capable of conducting combustion tests under the same conditions (air pressure and temperature) using a single combustor of the same scale as the actual equipment, and employs a blowdown system in which high-pressure air used for the test is stored in a large-capacity air tank in advance, heated to the same temperature as that of the actual equipment through an air heater at the time of the test, and supplied to the test equipment. Compared to the actual-pressure combustion test facility, in which high-temperature, high-pressure air is supplied using a gas turbine-powered large-capacity compressor, described in Section 3.1 above, this facility has a limited air capacity and its test time is shorter, but it can efficiently gather data at multiple points and can conduct tests at low cost. In addition, this facility has two test shells in which prototype combustors can be assembled, and therefore, tests can be performed by switching between them to speed up the development process. This facility has a variable acoustic device that can simulate combustion pressure fluctuation that occurs uniquely in actual equipment having 16 or more combustors in combustion tests using only one combustor, enabling more accurate verification tests in the development of combustors with reduced combustion pressure fluctuation. This facility is useful for screening and verification of multiple prototype combustors. Verification tests of the hydrogen single-fired combustor for large gas turbines are being conducted using this facility.

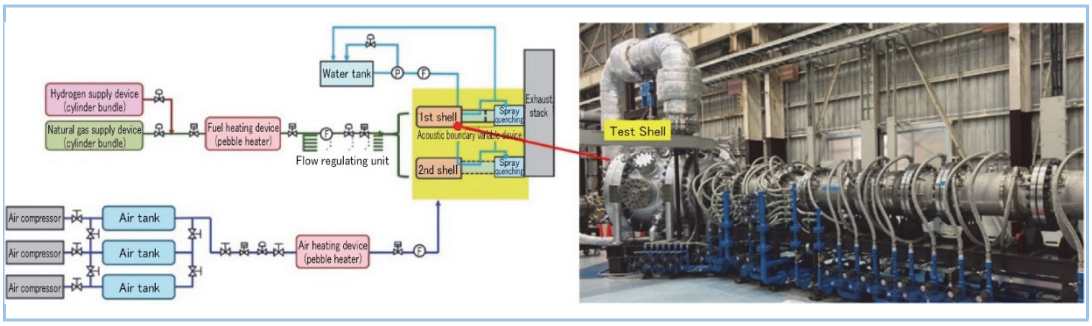

Figure 11　Blowdown combustion test facility

In the combustion test of the aforementioned modified prototype combustor, natural gas was used for ignition and switched to hydrogen fuel at partial load, as in the verification performed with the small and medium-size H-25 gas turbine. In the course of the switching, hydrogen fuel was increased while performing fuel staging between multiple divided nozzle blocks to control the fuel ratio to avoid combustion pressure fluctuation and backfires and maintain stable combustion conditions. After reaching 100% hydrogen (hydrogen single-firing), the load was further increased to confirm stable operation under test conditions that exceeded the output (TiT) of a small and medium-size gas turbine (**Figure 12**).

The efforts to proceed with the development so as to ensure stable operation under conditions will continue with even higher power (higher TiT) to enable operation with a large, state-of-the-art JAC gas turbine.

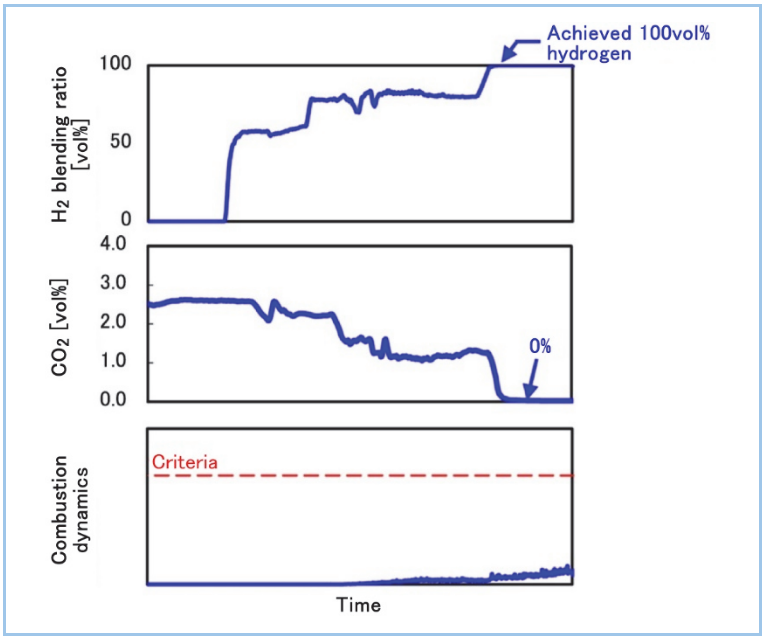

Figure 12　JAC GT Hydrogen single-fired multicluster combustor test results at MHI's blowdown test facility

4. Development status of ammonia direct combustion GTCC system

Since ammonia has a lower calorific value and burning velocity than natural gas, its combustion tends to be unstable, in other words, ammonia is difficult to burn. Combustion of ammonia as a gas turbine fuel involves difficulties associated to maintaining a stable flame in the combustor. In addition, control of fuel NOx emissions generated by oxidation of nitrogen (N) in ammonia (NH_3) during combustion implies an added challenge.

MHI is considering two types of GTCC systems that use ammonia: (i) a direct ammonia combustion system and (ii) an ammonia decomposition GTCC system that uses the waste heat from a gas turbine to decompose ammonia into hydrogen fuel and nitrogen by-product. This chapter presents ammonia direct combustion GTCC system that combines an ammonia combustor to reduce NOx emissions and a high-efficiency Selective Catalytic Reduction (hereinafter referred to as SCR) system as shown in **Figure 13**. Ammonia combustor and high-efficiency SCR system are being developed and verified toward the application to small and medium-size gas turbines (H-25).

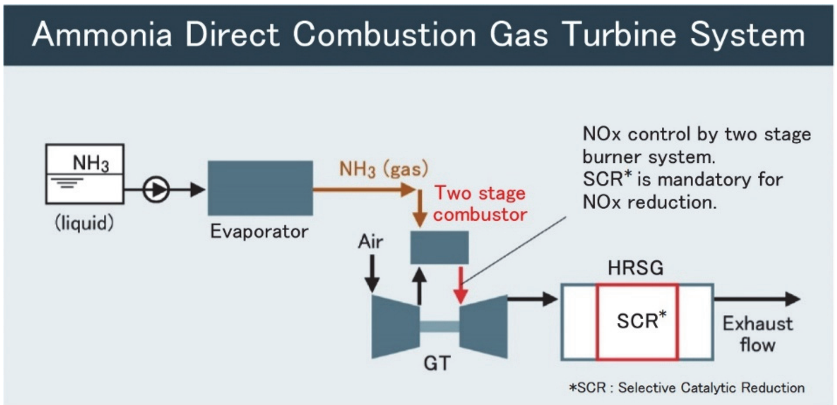

Figure 13　Ammonia direct combustion GTCC system

4.1　Development status of ammonia combustor

An ammonia combustor that employs a rich-lean two stage burner system is being developed based on a combustor with a proven track record (**Figure 14**). The rich-lean two stage burner system is a combustion method in which fuel ammonia and air (primary combustion air) are combusted in the upstream of the combustor in a fuel-rich state with an equivalent ratio $\varphi = 1$ (stoichiometry) or higher (rich zone), and then rapidly mixed with secondary combustion air to shift to a lean combustion state (lean zone). By applying this combustion method to ammonia fuel, stable combustion can be achieved and NOx emissions can be reduced.

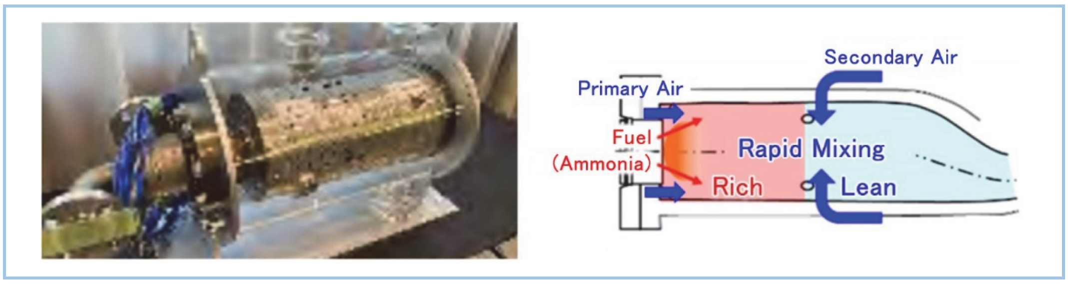

Figure 14　Rich-lean two stage burner Ammonia combustor system

In developing this combustor, the concept was confirmed through computational fluid dynamics (hereinafter referred to as CFD) analysis and utilized an elemental test facility and atmospheric pressure test facility to select a shape that would enable more stable combustion and lower emissions. Specifically, the concept geometry that had achieved good results through CFD and elemental tests was applied to a full-scale prototype combustor, and conducted atmospheric pressure combustion tests using one full-scale combustor to confirm flame retention, emissions at the combustor outlet, and various characteristics when switching from hydrocarbon fuel to ammonia fuel, as well as to understand the combustion characteristics for each of the rich and lean combustion fields. **Figure 15** shows a photograph of the atmospheric pressure test facility and a case study of the combustion test results. It was found that the unburned ammonia concentration among the measured emissions at the combustor outlet was significantly reduced by improving the combustor. As shown in this case study, MHI is making good use of elemental testing and CFD to develop ammonia-fired combustors ahead of the rest of the world.

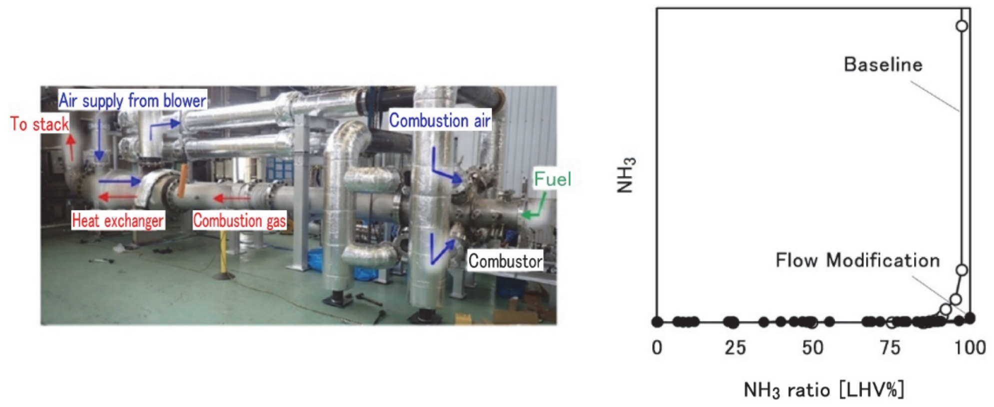

Figure 15 Photograph of atmospheric pressure test facility and case study of reducing unburnt ammonia due to modified combustor

To use the prototype combustor that had produced favorable test results in the atmospheric pressure combustion testing to confirm combustion states under actual-equipment operating conditions (air temperature and pressure), a high-pressure, large-capacity ammonia supply facility was developed at Hitachi Works (Katsuta) actual-pressure combustion test facility, as shown in **Figure 16** and have been conducting combustion tests since 2023. The purpose of ammonia-fired gas turbines is to reduce GHG emissions, but there is a concern that it will generate nitrous oxide (N_2O), which has a global warming potential 298 times that of CO_2 if the combustor design is inappropriate. **Figure 17** shows the relationships between GHG reduction rates and ammonia co-firing ratios and between ammonia co-firing ratios and combustor outlet NOx values calculated based on actual-pressure combustion test results at MHI Hitachi Works. It is found that the ammonia-fired combustor being developed by MHI can reduce GHG in proportion to the increase in ammonia co-firing ratio, achieving 100% GHG reduction under ammonia single-firing conditions (on the left of Figure 17), and that the resultant NOx value is sufficiently low compared to the target value (on the right of Figure 17). The knowledge gained will continue to improve the combustor with a view to commercialization.

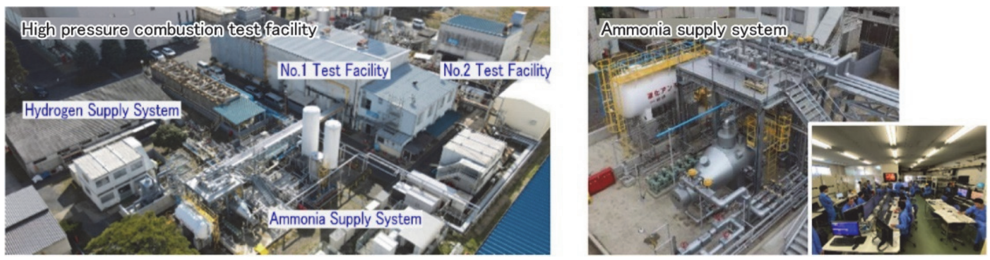

Figure 16 Actual-pressure test facility at MHI Hitachi Works

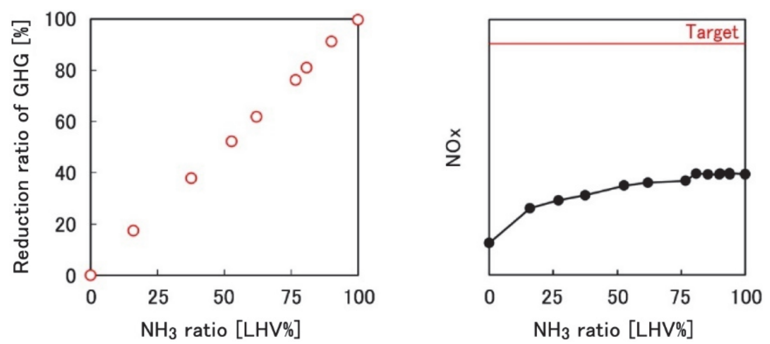

Figure 17 Combustion test results obtained in actual-pressure test facility at MHI Hitachi Works
(Left: Relationship between GHG reduction rates and ammonia co-firing ratios.
Right: Relationship between ammonia co-firing ratios and NOx)

4.2 Development of high-efficiency SCR system

The ammonia direct combustion GTCC system requires a high-efficiency SCR system in addition to the aforementioned ammonia combustor to reduce ammonia-derived fuel NOx emissions. One of the issues with the high-efficiency SCR system is suppression of ammonia leakage caused by the reducing agent injected to achieve a high deNOx efficiency. MHI has been developing this system since 2020. It has been confirmed that by applying catalyst technology, the target deNOx efficiency can be achieved with suppressing ammonia leakage. In the SCR system, NOx and ammonia react on a catalyst as shown below equation. To achieve high-efficiency SCR performance, it is essential to reduce the molar ratio (NH_3/NOx) maldistribution at the time of ammonia injection to mix NOx and ammonia in the exhaust gas as completely as possible.

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

An ammonia injection grid that takes into account the molar ratio maldistribution caused by the temperature rise during ammonia injection, and an ammonia/exhaust gas mixer that utilizes swirling flow to reduce the molar ratio maldistribution were developed as shown in **Figure 18**, and it was confirmed that molar ratio maldistribution within a certain level can be achieved (**Figure 19**).

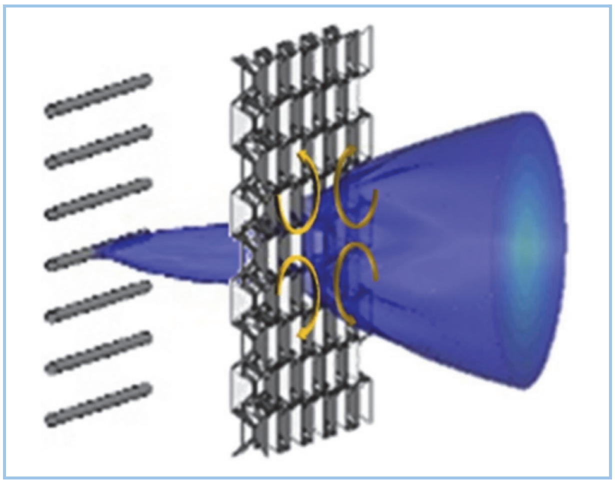

Figure 18　Illustration of ammonia diffusion by ammonia/exhaust gas mixer

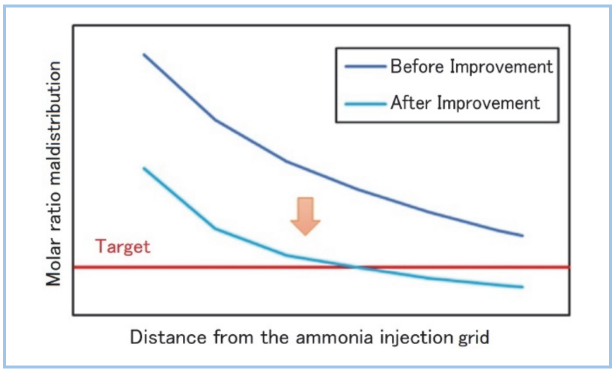

Figure 19　Relationship between distance from ammonia injection grid and molar ratio maldistribution

In addition, SCR systems for GTCC are integrated into Heat Recovery Steam Generators (hereinafter referred to as HRSG), and therefore, their catalyst reactor must be designed taking into account the thermal expansion of HRSGs. However, this structure causes some exhaust gas to pass through without coming into contact with the SCR catalyst, therefore, reducing gas leakage (gas blow-through) is important in the design of a high-efficiency SCR system for ammonia direct combustion GTCCs.

MHI is the only manufacturer capable of designing and supplying gas turbines and SCR systems, and has a strong advantage in being able to share and coordinate technical matters specific to ammonia direct combustion GTCC systems with gas turbine design. The development of high-efficiency SCR systems with a view to practical application will continue in the future.

5. Conclusion

This report presents the development and verification status of hydrogen and ammonia gas turbines that MHI is working on to achieve carbon neutrality.

Regarding hydrogen-natural gas co-fired gas turbines, the Takasago Hydrogen Park incorporated to the Takasago validation facility, facilitates development and validation of new technologies including hydrogen production to power generation can be verified in an integrated manner. The verification of 30% hydrogen co-firing using the latest JAC gas turbine is being conducted at the demonstration power generation facility. The development toward hydrogen co-firing continues to advance at a co-firing ratio of 50%.

Regarding hydrogen single-fired gas turbines, actual-equipment verification using an H-25 gas turbine was conducted at the Takasago Hydrogen Park to confirm hydrogen single-firing operation. Actual-equipment verification tests will continue to enhance reliability. Additionally, the efforts to confirm combustors for large gas turbines will continue under actual-equipment operating conditions.

Regarding an ammonia direct combustion GTCC system, a prototype combustor was developed and its associated tests under actual-equipment operating conditions are ongoing at an actual-pressure combustion test facility at Hitachi Works (Katsuta), where high-pressure, large-capacity ammonia supply facility was developed to confirm ammonia single-firing operation. Furthermore, a high-efficiency SCR system was developed, for which a reduced molar ratio maldistribution is applied by improving the ammonia injection grid and ammonia/exhaust gas mixer and suppressed ammonia leakage by applying catalyst technology. It was confirmed that the high-efficiency SCR system can achieve the target SCR performance and the effort will continue to advance the development toward practical application.

MHI will continue to advance the development and actual-equipment verification of these carbon-free power generation systems and expand the lineup to promote initiatives aimed at achieving decarbonization by 2030 in accordance with its roadmap.

Acknowledgments:

The hydrogen co-fired combustor described in Chapter 2 and the hydrogen single-fired combustor described in Chapter 3 of this report are part of the results of the grant project (Development of Technologies for Realizing a Hydrogen Society: JPNP14026) and the content described in Section 2 of Chapter 3 is part of the results of the grant project (Development of Technologies for Carbon Recycling and Next-Generation Thermal Power Generation: JPNP16002) , subsidized by the New Energy and Industrial Technology Development Organization (NEDO). We would like to express our gratitude for the support.

References

(1) IEA, World Energy Outlook 2023
(2) Mitsubishi Power Americas Inc., News, Mitsubishi Power, Georgia Power, EPRI Complete World's Largest Hydrogen Fuel Blending at Plant McDonough-Atkinson
(3) Mitsubishi Heavy Industries Ltd., Press Information, Mitsubishi Power Successfully Operates an Advanced Class Gas Turbine with 30% Hydrogen Fuel Co-Firing at Grid-Connected T-Point 2
(4) Mitsubishi Power Americas Inc., News, 50% hydrogen blend testing successfully completed at Georgia Power's Plant McDonough-Atkinson
(5) Mitsubishi Heavy Industries Ltd., Press Information, First order received for a 840,000 kW-class hydrogen-fired JAC unit for Intermountain Power (IPA), a GTCC power generation project using hydrogen derived from renewable energy in Utah, USA (in Japanese)
(6) T. Saito et al., Blowdown Combustion Test Facility Supporting Decarbonization of Gas Turbines, Mitsubishi Heavy Industries Technical Review Vol. 62 No. 1 (2025)