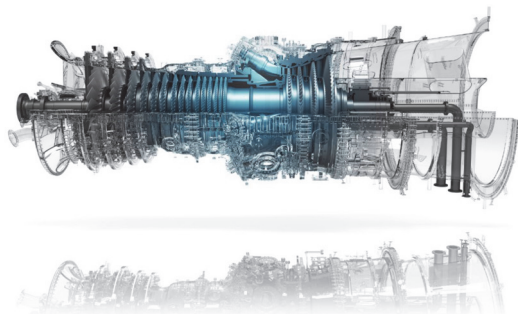


Hydrogen-fired Gas Turbine Targeting Realization of CO₂-free Society



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Gas turbine combined cycle power generation (GTCC) is clean and highly efficient and accounts for a large proportion of power generation today. Therefore, for the realization of a CO₂-free society, it is important to use hydrogen for large power generation gas turbines on a largescale. Mitsubishi Heavy Industries group is proceeding with the development of natural gas and hydrogen co-fired and hydrogen-fired large gas turbines, and has succeeded in a 30 vol% hydrogen co-firing test. In addition, we also started research on the use of ammonia, which shows promise as one of the energy carriers of hydrogen, in GTCC carriers, and are participating in a GTCC plant hydrogen firing conversion project in Europe. Through these activities, Mitsubishi Hitachi Power Systems, Ltd. (MHPS) will contribute to the realization of a hydrogen society by leading the establishment of an international hydrogen supply chain for the supply, transportation, and storage of hydrogen.

1. Introduction

To handle the rapid increase in electricity demand since the 1980s, GTCC power generation using natural gas/LNG (liquefied natural gas) as fuel has attracted attention, and its capacity and efficiency improvement have been promoted. GTCC power generation is the cleanest and most efficient facility among the thermal power generation systems using fossil fuels. In Japan, primary energy is converted mainly to electricity, which accounts for as much as 43% of the total. Among this total, the proportion of electricity supply from thermal power generation is as high as 85% (as of 2015). For this reason, GTCC power generation is required to continue to handle lively energy demand and to further reduce CO₂ for the effective use of resources and the realization of a low-carbon society.

In Japan, as a basic hydrogen strategy for a low carbon society, the commercialization of hydrogen power generation around 2030 has been targeted. To more realistically promote commercialization (from the development of technologies to the introduction of equipment to electric power companies) in a short term of 10 or more years, we devised a system that can carry out hydrogen power generation using existing gas turbine equipment. This system does not require a large-scale renewal of power generation equipment other than gas turbine combustors. Therefore, it is expected to lower the cost hurdle for hydrogen conversion and to promote a smooth shift to a hydrogen society. Currently, with the support of the New Energy and Industrial Technology Development Organization (NEDO), we have succeeded in developing a combustor that can use 30% hydrogen mixed with LNG fuel for large power generation gas turbines. The emission of NO_x, which is a concern along with the combustion of hydrogen, can be suppressed to the conventional level. This technology can handle output equivalent to 700,000 kW (GTCC power

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generation with a turbine inlet temperature of 1,600°C), and the CO₂ emissions during power generation can be reduced by approximately 10% in comparison with conventional GTCC power generation. This is a big step toward building a hydrogen society. This report presents our efforts toward realizing a hydrogen society, centered on hydrogen-fired gas turbines.

2. Large power generation gas turbines and hydrogen society

Efforts toward achieving the greenhouse gas reduction targets in the “Paris Agreement” adopted at the 2015 United Nations Climate Change Conference (COP 21) have begun in countries around the world, and the introduction of renewable energy has been accelerating. **Figure 1**⁽¹⁾ shows the forecast of the total global CO₂ reduction amount from the present to 2060 in the IEA (International Energy Agency) report. The reduction of CO₂ emissions using renewable energy is estimated to account for about 30% of the total.

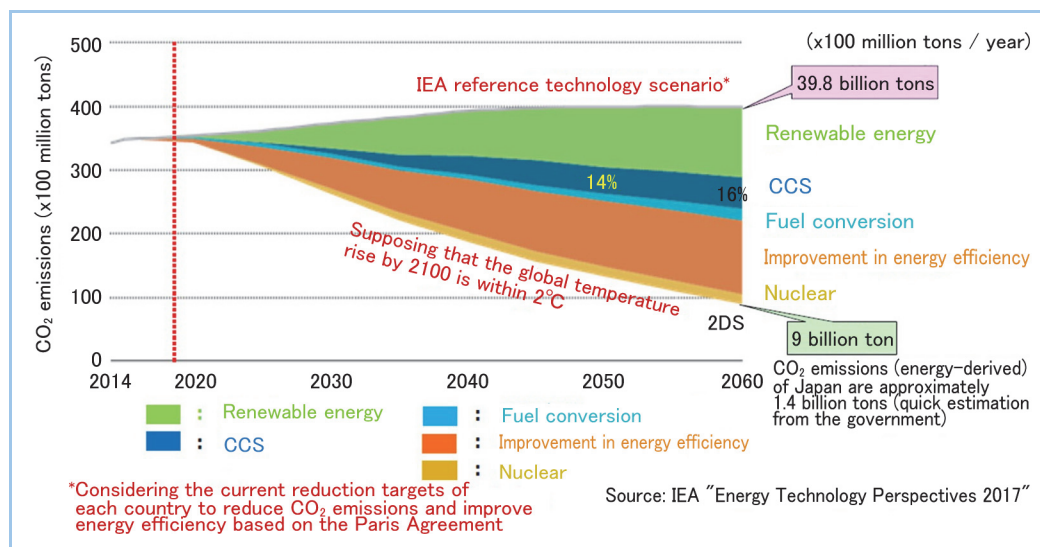


Figure 1 Forecast of total global CO₂ reduction amount from the present to 2060⁽¹⁾

Power generation using renewable energy such as wind power generation, photovoltaic power generation, and hydroelectric power generation requires flexible and stable power production and supply systems for the efficient utilization of such electric power because the power generation amount fluctuates depending on the climate and weather conditions and the time zone (day and night), and the power generation amount is unevenly distributed around the world. On the other hand, it is considered that converting renewable energy into hydrogen for storage, transportation, and usage is effective against energy fluctuations. Even in Japan, which is far away from large-scale power generation areas using renewable energy, it is important and urgent to build a hydrogen supply chain and develop relevant technologies.

In addition, in the previous report⁽¹⁾, it is expected that the use of hydrogen produced by reforming fossil fuels including natural gas will start to increase from around 2030 and will account for 14% of the cumulative CO₂ reduction amount to 2050. Together with carbon dioxide capture and storage (CCS), which collects CO₂ generated in large quantities at the time of manufacturing and stores it in the ground, technology for the utilization of hydrogen produced from a combination of fossil fuel reforming and CCS is also required in the transition period of shifting to a renewable energy-based society.

As illustrated in **Figure 2**, we are working on maximizing the utilization of hydrogen derived from renewable energy and fossil fuel and applying power generation products, one of our major strengths, to the hydrogen value chain. Among these efforts, large gas turbines for power generation can not only generate power with high efficiency, but can also use low-purity hydrogen (with relatively low hurdles of manufacturing cost and technology), which leads to large and stable hydrogen demand. As the hydrogen usage vision, including the expansion of infrastructure and various methods of utilization toward realizing a hydrogen society, has been presented, the role of our large gas turbines for power generation will increase further in the future.

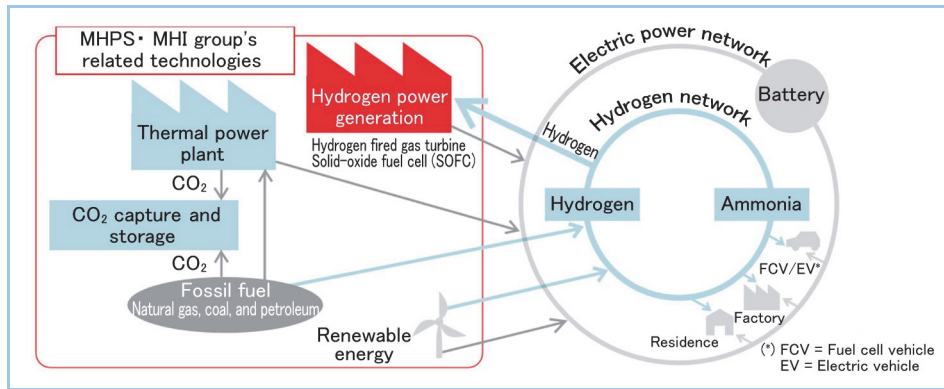


Figure 2 Relationship between our hydrogen power generation technologies and hydrogen network

3. Combustor for hydrogen gas turbine

The development of large gas turbines for power generation has advanced up to now, while the turbine inlet temperature (combustion temperature) has been raised to achieve high efficiency. To handle the NOx emissions increasing exponentially along with the rise in the combustion temperature, a premixing combustion method is adopted for the Dry Low NOx (DLN) combustor installed in our large gas turbines for power generation.

The premixing combustion method mixes fuel and air in advance to put them into the combustor. Since the flame temperature can be made uniform compared with the diffusion combustion method, steam or water injection for NOx reduction is unnecessary and a decrease in the cycle efficiency does not occur. On the other hand, the stable combustion range is narrow, there is a risk of the occurrence of combustion oscillation and backfire (flashback), and unburned hydrocarbons tend to be easily discharged.

Depending on the hydrogen mixing ratio, the fuel component changes, resulting in a change in the flame property. Hydrogen has a higher combustion speed in comparison with natural gas, so the risk of flashback phenomenon in the case of natural gas and hydrogen co-firing is higher than that in the case of natural gas firing. Therefore, for the development and practical realization of combustors for hydrogen gas turbines, the reduction of NOx and the stabilization of combustion centering on improvements for the prevention of flashback together with improvements in marketability (low cost, long service life, etc.) are necessary.

The development status of our combustors for hydrogen-fired gas turbines that can be used for the co-firing and firing of hydrogen is described below. **Figure 3** provides an overview.

Combustor	Multi-nozzle combustor	Multi-cluster combustor	Diffusion combustor
Combustion method	Premixed flame combustion	Premixed flame combustion	Diffusion flame combustion
Structure			
NOx	Low NOx due to flame temperature uniformed by premixing nozzle	Low NOx due to flame temperature uniformed by small premixing nozzle	Fuel is injected in to air. There is a high-flame temperature region and the NOx is high
Flashback	High flashback risk in the case of hydrogen mono-firing because of the large flame propagating area	Low flashback risk due to the narrow flame propagating area	No flashback risk because of diffusion flame
Cycle efficiency	No efficiency drop due to no steam or water injection	No efficiency drop due to no steam or water injection	Efficiency drop occurs because steam or water are injected to reduce NOx
Hydrogen co-firing ratio	Up to 30 vol%	Up to 100 vol% (under development)	Up to 100 vol%

Figure 3 Our combustors for hydrogen gas turbines

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

Figure 4 gives an overview of a newly developed combustor for hydrogen co-firing based on the conventional DLN combustor with the aim of preventing an increase in the occurrence risk of flashback because of hydrogen co-firing. The air supplied from the compressor to the inside of the combustor passes through a swirler and forms a swirling flow. Fuel is supplied from a small hole provided on the wing surface of the swirler and mixed rapidly with the surrounding air due to the swirling flow effect. On the other hand, it is clear that a region with a low flow rate exists in the center part of the swirling flow (hereafter the vortex core). A flashback phenomenon in a swirling flow is considered as flame moving back in a slow-flow velocity portion of the vortex core. The new-type combustor characteristically injects air from the tip of the nozzle to raise the flow velocity of the vortex core. The injected air compensates for the low flow velocity region of the vortex core and prevents the occurrence of flashback.

As a result of a combustion test under the actual engine pressure using one full-scale new combustor, NOx was within the operable range even under the condition where 30 vol% of hydrogen was mixed in, so it was found that operation without the occurrence of flashback or a remarkable increase of combustion oscillation is possible.

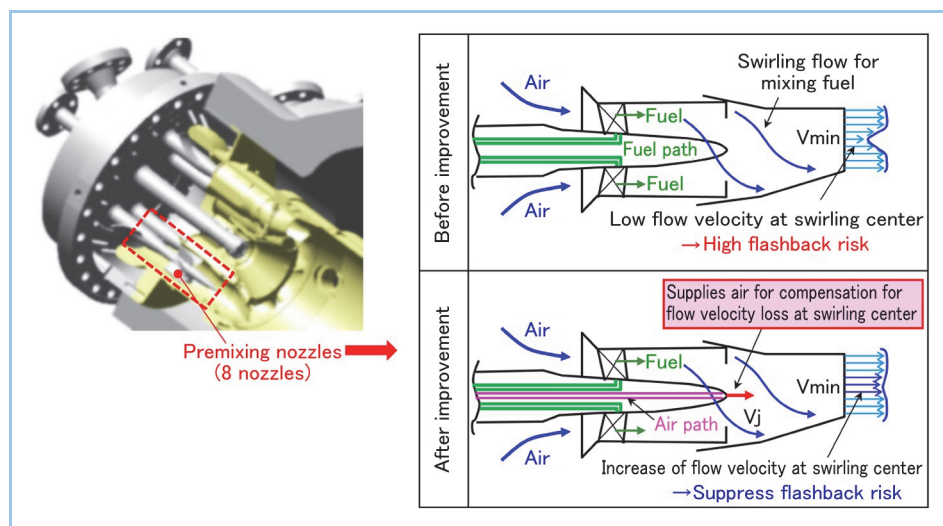


Figure 4 Outline of new combustor for hydrogen co-firing

(2) Multi-cluster combustor for hydrogen firing (**Figure 5**)

The higher the concentration of hydrogen is, the higher the risk of flashback becomes. To mix fuel and air using swirling flow like a hydrogen co-firing DLN combustor, a relatively large space is necessary and the risk of flashback increases, so it is necessary to mix them in a short time in a narrow space. Therefore, we devised a mixing system that disperses the flame and blows out the fuel smaller and more finely. Based on the multi-cluster combustor illustrated in Figure 5 with a greater number of nozzles than the fuel supply nozzles (eight nozzles) of a DLN combustor, for the hole of one nozzle, we adopted a system where the nozzle hole was made smaller, air was fed in, and hydrogen was blown in for mixing. It is possible to mix air and hydrogen at a smaller scale without using swirling flow, which may allow for the compatibility of high flashback resistance and low NOx combustion. We are currently studying the basic structure of the fuel nozzle.

(3) Diffusion combustor

A diffusion combustor injects fuel to air into the combustor. Compared with a premixed combustion method, a region with a high flame temperature is likely to be formed, and the amount of NOx generated increases, so a measure for NOx reduction using steam or water injection is necessary. On the other hand, the stable combustion range is relatively wide, and the allowable range for the fluctuation of the fuel property is also large.

Figure 6 is our diffusing combustor. This combustor has actual results with fuels with a wide range of hydrogen content (up to 90 vol%) through the utilization of offgas (exhaust gas generated in refinery plants, etc.) as fuel in small to medium size gas turbine power generation

facilities, and also succeeded in a hydrogen-fired combustion test when taking part in the International Clean Energy Network Using Hydrogen (World Energy NETWORK (WE-NET) technological research and development project.

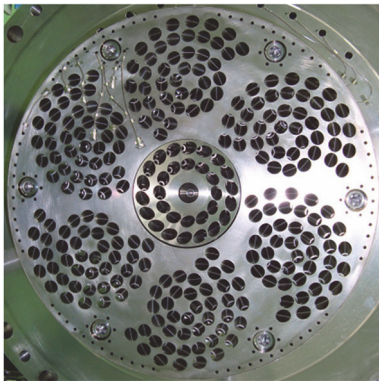


Figure 5 Multi-cluster combustor (under development)



Figure 6 Diffusion combustor

4. Ammonia cracking GTCC

To make it possible to stably use the large amount of hydrogen required for a large-sized gas turbine for power generation, it is a prerequisite that a supply chain that produces, transports, stores, etc., hydrogen is established. The transportation and storage of hydrogen presented in the Hydrogen Basic Strategy⁽²⁾ includes not only a method of liquefying hydrogen before transporting and storing, but also the utilization of energy carriers such as ammonia and organic hydride.

MHPS has been participating in the SIP (Strategic Innovation Promotion Program) of the Cabinet Office and studying gas turbine systems using ammonia as an energy carrier since fiscal 2017. Ammonia has a volumetric hydrogen density 1.5 times higher than that of liquefied hydrogen, and has the feature that existing transportation and storage infrastructure for liquefied petroleum gas can be used. In the program, studies have been made to directly burn ammonia as a fuel in a micro gas turbine⁽³⁾ and a small gas turbine. However, there are problems as can be seen in **Table 1** with its application to large gas turbines. Therefore, as noted in **Figure 7**, we are studying a system that thermally cracks ammonia to hydrogen and burns it in a gas turbine. To crack ammonia, it is necessary to introduce a heat of reaction of 46 kJ/mol per 1 mole of raw ammonia while heating ammonia to high temperature under catalytic contact. Since this heat of the reaction results in an increase in the heat value of hydrogen (chemical recuperation), there is no efficiency reduction in principle. Since a trace amount of residual ammonia remaining after cracking causes NOx formation in the combustor, the configuration of a cracker capable of reducing the amount of residual ammonia, the selection of the cracking catalyst, etc., are being promoted through the program.

Table 1 Characteristics of ammonia combustion and consideration for large gas turbines

Characteristics of ammonia combustion	Considerations for large gas turbines
Low combustion speed (about 1/5 ⁽³⁾ of that of methane)	<ul style="list-style-type: none"> - The size of the combustor increases to secure the time necessary for completing the combustion. - Since the large gas turbine is composed of a multi-can combustor, there is a restriction on the size expansion of the combustor.
Nitrogen contained in fuel	<ul style="list-style-type: none"> - Fuel NOx is generated, but the combustion gas temperature of a large gas turbine has been increased to the extent permitted by Thermal NOx, and there is little room to allow Fuel NOx. - Lowering of NOx by two-stage combustion is considered, but in the case of a large gas turbine, there are many technical problems such as upsizing and complication of the combustor.

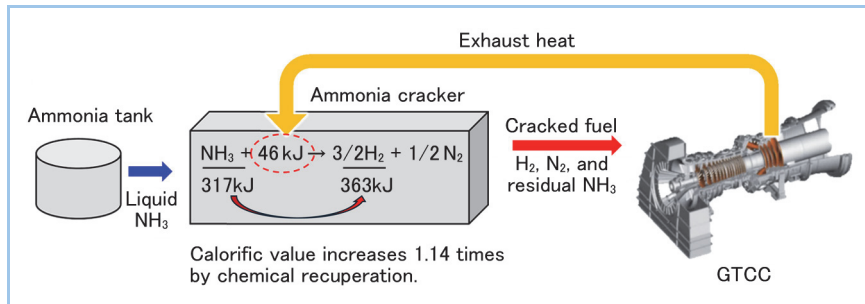


Figure 7 Concept of ammonia decomposition gas turbine cycle

As presented in **Table 2**, this system can be characteristically applied to high-efficiency and large-capacity GTCC systems with a relatively small number of modifications, thereby contributing to a large amount of CO₂ reduction by using CO₂-free ammonia. By applying this system, it is possible to not only utilize a hydrogen combustor for gas turbines currently under development, but also to use the developed ammonia cracker as a component of a general-purpose hydrogen supply chain.

Table 2 Characteristics of ammonia cracking gas turbine system

Item	Characteristic
High efficiency	<ul style="list-style-type: none"> - Since the heat necessary for the ammonia decomposition reaction is used for increasing the heat value of hydrogen produced (chemical recuperation), there is no theoretical efficiency drop. - A system with high overall efficiency can be constructed by combining with a high-efficiency GTCC.
Introducibility	The major development equipment is ammonia cracker, so the number of modifications on the gas turbine side that is necessary for the application of the system is relatively small such as modification of hydrogen combustor, etc.
Flexibility	By changing the type of the combustor, such as hydrogen mono-firing or co-firing with natural gas, a system suitable for the fuel infrastructure and site conditions can be built.
CO ₂ reduction effect	In cases where the GTCC output is 500 MW, the capacity factor is 70%, and 100% ammonia-cracked gas is used, 800,000 tons of CO ₂ emissions can be reduced annually.
Expandability	The heat source required for the ammonia cracker is not limited to exhaust heat of the gas turbine, so the system can be used as a component of a general-purpose hydrogen supply chain.

5. Efforts in overseas projects

Overseas, a comprehensive hydrogen utilization plan that covers the supply, transport, storage, and use of hydrogen is proposed, such as a system that processes CO₂ generated during the production of fossil fuel-derived hydrogen using CCS. Especially in Europe where there is an advantage that existing natural gas pipelines have been developed, hydrogen utilization projects are underway as cross-border comprehensive infrastructure.

Among them, we are participating in a project to convert a natural gas-fired gas turbine combined cycle (GTCC) power generation plant with 1.32 million kW-class output operated by N.V. Nuon, a Dutch energy company, to hydrogen-fired power generation. This project calls for the conversion of one of the three units of the M701F gas turbine power generation plant, which we delivered to the Nuon Magnum power plant (**Figure 8**) located in the state of Groningen in the northernmost part of the Netherlands, to a 100% hydrogen-fired power generation plant by 2023. We have carried out an initial feasibility study where we examined the application of a diffusion combustor, which is existing technology, and verified that the conversion to hydrogen-fired power generation is possible. Natural gas-fired power generation emits approximately 1.3 million tons of CO₂ annually per system of 440,000 kW GTCC power generation, most of which can be reduced by conversion to a hydrogen-fired power generation plant. We will continue to handle the feasibility study in the field of gas turbine technology and will continue to cooperate toward the realization of the project including planning specific modification ranges, etc.

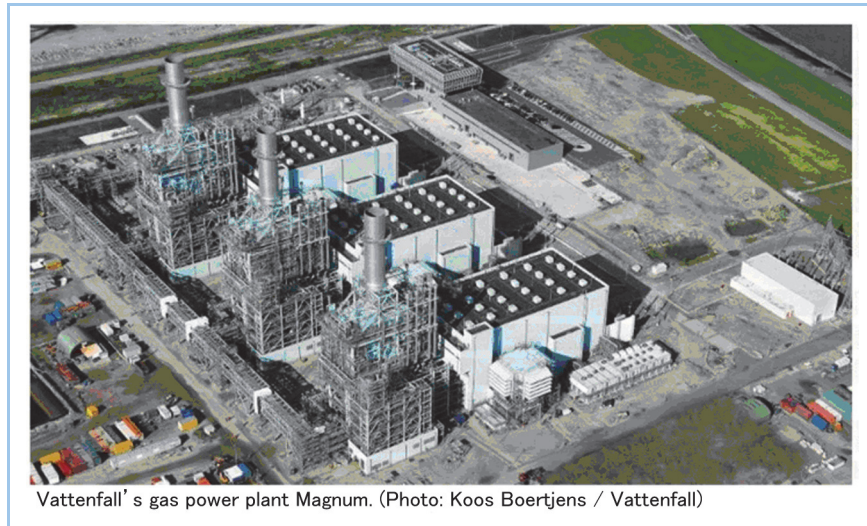


Figure 8 Nuon Magnum power plant in the Netherlands

6. Conclusion

The contents described in chapter 3 of this paper are part of the outcome of the project "Technology Development for the Realization of a Hydrogen Society" of the New Energy and Industrial Technology Development Organization (NEDO). In this grant project, we worked on the development of combustors for hydrogen and natural gas co-fired gas turbines and found that gas turbine operation under a 30 vol% co-firing condition is possible. We are continuing with the development of hydrogen-fired systems.

The contents described in chapter 4 of this paper are part of the outcome of the Council for Science, Technology and Innovation (CTSI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Energy Carriers" (Funding agency: JST). With this research, we began the development of ammonia cracking GTCC systems using ammonia, which is promising as one of the energy carriers for hydrogen.

Our hydrogen-fired gas turbines play a major role in the realization of a global CO₂-free hydrogen society using renewable energy by 2050 and in the utilization of fossil fuel-derived hydrogen combined with CCS in the transition period. We will continue to lead the construction of an international hydrogen supply chain with hydrogen power generation that produces a large and stable supply of hydrogen to contribute to the realization of a CO₂-free hydrogen society.

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