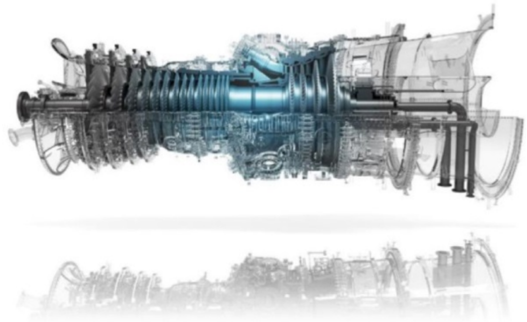
Development of Hydrogen/Ammonia Firing Gas Turbine for Decarbonized Society



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In the midst of globally accelerating moves toward a decarbonized society, Mitsubishi Power, Ltd. (Mitsubishi Power) has made continuous efforts to develop hydrogen/ammonia-firing Gas Turbine Combined Cycle (GTCC) power generation systems. The development of a gas turbine combustor that can operate with a mix of natural gas and 30 vol% of hydrogen has been completed for large frame gas turbines. Mitsubishi Power is also developing a 100% hydrogen-firing combustor. A promising Gas Turbine Combined Cycle using ammonia is also under development, facilitating energy transportation of hydrogen to further expand the lineup of carbon-free power generation systems. With these technologies, Mitsubishi Power is participating in hydrogen-firing GTCC projects in Europe, North America and other continents targeting commercialization in the mid-2020s.

By increasing hydrogen demand, especially through large-capacity and high-efficiency GTCC systems, Mitsubishi Power is set to lead the establishment of an international hydrogen supply chain and contribute to the realization of a decarbonized society.

1. Introduction

In 2015, the "Paris Agreement", which constitutes the international framework on prevention of global warming, was adopted at COP 21. Since then, many governments, financial institutions, investors and companies throughout the world have committed to make efforts toward decarbonization. The actual implementation of the agreement started in 2020 and movements toward the achievement of CO_2 emissions reduction targets are being proactively initiated around the world. The EU, including the environmentally-advanced regions in northern Europe, has already announced guidelines for becoming carbon neutral by 2050. China and the United States, which are the world's largest and second largest CO_2 emitters, issued a joint statement recently committing to cooperate on tackling global warming. Japan being a large energy-consuming country and mostly dependent on imports for its energy has also committed to become carbon neutral by 2050.

The Great East Japan Earthquake in 2011 triggered substantial efforts to dispatch renewable energy, however, roughly 80%[(1)] of the total electricity supply in the country is produced from thermal power generation which emits considerable CO_2. The degree of dependence on thermal power generation still remains high representing approximately 44% of the total primary energy consumption.

GTCC systems provide highly-efficient power generation, therefore emitting the lowest amount of CO_2 among conventional thermal power generation systems. The GTCC deployment

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will continue to meet growing energy demand while contributing to effort to reach a decarbonized society. On the other hand, the acceleration of the introduction and dissemination of renewable energy and the effective utilization of fossil fuels with consideration given to environmental impact are required.

Mitsubishi Power has continuously worked on the development of decarbonization technologies for thermal power generation. Development of advanced technologies for GTCC power generation facilities are focused on:

(1) reduction of CO_2 emissions by a further increase in efficiency and capacity through higher combustion gas temperature, and other key technologies(2)
(2) promotion of technical development(3) for enhanced gas turbine flexibility targeting a rapid and flexible response to compensate for power generation fluctuations resulting from the increase of renewable energy use and
(3) promotion of technical development of gas turbines using hydrogen (H_2) or ammonia (NH_3) as fuel with lower or zero CO_2 emissions, thereby aiming at realizing a decarbonized society by 2050.

In Japan, as a basic hydrogen strategy(4) for a decarbonized society targets the commercialization of hydrogen power generation by around 2030. The development and commercialization of technologies for the introduction of equipment to electric power companies must be promoted in a short period of around 10 years. With the support of the New Energy and Industrial Technology Development Organization (NEDO), the development of combustors capable of operating on a mix of natural gas and 30 vol% of hydrogen have been successful for large frame gas turbines for power generation(5). The developed combustor is expected to lower the hurdle for the implementation of hydrogen power generation and promote a smooth shift to a hydrogen society. With the continuous support of NEDO, 100% hydrogen-firing power generation is also under development. Research and development of a GTCC system using ammonia is also under development, with the associated promising future as an effective hydrogen energy carrier.

This report presents Mitsubishi Power efforts toward the realization of a decarbonized society, mainly covering prior studies about gas turbines for power generation under the application of hydrogen and ammonia for power generation projects around the world.

2. Decarbonized society and gas turbines for power generation

Power generation using renewable energy, including wind and photovoltaic power generation, will continue to spread and expand globally toward the realization of a decarbonized society. There is an estimation(6) that the reduction of CO_2 emissions through the utilization of renewable energy will account for about 30% of the total emission in 2060. The output of renewable energy is greatly affected by the ambient or meteorological conditions of the sites. The effective utilization or storage of electric energy surplus needs to be addressed using batteries, conversion into hydrogen and other technologies to avoid energy waste. Long and significant cycle fluctuations can involve considerable amounts of energy, converting renewable energy into hydrogen for utilization is effective to avoid energy waste. GTCC power generation has the capability and operability to follow abrupt output fluctuations of renewable energy and can flexibly fill the gap between the electric power demand and the renewable energy output. In addition, GTCC power generation can effectively use hydrogen as fuel, thereby producing large and stable hydrogen demand. Therefore, expectations for GTCC power generation have been growing.

A potential future scenario toward decarbonization is shown in **Figure 1**. In the mid-term, the spread of fossil fuel-derived hydrogen (blue hydrogen) using Carbon Capture Utilization and Storage (CCUS) is expected. GTCC will offer increased power generation efficiency and reduced CO_2 emissions while providing conventional inexpensive, safe and stable power generation using fossil fuels. The utilization of blue hydrogen will be promoted to generate power through the co-firing of hydrogen or ammonia fuels, which do not emit CO_2. In the long term, cost reduction and technical innovation will prioritize the use of renewable energy-derived hydrogen (green hydrogen), eventually becoming mainstream with hydrogen-firing power generation using green hydrogen helping reach the goal of eliminating CO_2 emissions.

The use of hydrogen for large-capacity and highly-efficient power generation gas turbines offers the environmental and economic advantages described below (**Figure 2**).

First, existing gas turbine facilities can be used with minimum modifications toward decarbonization, mainly requiring adjustments of the gas turbine combustion components and fuel supply systems. This reduce investment costs and lowers the cost hurdle for hydrogen conversion, promoting a smooth transition to a hydrogen society.

Next, in addition to liquid hydrogen, hydrogen carriers such as methylcyclohexane and ammonia can be transported and hydrogenerated to be used as fuel. There are flexible options for carriers and hydrogen with lower purity can be used compared to hydrogen for fuel cell electric vehicles. Therefore, the hydrogen cost can be reduced.

Lastly, power generation hydrogen-firing gas turbines require large amounts of hydrogen compared to fuel cell electric vehicles (the hydrogen consumption of one large frame GT equates 2 million fuel cell vehicles). The hydrogen use for power generation is expected to facilitate large hydrogen demand and to promote the expansion of the supply chain and the reduction of hydrogen cost.

As described above, it is considered that the utilization of hydrogen for large-capacity and highly-efficient gas turbines for power generation has an essential and important role in realizing a decarbonized society.

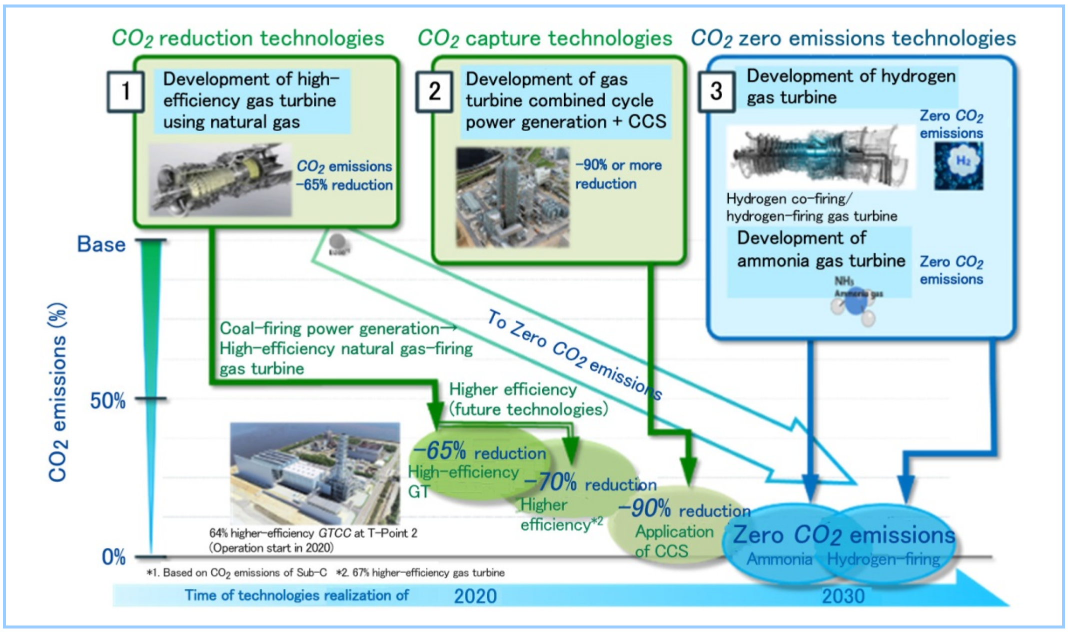

Figure 1 Scenario toward decarbonization

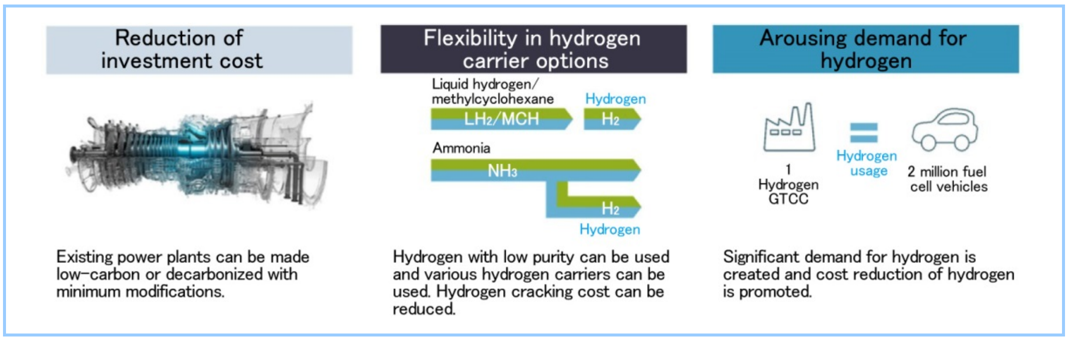

Figure 2 Environmental and economic advantages of hydrogen gas turbines

3. Hydrogen-firing gas turbines

The key point in the development of hydrogen-firing gas turbines is the development of combustors, which are the heart of gas turbines and combustion technologies.

Targeting higher efficiency for power generation large frame gas turbines typically involves increase of the Turbine Inlet Temperature (TiT), as well as the combustion temperature, leading to an exponential increase in NOx emissions. Mitsubishi Power large frame gas turbines apply premixing combustion method to the Dry Low NOx (DLN) combustor. Fuel and air is mixed prior to combustion to reduce NOx emissions. This approach results in a lower flame temperature in the combustor compared with the conventional diffusion combustion method, therefore, steam or water injection for NOx reduction is unnecessary and prevents a decrease in the cycle efficiency. On the other hand, the stable combustion range is narrow, there is a risk of the occurrence of combustion dynamics and backfire (flashback) and unburned hydrocarbons tend to be discharged.

Hydrogen has a higher combustion speed in comparison with natural gas. Therefore, in the case of natural gas and hydrogen co-firing or hydrogen firing in a premixed combustor, the risk of the occurrence of flashback is higher than firing natural gas. There is a possibility that flame from the flashback moves back upstream of the combustor, causing overheating of upstream components. Therefore, combustors for hydrogen-firing gas turbines should be designed to prevent flashback while also reducing NOx emissions with stable combustion. **Figure 3** provides an overview of Mitsubishi Power combustors for gas turbines hydrogen co-firing and hydrogen firing.

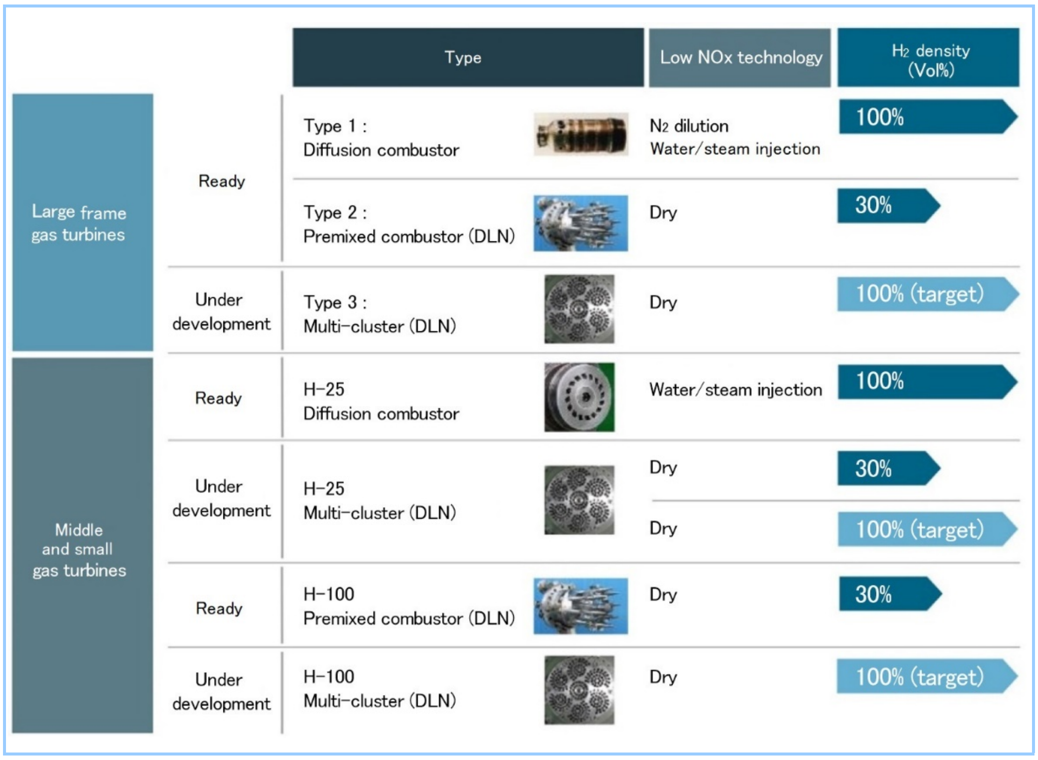

Figure 3 Combustors for hydrogen-firing gas turbines

(1) Dry Low NOx (DLN) multi-nozzle combustor for hydrogen co-firing

Figure 4 gives an overview of the newly developed combustor for hydrogen co-firing based on the conventional DLN combustor. It aims reduced risk of flashback under operation with hydrogen co-firing. The air supplied from the compressor to the combustor passes through a swirler and forms a rotating flow. Fuel is supplied from a small hole provided on the surface of the swirler and mixed rapidly with the surrounding air by the swirling flow. On the other hand, a low flow rate region exists in the center part of the swirling flow (hereinafter referred to as "vortex core") and it is considered that flashback occurs as flame moves back toward the low flow rate region. The new-type combustor injects air from the tip of the nozzle to raise the flow velocity of the vortex core, so that the injected air compensates for the low flow velocity region of the vortex core and prevents the occurrence of flashback.

The main combustion issues of gas turbine combustors are emissions, including NOx and combustion oscillation. Since they are affected by the combustion pressure condition, verification is needed under actual equipment pressure condition. Combustion tests need to be conducted under the actual equipment pressure (hereinafter referred to as "actual pressure combustion test") using one full-scale hydrogen co-firing combustor out of 16 to 20 combustors (60 and 50 Hz respectively) installed in the actual equipment, to evaluate the hydrogen co-firing effects on the combustion characteristics.

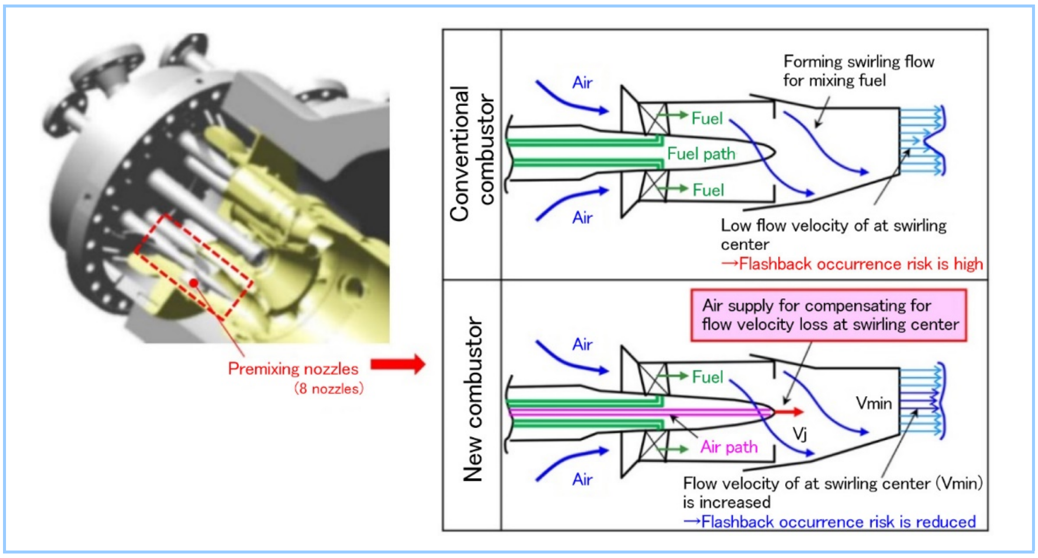

Figure 4　Combustor for hydrogen co-firing

Figure 5 shows the change in NOx with respect to the hydrogen mixing ratio under air and fuel ratio conditions in the test that correspond to the rated load of a gas turbine with a turbine inlet temperature of 1600°C. It was observed that as the hydrogen mixing ratio increased, NOx gradually increased by a small amount. It is considered that when hydrogen is mixed in the fuel, the combustion speed increases, the flame position in the combustor moves to the upstream and combustion occurs under an insufficient mix of fuel and air ratio. However, even under the condition where 30 vol% of hydrogen was mixed in the fuel, NOx was almost the same as that in the operation with natural gas and no hydrogen, within the operable range.

Figure 6 shows the change in combustion dynamics under the same condition. The combustion vibration pressure level is also equal to or lower than that in the operation with natural gas and it was verified that the combustion dynamics was not greatly affected by a change in the hydrogen mixing ratio. In addition, no flashback was observed in 30 vol% hydrogen co-firing. With these test results, it became clear that the DLN multi-nozzle combustor for hydrogen co-firing can be operated without the occurrence of flashback or a significant increase in combustion dynamics.

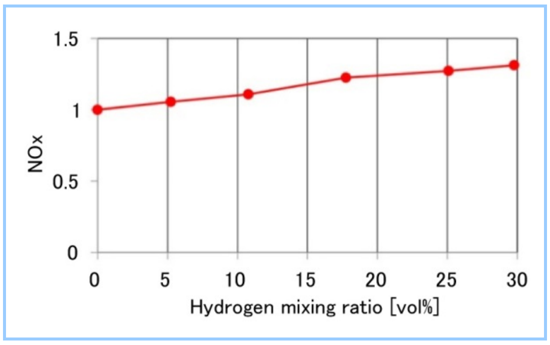

Figure 5　Change in NOx with respect to hydrogen mixing ratio (when NOx is 1 with 0% hydrogen)

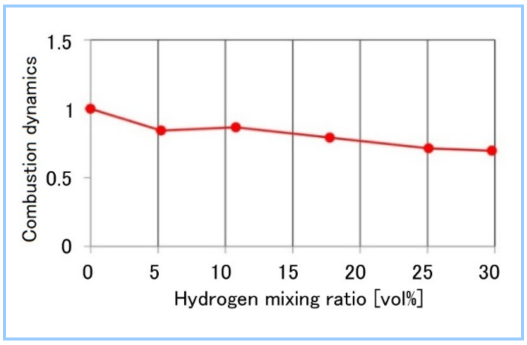

Figure 6　Change in combustion dynamics with respect to hydrogen mixing ratio (when the combustion vibration 1 with 0% hydrogen)

(2)　Multi-cluster combustor for hydrogen firing

When the concentration of hydrogen becomes higher than 30% vol, the fuel and air mixing method using swirling flow adopted for the hydrogen co-firing combustor described in the previous section (shown in Figure 4) involves higher risk of flashback occurring in the low flow velocity region of the vortex core. A smaller scale of air and hydrogen mixing method without applying swirling flow is considered to provide resistance to flashback. Mitsubishi Power is developing a hydrogen-firing combustor based on the so-called multi-cluster design that was developed for IGCC(7) applications and currently in operation at the Osaki CoolGen facility in Japan. This design shown in **Figure 7**, has a greater number of fuel supply holes compared to the eight nozzle design of the hydrogen co-firing combustor described in the prior section. The size of the holes is smaller. It is possible to mix supplied air and hydrogen on a smaller scale resulting in a more effective flame dispersion allowing high flashback resistance and lower NOx combustion.

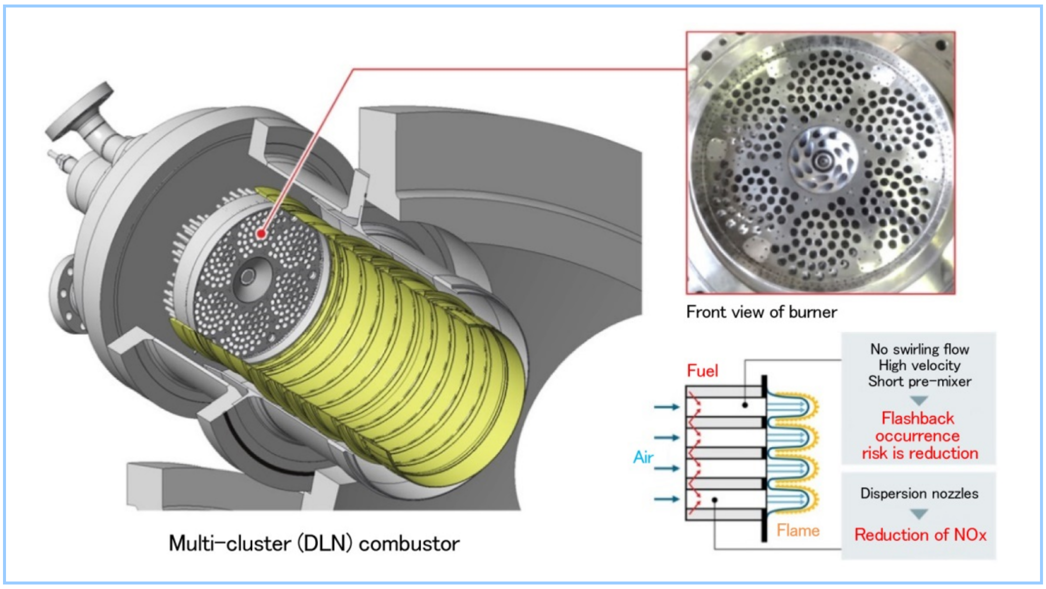

Figure 7 Multi-cluster combustor

(3) Diffusion combustor

A diffusion combustor injects fuel and combustion air separately into the combustor. Compared with the premixed combustion method, the flame temperature is higher and the amount of NOx emissions increases and imposes steam or water injection as a countermeasure for NOx reduction. On the other hand, it features a relatively wide stable combustion range and is more tolerant to fuel property fluctuations.

Figure 8 shows Mitsubishi Power diffusion combustor. This mature design has a long track of successful operation with fuels featuring a wide range of hydrogen content (up to 90 vol%). A long list of plants that have successfully operated with these combustors under high hydrogen content includes, among others, refineries and other industrial plants' off-gas . These include small to medium size gas turbine for power generation facilities and also succeeded in a hydrogen-firing combustion test as part of the International Clean Energy Network Using Hydrogen (World Energy NETWORK (WE-NET) technological research and development project[8]. The application of this diffusion combustor to the hydrogen-firing conversion project at Vattenfall's Magnum power plant in the Netherlands will be described in point 5 below.

Figure 8 Diffusion combustor

4. Ammonia-firing gas turbine

The stable application of large amount of hydrogen for a large frame gas turbine for power generation imposes stringent requirements to its supply chain including production, transportation and storage of hydrogen. One alternative to liquefied hydrogen is the use of other chemical compounds such as ammonia (NH_3), methylcyclohexane and others, as carriers for transportation and storage of hydrogen. Compared to liquid hydrogen or methylcyclohexane, ammonia has a higher volumetric hydrogen density and is a carrier that can transport and store hydrogen with high efficiency. In addition, existing transportation and storage infrastructure for liquefied petroleum gas and other industrial applications can be used for ammonia simplifying the development of hydrogen processing infrastructure. This facilitates hydrogen usage in remote locations including islands where large-scale hydrogen infrastructure development is difficult. Ammonia can also be directly combusted as a carbon-free fuel. Early introduction of ammonia-based power generation equipment is expected to be considered by power companies and independent power providers (IPPs) as a future use in a carbon-free fuel society.

Mitsubishi Power has commenced the development of a 40 MW-class gas turbine system for small to medium-scale power plants that uses 100% ammonia as a fuel for gas turbine power generation. One challenge that is being addressed with the direct combustion of ammonia is the production of nitrogen oxide (NOx) caused by oxidation resulting from the combustion of the nitrogen component of the fuel. Mitsubishi Power is aiming to resolve this issue through the establishment and commercialization of a gas turbine system that combines NOx removal equipment with a newly developed combustor that reduces NOx emissions. This is being applied to the H-25 series gas turbines (output: 40MW class) shown in **Figure 9**(9). The direct combustion of ammonia has never been applied to this scale of power output gas turbine and it is expected that it will increase demand of hydrogen and ammonia and contribute to decarbonization.

Figure 9 H-25 series gas turbine

Table 1 lists issues to be considered for the combustion of ammonia in large frame gas turbines. Mitsubishi Power is evaluating the use of waste heat from a gas turbines in GTCC systems used to reconvert ammonia into hydrogen and nitrogen as shown in **Figure 10**. Simultaneous efforts include the developed hydrogen co-firing combustor or the developing hydrogen-firing combustor(10).

Decomposing ammonia requires heat in the order of 46 kJ per one mol of ammonia. This heat is chemically recuperated through a 1.14 times increase in the heat value of the fuel as a result of the conversion of ammonia to hydrogen. Therefore in principle, there is no reduction in thermal efficiency with the exception of energy losses that take place at the gas processing unit installed downstream of the ammonia decomposer.

Table 1 Characteristics of ammonia combustion and consideration for large frame gas turbine

Characteristics of ammonia combustion	Considerations for large frame gas turbines
Low combustion speed (about 1/5 of that of methane)	- The size of the combustor increases to secure the time necessary for completing the combustion. - Large frame gas turbines are limited in the size expansion of combustors because they are multi-combustors.
Nitrogen contained in fuel	- The combustion gas temperature of a large frame gas turbine is high and a large amount of Fuel NOx is generated by the combustion of ammonia. - Lowering of NOx by two-stage combustion is being considered, but in the case of a large frame gas turbines, there are many technical problems such as upsizing and complexity of the combustor.

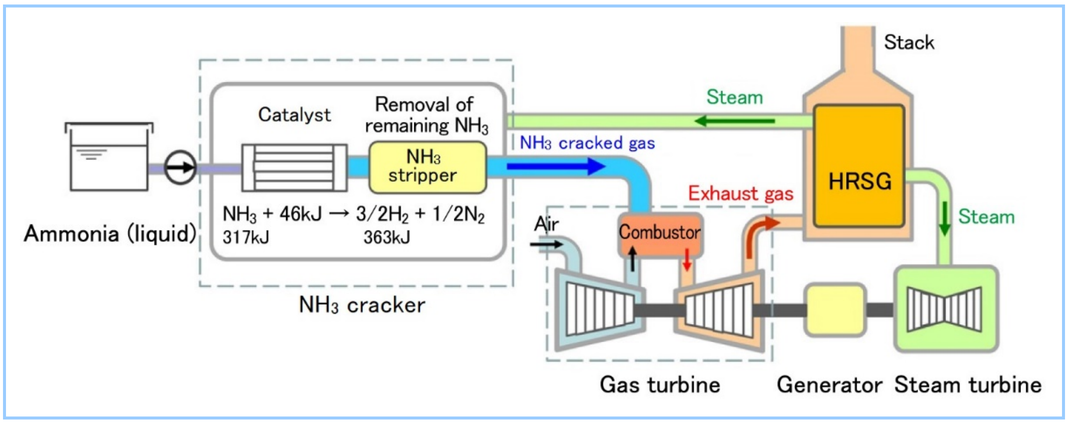

Figure 10 Concept of ammonia decomposition gas turbine cycle

It should be noted that in the combustion of ammonia decomposed gas, any trace amount of residual ammonia remaining after decomposition would be converted to fuel NOx in the combustor. It is considered that the fuel NOx is emitted together with the NOx originally produced in the combustor. In order to meet the NOx emission standard value, it is necessary to determine the amount of NOx increased by the remaining amount of ammonia. A combustion test under the actual pressure using a 1650℃-class hydrogen co-firing gas turbine combustor was conducted to evaluate how the trace amount of remaining ammonia contained after decomposition affects NOx while verifying the stability of combustion. **Figure 11** shows the relationship between the concentration of ammonia in the fuel and the concentration of NOx in exhaust gas at a JAC rated condition turbine inlet temperature of 1650℃ and in co-firing of natural gas and ammonia decomposition gas (fuel composition: 20 vol% of hydrogen, 6.7 vol% of nitrogen, 73.3 vol% of natural gas, trace amount of ammonia). As the concentration of ammonia in fuel increased, the concentration of NOx increased linearly (indicated by ● marks in the figure) and the conversion ratio of ammonia to NOx (CR in the figure: Conversion Ratio) was about 90%. Even if the concentration of ammonia in fuel was changed, the pressure level of combustion dynamics did not largely change, keeping a sufficient margin to the control value. It was verified that the combustion was stable without the occurrence of flashback.

Through the development of the gas turbine systems using ammonia as described above, it is expected to expand the lineup of carbon-free power generation systems.

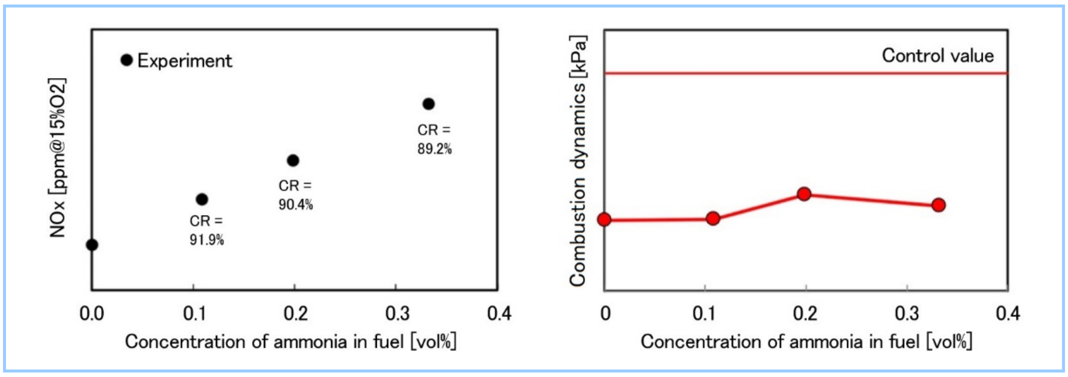

Figure 11 Relationships between the concentration of ammonia in fuel and the concentration of NOx in exhaust gas and between the concentration of ammonia in fuel and combustion dynamics (at the turbine inlet temperature of 1650℃)

5. Overseas gas turbine projects toward decarbonization

Many comprehensive hydrogen utilization plans are being considered oversees. These include the production, transportation, storage and utilization of hydrogen for the development of large-scale system ranging from the production to the utilization of renewable energy-derived green hydrogen and plans for the development of systems including CCUS processing of CO_2 generated from hydrogen production under utilization of fossil fuel-derived blue hydrogen. Various effects from the utilization of hydrogen are expected, such as an increase in the reliability and independence of energy in a region, job creation, avoidance of construction of uneconomical grids, reuse of existing infrastructure and diversification of fuels in multiple industrial sectors. Transnational projects have been implemented by nations, local governments and consortiums of companies in cooperation.

Among them, three hydrogen gas turbine projects in Europe and the United States involve Mitsubishi Power's participation are described below.

5.1 Vattenfall's Magnum power plant

The first project is intended to convert a 1,320 MW-class natural gas-firing GTCC power generation plant operated by Vattenfall, a Swedish energy company, to hydrogen-firing power generation. This project aims to convert one of three M701F gas turbines power generation blocks featured by the Vattenfall's Magnum power plant to a 100% hydrogen-firing power generation plant by 2027. This plant shown in **Figure 12**, is located in the Groningen province in the northernmost part of the Netherlands. The initial feasibility study (FS) was conducted considering the application of conventional diffusion combustor technology —and verified that the conversion to hydrogen-firing power generation is possible. One line of 440 MW-scale natural-gas-firing GTCC power generation units emits about 1.3 million tons of CO_2 annually, most of which can be reduced by conversion to a hydrogen-firing power generation plant. Evaluation, planning and design of specific modification ranges in the gas turbine technological field continue to be conducted by Mitsubishi Power.

Figure 12 Vattenfall's Magnum power plant in the Netherlands

5.2 Humber Cluster/ Saltend Power Plant

The second project involves a decarbonization efforts for the UK's largest scale industrial cluster in the delta area of the Humber River basin (east coast of Britain). Several companies and organizations actively working on decarbonization related industries are globally expanding their businesses toward the utilization of hydrogen (blue hydrogen) produced from natural gas with application of carbon dioxide capture and removal technologies, aiming net zero CO_2 emissions by 2040. In this project, Mitsubishi Power is conducting a technological and feasibility study of the conversion of one of the M701F gas turbines originally supplied to the Saltend Power Plant for the natural gas-firing GTCC (**Figure 13**). This effort includes conversion of one unit to 30 vol% hydrogen co-firing toward full hydrogen firing in the future.

Figure 13 Saltend power plant in UK

5.3 Intermountain Power Agency in Utah in the United States

The third project involves a brand new GTCC power generation using hydrogen planned by the Intermountain Power Agency in Utah in the United States. Mitsubishi Power received an order for this 840 MW-class GTCC power generation facility with two M501JAC gas turbines as the core. It aims achieving 30 vol% hydrogen co-firing power generation by 2025, followed by full hydrogen firing by 2045. This project involves replacement of an existing coal-firing power generation facility to reach initial CO_2 emissions reduction in the order of up to 4.6 million tons per year. The hydrogen fuel is expected to be supplied from an adjacent energy storage project using renewable energy-derived electricity in Utah. Mitsubishi Power is involved in this effort and the generated electricity will be supplied from the Intermountain Power Plant to a wide area in Utah and California across the Rocky Mountains.

Mitsubishi Power has promoted utilization of hydrogen for thermal power generation through participation in various projects in Japan and overseas for power generation using hydrogen including those mentioned above. Mitsubishi Power will continue generating momentum for the Energy Transition to low environmental load contributing to the realization of a decarbonized society.

6. Schedule toward commercialization

The introduction of hydrogen power generation is expected to start in the mid-2020s. Mitsubishi Power will promote demonstrations using actual gas turbines for the next several years, based on the results of past element developments, that have included verification tests for each element at the basic design stage, reflecting the test results in the detailed design and finally conducting demonstration using actual equipment. By implementing this development cycle in the same works, Mitsubishi Power has promoted rapid and secure development and commercialization. Regarding hydrogen gas turbines, detailed demonstrations will be conducted on hydrogen co-firing (30 vol%) large frame gas turbines for near future commercialization as shown in **Figure 14**. These efforts will be followed by commercialization of hydrogen-firing large frame gas turbines in the project in Utah in the United States. Demonstrations using the H-25 gas turbines will be also conducted for hydrogen-firing middle and small gas turbines as well as ammonia-firing toward commercialization.

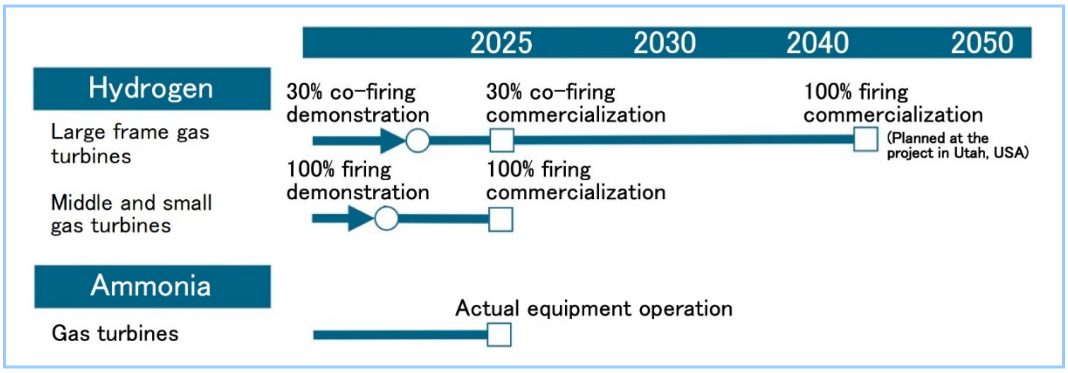

Figure 14 Schedule toward commercialization

7. Conclusion

This paper describes Mitsubishi Power efforts to use hydrogen and ammonia on power generation gas turbines. It also discusses the company's involvement in overseas hydrogen power generation projects efforts toward the realization of a decarbonized society. The contents described in point 3 of this paper are part of the outcome of the grant project ("Technology Development Project for Building a Hydrogen-based Society": JPNP14026) of the New Energy and Industrial Technology Development Organization (NEDO). In this grant project, Mitsubishi Power worked on the development of combustors for hydrogen and natural gas co-firing gas turbines and found that the operation of gas turbines under the 30 vol% co-firing condition is possible by modifying current combustion hardware.

The development of GTCC using ammonia decomposition gas contents described in point 4

of this paper was implemented by the Cross-ministerial Strategic Innovation Promotion Program (SIP), "Energy Carriers" (Funding agency: JST) and the grant project ("Technology Development for Building a Hydrogen-based Society": JPNP14026) of the New Energy and Industrial Technology Development Organization (NEDO).

The utilization of fossil fuel-derived hydrogen combined with Carbon Capture Utilization and Storage (CCUS) will start in the mid-2020s. This will contribute to the realization of a society using mainly renewable energy-derived hydrogen by 2050. Mitsubishi Power will contribute to the realization of a decarbonized society by leading the establishment of an international hydrogen supply chain through hydrogen- and ammonia-firing gas turbines being developed.

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