INTRODUCTION

Hydrogen—atomic element number 1.
It’s the first element we learn about as students.
It forms water, which is essential for life on Earth, the planet of water.
It is abundant throughout the universe.
It is light, diffuses rapidly, and burns.

“Burning” forms the foundation of civilization, because it is a source of energy.
Energy is essential to our daily lives, and meeting the world’s increasing needs, while
reducing CO2 emissions, is a critical issue of our times.

We have arrived at a watershed in the history of energy with the diversification of energy
sources such as renewables and the impact of their evolution on the best energy mix, and the
revolution in smart grid electricity distribution.

Hydrogen is a clean energy source that does not emit CO2 upon combustion.
The accelerated introduction of IT, continued economic development in emerging nations, and
a forecast for increased demand, plus reliable technology for control of the highly flammable
element, make hydrogen power generation—clean and abundant—a viable alternative.

Competition among developers of the technology is taking place around the world, where
engineers are solving a host of issues.

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Realizing a Hydrogen Society

Decarbonization with a power-generation technology that emits no CO₂

The world currently faces two major problems: growing demand for electric power and a need to cut CO₂ emissions. The spread of renewable energies such as wind and solar power are prominent responses to these problems. On the other hand, there is an increasing need for a stable supply of electricity from thermal power generated electricity, which does not rely on the weather.

As a company playing a central role in thermal power generation, Mitsubishi Power is working to reduce the environmental impact by developing efficient power generation technologies. The hydrogen power plant technologies introduced in this pamphlet will contribute greatly to decarbonization with a power-generation technology that emits no CO₂. On a global scale, we convert the fuel for gas turbine combined cycle thermal power generation that emits the least CO₂ to hydrogen, that emits no CO₂. With our hydrogen power generation technology, Mitsubishi Power’s concept is to transition to hydrogen power, making maximum use of our existing equipment, and make it possible to reduce adoption costs.

Against the backdrop of the Paris Agreement’s objective of limiting the increase in average global temperatures to below 2 degrees Celsius (stretch target of 1.5 degrees), Japan has set a goal of reducing its CO₂ emissions to 60 percent of the 2013 level by 2050. It is proactively promoting the use of hydrogen to achieve this goal. Moreover, the lack of energy resources is causing Japan to focus on hydrogen as a key to solving issues related to a stable energy supply.

In 2014, the government published a roadmap for the use of hydrogen ahead of the rest of the world and began an initiative on international partnerships to configure a supply chain. A 450MW class GTCC thermal power-generation plant uses about the same amount of hydrogen as 2 million fuel cell vehicles. By developing hydrogen power generation technology, we are aiming to contribute to the realization of a hydrogen society by creating a virtuous cycle of stimulating large-scale hydrogen utilization and cost reduction.

To respond to diversifying demands in the power market, we are moving forward with the development of solid oxide fuel cells (SOFC), as we are advancing initiatives for both the concentrated power supply of large-scale GTCC and the distributed power supply of SOFC.

The Mitsubishi Heavy Industries Group, including Mitsubishi Power, has a track record of producing and supplying various hydrogen-related products including rocket engines that use hydrogen as a liquid fuel and hydrogen production facilities. In the half century between 1970 and the present, we have abundant accomplishments in the use of by product gas that contains hydrogen for utilization of the power we generate. Using our technological expertise, we intend to continue striving to realize a hydrogen society.

Ken Kawai
President and CEO
All eyes are on Hydrogen Energy

Accelerated effort towards a Hydrogen Society

On October 23, 2018, the world’s first international conference on the use of hydrogen, Hydrogen Energy Ministerial Meeting, was held in Tokyo. Joining the ministers were over 350 members from the auto and energy industries, the governments, and research. As Mitsubishi Power is currently driving the practical application of large-size ‘hydrogen gas turbine,’ its executive Senior vice president assistant to president and CTO, Chief Technology Officer, Akimasa Miyama, gave a talk titled, "Upstream & Global Supply chain for Global Hydrogen Utilization."

There are increasing number of examples of hydrogen application coming out of Europe. In January 2017, the Hydrogen Council, a global initiative to position hydrogen as the new energy, was set up, which started with 13 world-leading companies in energy transport, and manufacturing. As of January 2020, over 80 companies have joined the initiative. With Mitsubishi Heavy Industries being a supporting member of the Council, Mitsubishi Power is also participating in the initiative as part of the Mitsubishi Heavy Industries Group.

Why much expectation is riding on hydrogen energy

Why is there much focus on hydrogen energy? First of all, it’s an energy that greatly contributes to the issue of global warming as it produces no CO2 upon use. Secondly, it offers greater energy security. Japan is heavily reliant on import for the fossil fuel we use. On the other hand, we can expect to reduce the sourcing and supply risks as hydrogen can be obtained from a wide variety of sources, along with greater storage and transport potential.

So how is hydrogen produced? There are mainly three ways to produce hydrogen:

First, we have the hydrogen produced from fossil fuels. These are byproducts from the existing chemical factories as well as from reformulating or gasifying oil, natural gas, and coal.

The second method is to combine the hydrogen derived from fossil fuel with CCUS (Carbon Capture, Utilization, and Storage). This is the method considered for hydrogen production in the project Mitsubishi Power is currently engaged in where a feasibility study is underway to convert the thermal power generation facility in the Netherlands which burns natural gas into a 100% hydrogen-fired power generation plant.

The third method is to produce hydrogen from electrolyzing water. If we use renewable energy for the electricity necessary for the electrolysis, no CO2 is emitted even in the production phase.

Miyama(Mitsubishi Power) of Mitsubishi Power shared his projection where, "Given the future trend in hydrogen, I suspect hydrogen from fossil fuel using CCUS will be the common method in the mid-term. The cost reduction and technical advances in the long term will make hydrogen from renewable energy the norm."
Shifting to hydrogen in power generation

Since the adoption of the Paris Agreement, the global effort to decarbonize or to realize a low carbon society is gathering pace and there is a growing expectation for electrical power generation to reduce their CO2 emission.

"What is the situation for power generation in Japan today?" Although we see a fast growing production of renewable energy from sun and wind, as of 2016, 13.3% of all energy is produced from renewable generation using fossil fuel (LNG, oil, coal, etc.).

Continuous efforts are being made to improve the efficiency of energy conversion from fuels. In the latest system gas turbine combined cycle (STGCC) power generation, the efficiency has reached around 64%, taking the CO2 production compared to conventional coal-fired power generation.

The plan is to continuously develop technology to improve the efficiency in thermal generation as well as expand the use of renewable energy. In addition, there is much expectation for the potential of hydrogen as the fuel for power generation as it can dramatically reduce CO2 emission.

Miyazaki (Mitsubishi Power) of Mitsubishi Power says, "In the move to reduce CO2 emission in thermal energy generation in Japan, we would probably first deploy the method where we combine burning natural gas and hydrogen together and eventually shift to 100% hydrogen. By using the latest technology in thermal power generation, we must first stabilize the supply by converting fuel to hydrogen, which will evidently allow for CO2-free power generation."

There are various application possibilities in hydrogen, but one issue remains which is the cost. In the roadmap for "Basic Hydrogen Strategy," the Japanese government has set a target of reducing the cost by a factor of 10 by 2030 to ¥3/kg (current station price: ¥10/kg) when the international hydrogen supply chain is set up.

Miyazaki (Mitsubishi Power) of Mitsubishi Power continued to say that "When you run a 400MW-class gas turbine combined-cycle power generation for a year, the hydrogen consumed will equal 3 million TCVs. The power generation will directly lead to massive hydrogen consumption, which will contribute to the cost reduction." The use of hydrogen in power generation will reduce the cost of hydrogen production, which will potentially drive application in other areas.

Hydrogen as the Energy Carrier

The potential of hydrogen extends beyond being the secondary energy in power generation to be an "energy carrier" which allows energy to be stored and transported.

As the volume of power generated must be in line with the volume consumed, there may be excess energy produced from renewable generation given the unpredictability of nature. Being able to store hydrogen (gas) converted from such excess energy (power) will contribute to reducing the cost of hydrogen production itself. This process is called P2G (Power to Gas).

If this method is deployed, it is possible to "transport" energy, which is the hydrogen produced from the excess in the renewable power generation in locations where we have enough sunlight, wind, etc. (for example, in remote islands with no power grid or desolate area where energy consumption is limited with potential for excess energy). Being able to convert power generated from low-cost renewable power and other unutilized energy (sodium, by-product hydrogen, etc.) into hydrogen may also be an advantage for import into Japan. There are multiple options in hydrogen carrier which includes liquid hydrogen, MCH (methylohexane), ammonia amongst others, and various research is underway across a range of fields.

The Future for Hydrogen

In June 2019, Japan hosted the G20, where the role and the importance of hydrogen were discussed in the "Ministerial Meeting on Energy Transitions and Global Environment for Sustainable Growth" held in Karuizawa.

Also, the upcoming Tokyo Olympic/Paralympic Games will be a stage to showcase the potential of hydrogen energy in our daily lives. To realize a hydrogen-based society, the Tokyo Metropolitan Government has announced a target for the adoption of PV, FC, bus, hydrogen station as well as introduction of fuel cells in homes.

Globally, Mitsubishi Power is taking part in a feasibility study in the Netherlands, where a 440MW large-scale natural gas-fired gas turbine combined cycle (STGCC) power plant is being converted into a 100% hydrogen-fired power generation plant by 2025. This will reduce the current CO2 production (1.3 million tons/year) to almost zero.

When we look at the history of global energy policies, we can see a different source is chosen every decade, which is reflective of our value during that time period. Energy changes with the times, and society evolves with it.

There is no doubt that the roadmap to realizing a hydrogen society will pick up pace as nations, businesses, and researchers continue to devote their knowledge, wisdom, and expertise for the future.
The hydrogen gas turbine, successfully fired with a 30% fuel mix, is a major step towards a carbon-free society

Expectations for hydrogen energy and technologies

Copies with the conflict between robust energy demand and global decarbonization

"Energy is the cornerstone of industry," said Satoshi Tanamura—Chief Engineering and General Manager, Gas Turbine Technology & Products Integration Division, Mitsubishi Power—a leader in the development of hydrogen-fueled gas turbines that feature CO₂-free combustion technology. "If demand exists, supply will be provided by electric power companies, and power-generating facilities are necessary to provide this supply. At the same time, there is increasing public scrutiny toward power generation that produces CO₂ emissions. They want electricity, but they don’t want the attendant CO₂ emission. It’s the mission of engineers to pursue thermal power generation that emits zero CO₂."

In Japan, the country’s primary energy is mainly converted into electricity, accounting for 43% of all energy. Thermal power accounts for 45% of the electricity supply volume with the fuel type breakdown being as follows: LNG at 44%, oil and petroleum at 9%, and coal at 32% (as of 2015).

As energy choices steadily increase, thermal power still remains a key energy source. "With regard to thermal power using fossil fuels, efforts have continuously been made toward reducing emissions by enhancing efficiency through technological innovation," said Tanamura. "CO₂ emissions per unit with gas turbine combined cycle (GTCC) plants, which combine gas and steam turbines, are less than half those generated by coal-fired thermal power. But it doesn’t change the fact that CO₂ is still emitted in the generation of gas-fired thermal power; we cannot close our eyes to this fact. As an engineer, I’m particularly sensitive to global issues and expectations toward resolving them. And we must develop technology to cope with the conflicting issues of strong demands for energy and for CO₂ reduction."

A clear roadmap to the achievement of a hydrogen society

Tanamura’s focus is on thermal power generation that does not emit CO₂. "One area of involvement is the development of hydrogen gas turbines," he said.

Japan’s Basic Hydrogen Strategy includes the target of commercialization of hydrogen power generation by 2030. However, is it possible to commercialize hydrogen power generation in a little over ten years? Even if technology is successfully developed, how many power plant operators can afford to renew their facilities?

"Even if hydrogen power generating facilities are installed at power plants already scheduled for renewal, it’s not realistic to expect substantial power generation volume to be secured in only ten years," said Tanamura. "That’s where Mitsubishi Power comes in—we conceived a hydrogen power generation system that utilizes existing gas turbine facilities."

Tanamura and his colleagues at Mitsubishi Power succeeded in developing a large-scale hydrogen gas turbine combustor that uses a mix of LNG—the fuel used in gas-fired thermal power—and 30% hydrogen. It burns hydrogen while allowing suppression of NOx emissions to the level of gas-fired thermal power. The technology is compatible with an output equivalent to 700MW (with temperature at turbine inlet at 1400°C), and it offers a reduction of about 10% in CO₂ emissions compared with GTCC.

As this technology enables the use of existing facilities, large-scale modification of power generation facilities becomes unnecessary. This makes it possible to lower costs and other hurdles, promoting a smooth transition to a hydrogen society.

But can hydrogen be infused into the fuel mix of existing facilities so easily? Aspects such as fusion, combustion, and the quality and behavior of hydrogen must be different from those of LNG. What is this hydrogen-mixed combustion technology developed by Mitsubishi Power? Where was the technological breakthrough? And what is the next move? We will now introduce the many challenges that Tanamura had to overcome.
Successful 30% hydrogen combustion represents a major step toward a hydrogen society

Easy-to-burn hydrogen and the struggle for safety

Hydrogen—atomic element number 1—is the first element students learn about, and the lightest of all elements. Hydrogen is clean—when it burns, it produces only water. Conversely, it is a substance that is difficult to handle. It burns violently, so the idea of hydrogen is often accompanied by the ‘fear of explosions’. It is highly combustible, only needs energy equivalent to static electricity to ignite, and has a broad combustion range. These are difficulties that come with such a combustible element. Thus there are many challenges that engineers must overcome in order to realize a hydrogen fuel mix of 30%.

“In the case of a 20% hydrogen fuel mix, the existing gas turbine can be used,” said Satoshi Tanimura of Mitsubishi Power. “However, making it usable with 30% hydrogen poses quite a challenge for the gas turbine engineer. It is necessary to understand the combustion characteristics and control the air mixing and behavior.” Even with superior materials, the technology must control those aspects, the facilities be made durable, and high quality consistently maintained. It is the job of an engineer to resolve these issues.

Obstacles standing in the way of a 30% hydrogen mix are flashback, combustion pressure fluctuation, and NOx. The unique characteristics of hydrogen and the mixing of hydrogen with air are the cause of flashbacks. Flashback is a phenomenon where the flames inside the combustor travel up the incoming fuel and leave the chamber. As hydrogen burns rapidly, flashback commonly occurs.

Furthermore, the mixing method complicates the mitigation of flashback. This technology employs premixing combustion. The fuel and air are mixed prior to entering the combustor. While this enables low-NOx combustion, flashback occurs more commonly when fuel containing hydrogen is used. By securing sufficient distance, sufficient mixing can be accomplished while also achieving low NOx, but this ends up increasing the risk of flashback. To resolve this, improvements were made to the swirller nozzle. The low velocity area in the center of the nozzle was successfully reduced, significantly enhancing flashback resistance.

“Burning of fuel anywhere but inside the combustor absolutely must be avoided. If flashback cannot be prevented, a hydrogen gas turbine cannot be successfully developed.”

Innovative technology to control combustion pressure fluctuation that can destroy a combustor

Combustion oscillation presents yet another obstacle. Temperatures inside the combustor reach 1,600°C, and it is known that imposing an extremely high thermal load on the combustor cylinder results in the generation of a very loud noise due to the cylinder’s specified eigenvalue. This is the phenomenon known as combustion pressure fluctuation.

Put the oscillation from the loud sound together with the oscillation of the flames from combustion and they amplify, producing immense power. Also, given the particularly short interval when combustting hydrogen, the flame and the oscillation are more likely to match, increasing the likelihood of combustion pressure fluctuation.

So how loud is the sound?

“It’s actually beyond loud. And once oscillation occurs, it will destroy the combustor in an instant,” said Tanimura. “In order to avoid this, not only do we adjust the fuel burning location and method of burning; we have incorporated a number of innovations such as a sound absorption device.”

While suppressing these phenomena and satisfying the necessary conditions, Tanimura and his team must also extend the service life of the facility by enhancing maintenance capabilities and the performance of the facility overall. Moreover, they must constantly search for the best materials, the optimum form, and the ideal combination—from the optimization of the shape and material of the fuel delivery nozzle and the combustor shape and material to the quality of the thermal insulation ceramic coating and adjustment of particle size. The repetition of this trial-and-error process brings them ever closer to the development of a carbon-free power generation system and ultimately to the realization of a carbon-free society.

Of utmost importance to power plant operators—users of the gas turbine—are safety, stable supply, and cost. In providing a steady supply of electricity, naturally a stable supply of fuel is a requirement, along with the mitigation of outages, longer intervals between periodic inspections, and low operation costs. “The gas turbine has to withstand three years of continuous operation under rigorous conditions including a fast rotation speed of 3,600 revolutions per minute at over 8,000 hours per year,” said Tanimura. “The flexibility to continue generating power with only LNG should be the supply of hydrogen stop temporarily is undoubtedly another great benefit to the customer.”

A hydrogen gas turbine that can adjust flexibly to fluctuations in fuel supply and price, and highly resistant to thinning, wear, and oscillation results from the synergy of numerous technologies, which is demonstrated in its performance.
100% hydrogen power generation — achieving a complete hydrogen-fired gas turbine

The dream of a CO₂-free society—100% hydrogen thermal power generation

The values below are emissions per unit indicating CO₂ emission volume when generating kWh of electricity.

<table>
<thead>
<tr>
<th>Power Generation</th>
<th>CO₂ Emission (kg/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard coal-fired</td>
<td>863g</td>
</tr>
<tr>
<td>Ultra-supercritical</td>
<td>800g</td>
</tr>
<tr>
<td>SCIG power generation</td>
<td>340g</td>
</tr>
<tr>
<td>Hydrogen 30% mixed-combustion gas turbine</td>
<td>300g</td>
</tr>
</tbody>
</table>

As Mitsubishi Power has successfully achieved mixed-combustion power generation at 30% hydrogen, Satoshi Tanamura’s next objective is CO₂-free power generation, or 100% hydrogen power generation technology. However, with a high concentration of hydrogen, the risk of flashback rises, as does the concentration of NOx. A combustor for hydrogen-fired power generation demands technology that enables efficient mixing of hydrogen and air, and stable combustion.

“There are important conditions concerning the mixing of hydrogen and air as well,” said Tanamura. “It is difficult to mix hydrogen and air in a large space, and using a rotational current and mixing them well requires a rather large space. This is what puts the risk of flashback upward. In order to mix hydrogen and air in a short period of time, it has to be done in as confined a space as possible. The problem is that in this case the fuel nozzle and flame are in closer proximity, making flashback increasingly likely. We thought about how to deal with this, and it occurred to us that we needed to disperse the flame and reduce the fuel spray particle size. The key technology to this method is the fuel delivery nozzle. We upgraded the design, which normally features eight nozzles, and created the distributed lean burning, or multi-cluster combustion, which incorporates many nozzles. We reduced the size of the nozzle opening and injected air, and then sprayed hydrogen and mixed them. As this method does not employ a rotational current, mixing is possible on a smaller scale, and low-NOx combustion can be accomplished.”

Hydrogen is an excellent fuel, but difficult to handle. Changing thinking in mixing methods by upgrading the nozzle. That’s kind of challenges engineers are wrestling with in the battlefield of development.

Creating a hydrogen fuel supply chain as a bridge to the future

A gas turbine alone is not enough to achieve 100% hydrogen-fired combustion technology. Stable sources of hydrogen must be secured. Considering a supply source and way to transport the hydrogen to a pipeline-less Japan, developing technology to extract hydrogen from the source materials, as well as technology to collect and retain the CO₂ emitted during the process. Such hydrogen infrastructure must mature along with the development of hydrogen combustion technology.

“Simply increasing gas turbine efficiency does not necessarily lead to enhanced efficiency overall,” said Tanamura, when taking a comprehensive perspective of the practical use of hydrogen. “In Japan, we simply assume will have hydrogen transported from abroad and use it in fuel-cell vehicles and industry. Meanwhile, there is a blueprint overseas from the hydrogen supply phase through to use, including the CCS scheme for processing CO₂ emitted during manufacturing. In Europe, with the advantage of their existing natural gas pipeline being well-developed, they are proceeding with hydrogen use while taking a holistic view through to supply, considering it part of the overall infrastructure,” he said.

As engineers developing gas turbines, Tanamura and his colleagues have a clear understanding of the need for a comprehensive hydrogen usage plan. “In Japan, as we don’t have a developed pipeline, naturally the transport of hydrogen constitutes a major issue,” Tanamura said. “As of now, there are schemes for extracting hydrogen from renewable energy, petroleum, and natural gas. If renewable energy, regarded as unstable, is converted into hydrogen, the storage and transport of energy becomes possible, which is a huge benefit. Today, liquid hydrogen, methanol, and ammonia are regarded as the most promising hydrogen transport vehicles, and if demand increases further, we should see economies of scale emerge in transport as well,” said Tanamura.

Gas turbine engineers factor in everything from production to costs. “We need a vision for hydrogen use, encompassing everything from creation of infrastructure to the various methods of use,” Tanamura said. “For instance, a fuel mix of 20% hydrogen can be used without any technological improvements, and if we use a gas turbine with an output capacity of 500MW, and a turbine efficiency rating of 45, it requires 3.4 tons of hydrogen per hour. This equals the volume of hydrogen used by around 100,000 to 130,000 fuel-cell vehicles. If we are going to proceed in earnest with hydrogen use, it’s imperative that we quickly move to upgrade the hydrogen infrastructure, through measures such as proactively increasing the number of turbines using hydrogens. This is another reason hydrogen gas turbines will drive the forthcoming hydrogen society,” he said.

Human beings discovered fire and began using it purposefully about 500,000 years ago. And now we are about to obtain CO₂-free combustion technology that will turn into energy that supports society.

Tanamura and his colleagues remain dedicated to achieving 100% hydrogen combustion technology by 2025.
As a key corporation in the fields of thermal power generation and environmental technology, Mitsubishi Power is developing high-efficiency power generation technologies that contribute to reducing environmental impact and power generation costs.

- Development of Hydrogen and Nikari Gas-Cooling Gas Turbine: Hydrogen-fired gas turbines can contribute to the realization of a "safe and sustainable energy environment.
- Development of an 11th generation Gas-Cooling Gas Turbine: Mitsubishi Power is aiming for a 10% reduction in CO2 emissions compared to prior gas-fired power plants.
- Hydrogen-fired Gas Turbine: Mitsubishi Power is working on the realization of CO2-free Society hydrogen single-turbine technology in high-efficiency gas turbines. We are committed to creating an international hydrogen supply chain to achieve a CO2-free Hydrogen Society.
- Fuel Cells: Mitsubishi Power is developing a new generation, large-scale SOFC toward realization of a Hydrogen Society. Our fuel cell power generation technology meets today’s societal needs.

- Efforts toward Introduction of SOFC-MGT Hybrid System to the Market: Development with the goal of achieving low carbon society through the introduction of the "1MW class.

Source: Mitsubishi Heavy Industries Technical Review

Authors and affiliation names shown here are true and accurate at the time of writing.
cycle power plant verification facility in the MIHIS Takasago Works and since then we have been performing long-term operation. This paper presents the development and operational situation of MIHIS’s state-of-the-art high-efficiency gas turbine and the development of the next-generation 1650°C class JAC (J Air Cooled) gas turbine using the enhanced air-cooled system as its core technology.

![Figure 1 History of development of large gas turbine models](image)

## 2. Development and results of M501J gas turbine

The M501J was able to achieve a turbine inlet temperature of 1600°C based on the component technologies already demonstrated by the abundantly-proven F-series gas turbine and G-Hi-series gas turbines, with turbine inlet temperature classes of 1400°C and 1500°C, respectively, and the application of the development of the most advanced 1700°C class technology resulting from a national project. Due to the increase of the turbine inlet temperature and the adoption of the latest component technology, the GTCC power generation thermal efficiency has greatly increased in comparison with existing equipment. CO₂ emissions can be reduced by about 60% when a conventional coal-fired thermal power plant is replaced with a natural gas-fired J-series gas turbine combined cycle power plant. Figure 2 shows the technical features of the M501J.

![Figure 2 Technological characteristics of M501J gas turbine](image)

The development of the M501J gas turbine was carried out by conducting verification tests of each element at the basic design stage, reflecting the results in the detailed design, and finally verifying the actual operation of the entire gas turbine in the verification power generation facility. Figure 3 shows the appearance of the gas turbine combined cycle power plant demonstrator (T-point) in the MIHIS Takasago Works. We carried out 2,300 special measurements on the first model of the M501J and verified that the performance, mechanical characteristics, and combustion characteristics satisfied the target values, before the shipping of the commercial product. We have received orders for 65 J-series gas turbines from domestic and overseas customers, and are shipping them as they become available. Up to now, 23 units have been put into commercial operation, and the total operational time of more than 400,000 hours has been reached. (Figure 4)

![Figure 3 Gas turbine combined cycle power generation plant demonstrator (T-point) in the MIHIS Takasago Works](image)

![Figure 4 Operating results of M501J gas turbine (including 50 Hz units)](image)

## 3. Core technology of next-generation gas turbine

The J-series gas turbine adopts the steam-cooled system for cooling the combustor, but if an air-cooled system can be used while maintaining the high turbine inlet temperature, further improvement in the efficiency and operability of GTCC can be expected. Therefore, MIHIS worked on the development of next-generation GTCC that realizes air cooling of high-temperature gas turbines, and devised the enhanced air-cooled system that is a core technology thereof. By adopting this enhanced air-cooled system, air cooling of gas turbines even with a turbine inlet temperature of 1650°C can be realized, achieving high combined power generation efficiency and improving the operability of the entire plant. In the spring of 2015, we completed the actual equipment verification test of the entire system at T-point. This section presents an overview of the air-cooled system.

### 3.1 Overview of enhanced air-cooled system

In the enhanced air-cooled system, air extracted from the compressor outlet (combustor casing) is cooled by the enhanced cooling air cooler, pressurized by the enhanced cooling air compressor, used for cooling the combustor, and then returned to the casing. Figure 5 shows a schematic diagram of the enhanced air-cooled system.
The characteristics of the enhanced air-cooled system are described below.

(1) The efficiency of the system can be improved by recovering the waste heat of the enhanced cooling air cooler on the bottoming cycle side.
(2) Cooling performance equal to or higher than that of existing steam-cooled system can be achieved by optimizing the combustor cooling structure.
(3) The startup time of the entire GTCC can be shortened in comparison with the steam-cooled system.

It is important for the efficiency improvement of next-generation GTCC with an enhanced air-cooled system to develop a combustor that can perform efficient cooling with a small amount of cooling air, reduce the waste heat from the enhanced cooling air cooler, improve the recovery efficiency, and reduce the power of the enhanced cooling air compressor.

![Figure 5 Schematic diagram of enhanced air-cooled system](image)

3.2 Enhanced air-cooled combustor

The cooling structure of the enhanced air-cooled combustor adopts an MT-FIN structure utilizing convective heat transfer similar to the steam-cooled system adopted by the JSeries gas turbines. The upstream side of the combustor is cooled by air in the combustor chamber and the downstream side is cooled by enhanced cooling air through the enhanced cooling air compressor. The amount of cooling air passing through the enhanced cooling air compressor is minimized by limiting the cooling range using the enhanced cooling air only on the downstream side. Furthermore, the cooling direction on the downstream side is designed to perform cooling efficiently while securing the cooling capacity at the outlet by supplying the cooling air from the combustion liner outlet where the heat load is high. On the upstream side, an acoustic liner is installed to suppress combustion dynamics and the structure is designed so that the air that convectively cooled the combustion liner through the MT-FIN is pressed through the acoustic liner holes. Figure 6 shows a schematic of the cooling structure of the combustion liner. Prior to the verification of the entire enhanced air-cooled system to be described later, it was confirmed by the high-pressure combustion test facility that there was no problem in cooling performance and combustion stability of this enhanced air-cooled combustor.

![Figure 6 Cooling structure of combustion liner of enhanced air-cooled combustor](image)

3.3 Enhanced air-cooled system actual equipment verification

Figure 7 shows the overall view of the facility and the system overview of the enhanced air-cooled system verification executed at T-point. In the enhanced air-cooled system, the waste heat of the enhanced cooling air cooler is recovered in the bottoming cycle, but a radiator type cooler was added as an enhanced cooling air cooler because the verification at T-point used the existing bottoming system.

![Figure 7 Enhanced air-cooled system verification equipment and system of T-point](image)

In the spring of 2015, we verified the operability of the enhanced air-cooled system, that is, the responsiveness to transient changes such as start/stop, load change, and load rejection, using this demonstrator (T-point), and confirmed that there was no problem. The enhanced cooling air compressor operating point behavior during the gas turbine trip test was also tested and it was confirmed that the enhanced cooling air compressor could be stopped safely without entering the surging state at a trip from the 100% load of the gas turbine.

In addition, the metal temperature of the enhanced air-cooled combustor was measured and the cooling performance of the actual equipment was verified. Figure 8 shows the behavior of the combustor metal temperature when the amount of cooling air was changed. Although the metal temperature rose as the amount of cooling air decreased, it was lower than the design tolerance even if the amount was smaller than the initial planned amount of cooling air, and there was no problem in the cooling performance. In addition, the combustion dynamics characteristics and exhaust gas emissions were not problematic and it was confirmed that stable operation is possible.

![Figure 8 Metal temperature of enhanced air-cooled combustor](image)

Based on this enhanced air-cooled system, we also verified the system that enables clearance control during load operation. This system includes two supply systems: one supply method that supplies cooling air to the combustor directly by bypassing the turbine blade ring and the other method that supplies cooling air to the combustor after ventilating the turbine blade ring to...
maximize the performance by reducing the turbine clearance during load operation, and these two systems can be switched using the switching valve (three-way valve) even during load operation. The former makes it possible to cope with a large load changing operation by opening the clearance (Flexible Mode). On the other hand, the latter makes it possible to reduce the clearance during load operation and maximize the performance (Performance Mode). Figure 9 shows the clearance behavior when the three-way valve is switched during load operation. Using this system, it is expected that the operability can be improved more than before while maximizing the performance.

![Figure 9 Turbine Clearance Control Using Enhanced Air-Cooled System](image)

**4. Development of 1650°C class next-generation JAC gas turbine**

In the spring of 2015 we verified that there was no problem with the operation of the enhanced air-cooled system, conducting actual equipment verification at T-point. Even now, the enhanced cooling system is being verified at Point-T for its long-term operation. The JAC gas turbine, a 1650°C class next-generation gas turbine adopting this enhanced air-cooled system as the core technology, is being developed (Figure 10). Although the inlet temperature of the turbine becomes 50°C higher than that of the M501J, ultra-thick thermal barrier coating (TBC) developed based on the technology from the national project is adopted to achieve both high performance and reliability. In addition, by adopting a compressor with a high-pressure ratio design equivalent to that of the H-series gas turbine, the rise in the exhaust gas temperature at the gas turbine outlet is suppressed.

![Figure 10 Characteristics of Next-Generation Gas Turbine Using Enhanced Air-Cooled Combustor](image)

We plan to close the existing demonstrator (T-point) and renew it as a new demonstration facility because it is necessary for conducting verification test operation of a newly-developed GTCC to renew not only the main body of the gas turbine, but also the main equipment such as the existing generator, the main transformer, the plant recovery steam generator, etc., to meet the specifications of the next-generation gas turbine. Figure 11 shows the expected completion of the new demonstration facility. Currently, we are carrying out development with the goal of starting verification in 2020. Similar to the past G- and J-series gas turbines, we will steadily verify the newly-developed gas turbine using the new demonstration facilities and respond to social needs for further energy saving and the reduction of pollution.

![Figure 11 Next-Generation Gas Turbine Demonstration Facility and Its Schedule](image)

**5. Conclusion**

For the improvement of the efficiency of GTCC, increasing the gas turbine temperature plays an important role. MIHPS developed the highly-efficient M501J, which achieved the world’s first turbine inlet temperature of 1650°C, utilizing the development results from the national project “1750°C class Ultra-high-Temperature Gas Turbine Component Technology Development,” which we have participated in since 2004, and has been steadily accomplishing operating results. To further improve the efficiency and the operability of GTCC, we have devised the enhanced air-cooled system that enables air cooling of a high-temperature gas turbine. This enhanced air-cooled system was verified by actual an equipment demonstrator in the MIHPS Takasago Works in 2015, and there was no problem in operation. Since then, the system has been operating for a long time to the present. Currently, we are developing the next-generation 1650°C class JAC gas turbine using this enhanced air-cooled system as a core technology. We will close the existing T-point demonstrator, and verification using a new demonstration facility will commence in 2020.

**References**

4. Takada, Development of the Next Generation Gas Turbine Combined Cycle, the 4th G1SN Seminar material (2015-9)
Development of Hydrogen and Natural Gas Co-firing Gas Turbine

The necessity of fossil fuels through the introduction of hydrogen energy is an effective option indispensable for the sustainable development of economic activity. The Mitsubishi Heavy Industries Ltd. (MHI) Group is promoting the research and development of a large gas turbine for which a mixed fuel of natural gas and hydrogen can be used with support from the New Energy and Industrial Technology Development Organization (NEDO). Currently, with the newly developed combustor, etc., we succeeded in a co-firing test of 90 vol% of hydrogen. This co-firing makes it possible to reduce CO₂ emissions during power generation by about 10% in comparison with conventional natural gas thermal power generation.

1. Introduction

In order to continue economic activities sustainably, it is essential to secure and supply energy that is stable and has low environmental impact. In response to issues such as global warming and the depletion of fossil fuels, the maximum acceleration of introduction and dissemination of renewable energy and the effective utilization of fossil fuels with maximum consideration for environmental impact are required. In addition to electricity and heat, hydrogen is expected to play a central role as future secondary energy, and the MHI Group is developing technology to fully utilize it.

Regarding the introduction of renewable energy, for example, the amount of wind power generation introduced globally has been increasing at a pace of 40 GW annually since 2011 and is predicted to expand to a maximum of about 2,500 GW in 2050. Because renewable energy has large output fluctuations, the utilization of surplus electric energy, in addition to the increase of renewable energy power generation facilities, is considered to be an issue. In order to effectively utilize such surplus electric energy, energy storage technology that converts into a storage battery or hydrogen, etc., is necessary. In particular, when the fluctuation cycle is long and a significant amount of energy capacity is required, it is considered effective to convert it to hydrogen, etc.

One promising power generation method using hydrogen fuel is power generation with a gas turbine. Current gas turbines generally use natural gas that is distributed as a general-purpose product for fuel. Since CO₂ generated during the combustion of natural gas is considered to be one of the factors of global warming, there is a movement to regulate its emission worldwide. Since the combustion of hydrogen does not generate CO₂, the amount of CO₂ generated during power generation can be reduced by replacing a part of the hydrocarbon components in the fuel with hydrogen.

2. Issue of hydrogen co-firing

The Dry Low NOₓ (DLN) combustor installed in our large gas turbine adopts the premixed combustion method to reduce NOₓ (nitrogen oxide causing acid rain). Figure 2 compares the premixed combustor and the diffusion combustor. Since premixed combustion can reduce the flame temperature compared with diffusion combustion, NOₓ can be reduced without steam/water spraying, and it is a technology currently widely applied to low NOₓ combustor. On the other hand, the stable combustion range is narrower than that of the conventional diffusion combustor, and the flashback phenomenon tends to occur. Flashback is a phenomenon in which a flame moves upstream in the fluid when the propagation speed of the flame (hereafter referred to as the combustion speed) is higher than the speed of the fluid (hereafter referred to as the flow velocity). If flashback occurs inside the gas turbine combustor, there is a possibility of burning the upstream non-cooled part, so it is important to prevent its occurrence. Figure 3 provides an overview of the flashback phenomenon.

When natural gas and hydrogen are mixed, the properties of the flame change due to the change in the fuel component. Particularly, in order to stably operate the gas turbine, it is necessary to develop a technology to deal with the change in the combustion speed. It has been confirmed that hydrogen has a higher combustion speed rate in comparison with natural gas. For this reason, when hydrogen is mixed, it is considered that the risk of the flashback phenomenon is higher compared with the case where only natural gas is burned. Therefore, for the development of a hydrogen co-firing gas turbine, the improvement of the combustor for the prevention of flashback occurrence is important.

Inside the MHI Group’s DLN combustor, swirling flow is formed to promote the mixing of fuel and air. Several articles[1,2] reported that in order to prevent the occurrence of flashback in such swirling flow, it is necessary to raise the flow velocity at the center portion of the swirling flow beyond the rise in the combustion speed.
3. Outline of flashback prevention technology

3.1 Concept of new combustor

Figure 4 illustrates the outline of a combustor newly developed with the purpose of preventing an increase in the risk of flashback caused by hydrogen co-firing. The air supplied from the compressor to the interior of the combustor passes through the swirler and becomes a swirling flow. Fuel is supplied from a small hole provided on the blade 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 velocity exists in the central part (hereinafter referred to as swirling center) of the swirling flow. It is considered that the flashback phenomenon in the swirling flow is caused by the flame moving upstream in the portion of the swirling center where the flow velocity is slow.

In the new combustor, in order to increase the flow velocity at the swirling center, air is characteristically injected from the tip of the nozzle. The injected air compensates for the low flow velocity region of the swirling center and prevents flashback.

3.2 Verification by non-combustion test

In order to confirm the effect of the new combustor, flow velocity distribution was measured with an air flow test. Figure 5 is a photograph of the equipment used for the air flow test. The swirling center does not remain at a certain position, and its position changes from moment to moment. For this reason, in flow velocity measurement, it is necessary to perform measurement at the moment when the flow velocity lowers while the swirling center passes through the measurement point. Therefore, by applying a hot wire current meter (Kanomax 7000 Ser and ø5 μ I-type linear probe made of tungsten) for the flow velocity measurement and by achieving high-tension resolution, the evaluation of the instantaneous minimum flow velocity at the measurement position was made possible.

Figure 6 compares the flow velocity distributions of the conventional combustor and the new combustor in the region close to the swirling center. Paying attention to the minimum flow velocity, which is thought to dominate the occurrence of the flashback phenomenon, it was confirmed that the new combustor realized a flow velocity of 2.5 times or higher than that of the conventional combustor. Since the new combustor injects a very small amount of air from a small hole provided at the tip of the nozzle, regions other than the vicinity of the swirling center are hardly affected, and the flow velocity distribution is the same as that of the conventional combustor.

3.3 Confirmation of combustion characteristics by actual pressure combustion test

Representative items related to combustion characteristics of a gas turbine combustor include NOx and combustion vibration. Since NOx is one of the factors of acid rain, there is a regulation on the amount of emissions in terms of the environmental aspect. On the other hand, combustion instability needs to be kept below a certain level in order to operate gas turbines stably. Since both NOx and combustion instability are affected by the combustion pressure conditions, testing under pressure conditions corresponding to the actual machine is necessary. Therefore, through the actual machine pressure combustion test (hereinafter referred to as the actual pressure combustion test) using one full-scale combustor (in the actual machine 16 to 20 combustors are used), the influence of hydrogen co-firing on combustion characteristics was confirmed. For the actual pressure
4. Future prospects

In order to realize a hydrogen and natural gas co-firing gas turbine plant, it is necessary to further consider other auxiliary equipment attached to the plant and operation methods in parallel with the development of a combustor. Since current gas turbines mainly use natural gas distributed as a general-purpose product, piping materials and plant auxiliary equipment are selected on the premise of using natural gas. Hydrogen tends to leak and is easy to diffuse in comparison with natural gas, so it is necessary to devise safety measures suitable for the characteristics and to redesign specifications. In addition, since the hydrogen content rate may not be stable in actual plant operation, we will also work on the development of plant operation technology that can deal with an unsteady change in the hydrogen mixing ratio.

5. Conclusion

In order to respond to the use of hydrogen fuel targeting reduced CO₂ emissions in the field of thermal power generation, the MHI Group is working on the development of a hydrogen and natural gas co-firing gas turbine with support from the New Energy and Industrial Technology Development Organization (NEDO). For the prevention of the occurrence of the flashback phenomenon caused by hydrogen co-firing, a new combustor that suppresses the generation of the low flow velocity in the swirling center region was developed, and the prospect for gas turbine operation under 30 vol% hydrogen co-firing conditions was obtained. We are planning to develop plant operation technology in the future and in the future to promote the development of a gas turbine that enables further higher concentration hydrogen co-firing for plant verification operation target to be implemented in fiscal 2025.

References


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 large scale. 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 burden 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 NOₓ, 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 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 2050 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 2050](image)

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 each 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 (2), 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 can greatly reduce carbon in large quantities at the time of manufacturing and stores it in the ground, the technology for 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 cannot 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-scale 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.
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 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, and there is a risk of the occurrence of combustion oscillation and flashback. In the case of hydrogen, the fuel and air are evenly mixed, resulting in a decrease in the flame temperature that is lower than that of natural gas. Therefore, for the development and practical realization of combustors for hydrogen gas turbines, the reduction of NOx and the stabilization of combustion are necessary for the prevention of flashback together with improvements in operational conditions (low cost, long service life, etc.)

The development status of our combustors for hydrogen-fired gas turbines is described below. Figure 3 provides an overview.

<table>
<thead>
<tr>
<th>Combustor</th>
<th>Multi-nozzle combustor</th>
<th>Multi-cluster combustor</th>
<th>Diffusion combustor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Premixed flame combustion</td>
<td>Premixed flame combustion</td>
<td>Premixed flame combustion</td>
</tr>
<tr>
<td>NOx</td>
<td>Low NOx due to flame temperature uniformed by premixing nozzle</td>
<td>Low NOx due to flame temperature uniformed by premixing nozzle</td>
<td>Low NOx due to flame temperature uniformed by premixing nozzle</td>
</tr>
<tr>
<td>Flashback</td>
<td>High flashback due to no flame</td>
<td>High flashback due to no flame</td>
<td>Low flashback due to no flame</td>
</tr>
<tr>
<td>Cycle efficiency</td>
<td>No efficiency drop due to no steam or water injection</td>
<td>No efficiency drop due to no steam or water injection</td>
<td>No efficiency drop due to no steam or water injection</td>
</tr>
<tr>
<td>Hydrogen CO2 ratio</td>
<td>Up to 30%</td>
<td>Up to 100% (under development)</td>
<td>Up to 100% (under development)</td>
</tr>
</tbody>
</table>

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 the occurrence of flashback because of hydrogen co-firing. The air supplied from the compressor to the inside of the combustor passes through a swirl nozzle and forms a swirling flow. Fuel is supplied from a small hole provided on the wing surface of the swirl nozzle and is 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 (beneath 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.

(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 flows, 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 diffusion 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 scale 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 (WINET)) 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 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.

MRPS 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 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/mole 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 an inefficiency 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.

![Figure 7 Concept of ammonia decomposition gas turbine cycle](image)

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>
<thead>
<tr>
<th>Item</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>High efficiency</td>
<td>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.</td>
</tr>
<tr>
<td>Introductibility</td>
<td>The major development element in ammonia cracking is to increase the number of modifications on the gas turbine side so that a necessary heat for the application of the system is relatively small in order to avoid modifications of hydrogen power generation.</td>
</tr>
<tr>
<td>Flexibility</td>
<td>By changing the type of the combustor, such as mixing dual-fuel or co-firing with natural gas, a system suitable for the fuel infrastructure and site conditions can be built.</td>
</tr>
<tr>
<td>CO2 emission effect</td>
<td>In cases where the GTCC output is 500 MW, the capacity factor is 70%, and 100% renewable/green hydrogen gas is used, 80-90% of CO2 emissions can be reduced significantly.</td>
</tr>
<tr>
<td>Expendability</td>
<td>The heat source required for the ammonia cracker is not limited to exhaust heat of the gas turbine, so this system can be used as a component of a general-purpose hydrogen supply chain.</td>
</tr>
</tbody>
</table>

5. Efforts in overseas projects

Overseas, a comprehensive hydrogen utilization plan that covers the supply, transport, storage, and use of hydrogen is being 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 the 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 consisting of technology, and verified that the conversion to hydrogen-fired power generation is possible. Natural gas-fired power generation emits approximately 1.1 million tons of CO2 annually per unit of 400,000 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.

| 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 5% of that of methane) |  
|  
| Nitrogen contained in fuel |  
| 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.  
| Lowening of NOx by two-stage combustion is considered, but in the case of a large gas turbine, there are many technical problems such as sizing and configuration of the combustor. |
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 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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Development of Next-Generation Large-Scale SOFC toward Realization of a Hydrogen Society

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Masanori NISHURA*1 Kenichi HIKATA*1
Hiroshi KISHIZAWA*1 Koichi TAKENOZAWA*1

Mitsubishi Hitachi Power Systems, Ltd. (MHPS) is developing a combined power generation system by combining a solid oxide fuel cell (SOFC), which is a fuel cell that can operate at high temperature, with other power generation systems including gas turbines. For commercial application of the hybrid system, MHPS has been conducting demonstration tests at Tokyo Gas Co., Ltd.’s Senju Techno Station and the operation was started in March 2015. The pressurized-type SOFC-MGT hybrid system brought about by combining the 204-MW-Class SOFC with a micro gas turbine (MGT) achieved 4,100 hours of continuous operation for the first time in the world, and exhibited a stable operation state even during the heavy-load season in summer. Based on this accomplishment, a new compact-type demonstration system was designed and set up at a national university corporation Kyushu University in March 2015. It is planned to be used in demonstration studies and basic research in the future.

1. Introduction

In order to solve global warming problems, energy problems and economic problems at the same time, it is indispensable to reduce carbon emissions from energy sources and to increase efficiency in energy use. Therefore, to reduce emissions of CO2, one of the major greenhouse effect gases, it is necessary to combine centralized power sources rationally according to location and capacity on the basis of the present state of an electric power base infrastructure established with a centralized power source of high efficiency thermal power generation, etc., and then, to introduce new energies including renewable energies in the most economical and rational way possible. And, partly for global preservation of energy resources, it is indispensable and urgently required to use fossil fuel as effectively as possible by developing and quickly diffusing a high efficiency power generation system.

This article introduces the current development status of MHPS SOFC, the status of the demonstrations of the SOFC-MGT hybrid system, which is a combined power generation system of the SOFC and a MGT, being conducted through the project of the National Research and Development Agency New Energy and Industrial Technology Development Organization (NEDO), and future developments.

2. Composition of SOFC combined power generation system

2.1 Cell stack

Figure 1 illustrates the structure of a cell stack of MHPS’s tubular type SOFC. On the outer surface of the substrate tube, which is a structural component, a cell (anode, electrolyte, and cathode) reacting to generate power is formed and an electron-conductive ceramic used as an interconnector connects these cells in series. By selecting components with similar thermal expansion coefficients and the adoption of integral sintering through the improvement of manufacturing technology, the production cost has been reduced, the bonding strength of components has been increased, and the performance and durability have been improved.

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MEPS has been developing its own high performance cell stacks. The Model 10 cell stack raised the number of cells to 85, and at the same time, the power output per cell stack has been enhanced by 50% by optimizing the interconnector composition, adjusting the cathode, etc. In the Model 15 cell stack, with which we have been attempting to further improve efficiency, the interface between the electrodes and the electrolyte has been improved to further increase the output density by 50% compared with Model 10 (Figure 2).

2.2 Cartridge
A cartridge that outputs electricity of several tens of kW by binding the cell stacks is formed and a set of cartridges with the necessary capacity, which is collectively contained in a pressure vessel, constitutes a module (Figure 3).

The adoption of such a layered structure seeks systematization by taking installation and even maintainability into consideration. In addition, since the electric output can be adjusted by the number of cartridges or the number of modules, a required wide range of electric output can be covered.

For the cartridge, higher per unit volume output density is aimed at. The higher packing density is accomplished by a higher heating density, but the heat transfer/cooling design of cartridges controls the heat transfer characteristics, ensuring the conventional level of heat transfer in the power generation area as well as in the heat exchange area across the power generation area. In Model 15, the reduction of the diameter and increase of the length of a cell stack enable an increase in the output density per unit volume and reduction of the system installation area (Figure 4).

2.3 System
The hybrid system shown in Figure 5 generates electric power by the SOFC and the MGT in two steps. By installing waste heat recovery equipment on the exhaust gas line, it can function as a co-generation system that supplies steam and hot water at the same time.

3. Market introduction plan for the hybrid system
3.1 Demonstration at Tokyo Gas Co., Ltd. (Model 10 demonstration system)
Based on the achievements thus far, from fiscal 2011 to 2014, we conducted the development and evaluation of the Model 10 250 kW-class SOFC-MGT hybrid demonstration system, under the NEDO project at Tokyo Gas Co., Ltd.'s Senju Techno Station. An MGT made by Toyota Turbine and Systems Inc. was adopted (Figure 6).
3.2 Model 15 demonstration system at Kyushu University

Based on the achievements of the Model 10 demonstration system, we designed a Model 15 demonstration system, and it was set up at the Itto Campus of Kyushu University (Nishiku, Fukuoka City) in March 2015. In the future, it is planned that the Model 15 demonstration system will be used in verification studies and related basic research for improvement of performance, durability and reliability of SOFC at the Green Asia International Strategic Comprehensive Special Zone “Verification of a Smart Fuel Cell Society” in the “Next-Generation Fuel Cell Research Center (NEXT-FC)” (Figure 8).

* Next-Generation Fuel Cell Research Center (NEXT-FC): The institution established with the objective of promoting industry-academic collaboration toward utmost diffusion of SOFC.

![Figure 8 SOFC-MGT hybrid system for demonstration delivered to Kyushu University](image)

**Table 1** Specifications of the system

<table>
<thead>
<tr>
<th>Appearance</th>
<th>25 kW SOFC-MGT hybrid system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output (kW)</td>
<td>250</td>
</tr>
<tr>
<td>Net efficiency (% LHV)</td>
<td>55</td>
</tr>
<tr>
<td>Total heat efficiency (% LHV)</td>
<td>70 (heat recovery 65.6 (efficiency))</td>
</tr>
<tr>
<td>Dimensions of the unit (m)</td>
<td>12.0 x 3.2 x 3.2</td>
</tr>
<tr>
<td>Operation</td>
<td>For cogeneration</td>
</tr>
</tbody>
</table>

These specifications indicate planned values.

3.3 SOFC market introduction plan

Taking advantage of the high efficiency, co-generation, quietness, environmental feasibility and other outstanding characteristics of the SOFC-MGT hybrid system, we henceforth intend to introduce it to distributed power sources for business purposes and industrial applications to hospitals, hotels, banks, data centers, etc. The specifications of the system are shown in Table 1. In fiscal 2015, we are going to promote introduction of the SOFC-MGT hybrid system as a sample machine on the market for customers' evaluation. Toward the start of its full-fledged introduction on the market in 2017, we are going to make efforts to improve durability, transportability, etc., based on evaluations and findings obtained with the sample machine, improve the system specifications to increase marketability, and bring down costs.

4. Approaches to a hydrogen society

4.1 Multi-energy station (QuatroGen)

Towards a future low-carbon society/hydrogen society, operations using a hybrid system as noted below are under examination. The SOFC generates electricity and heat using hydrogen and carbon dioxide that are produced by internal reforming of city gas as shown in Figure 9 (a). In addition, as shown in Figure 9 (b), some of the hydrogen produced by internal reforming may be directly extracted and used without being used for electricity generation. Therefore, electricity, heat and hydrogen can be simultaneously supplied, making it possible to realize QuatroGen, which also supplies city gas as fuel. By applying this mechanism to hydrogen stations, fuel can be simultaneously supplied not only to FCVs (fuel cell electric vehicles), but also to low carbon vehicles such as EVs (electric vehicles) and CNGVs (compressed natural gas vehicles). As a result, an increase in station profitability can be expected (Figure 9 (c)).
4.2 Local production of energy for local consumption (use of renewable energy)

It is expected that digestive gas generated at sewage treatment plants in urban areas can be used for the generation of electricity. Furthermore, methane generally constitutes about 60% of digestive gas. Accordingly, it is also considered that the use of the CO₂ separation technique enables high-efficiency digestive gas power generation using high-purity methane as fuel. The application of the aforementioned Quatrogen enables the production of "hydrogen produced in urban areas" derived from digestive gas, and therefore, the "local production of energy for local consumption in urban areas" can be expected (Figure 10).

With the creation of these added values through the hybrid system, we would like to accelerate the introduction of SOFC into the market.

5. Conclusion

The Strategic Road Map for Hydrogen and Fuel Cells of the Ministry of Economy, Trade and Industry was developed in June 2014. In the roadmap, the introduction of stationary fuel cells for commercial and industrial use on the market in fiscal 2017 was also explicitly stated. MHPS would like to steadily establish the SOFC-MGT hybrid system and expedite its commercial application, thus greatly contributing to the development of "a safe and sustainable energy/environmental society."

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Efforts toward Introduction of SOFC-MGT Hybrid System to the Market

Figure 9 Image of Quatrogen
(a) Supply of electricity and heat by conventional SOFC
(b) Hydrogen production by internal reforming
(c) Application to a hydrogen station.

Toward a future low-carbon society, the development of the SOFC-MGT hybrid system, in which a Solid Oxide Fuel cell (SOFC) that can generate power with high efficiency and a gas turbine are combined, has been promoted. In a program subsidized by the National Research and Development Agency, New Energy and Industrial Technology Development Organization (NEDO) starting in fiscal 2015, 250 kW-class demonstration systems were set up at four locations in Japan. The verification of durability and demonstrations of start/stop tests and load change tests under an actual load environment were conducted toward introduction to the market, and stable operation was verified. As a result, the introduction of the 250 kW-class systems to the market started in 2017. Furthermore, since fiscal 2015, in another NEDO-commissioned project, the verification of the 1 MW-class system, which has increased capacity, has been conducted, and the demonstration test is currently being conducted at the Nagasaki Works of Mitsubishi Hitachi Power Systems, Ltd. (MHPS).

1. Introduction

Recently, the energy situation in Japan has reached a major turning point, and it seems that awareness of high-efficiency power generation and power security has increased. To strike a balance between CO₂ reduction to mitigate global warming and the stable supply of power, which is indispensable in modern society, it is important to combine an advanced power grid constructed with centralized power sources such as thermal power plants and high-efficiency distributed power sources or new energy sources such as renewable energy in the mix in terms of both quality and quantity. To preserve global energy resources, it is also a necessary and urgent issue to ensure the effective use of fossil fuels through the development and early adoption of high-efficiency power generation systems. In Japan, the industrial sector accounts for more than 40% of all energy consumption, and the consumer and industrial sectors account for slightly more than 60% combined. It is considered that the spread of the use of fuel cells in the commercial field is one effective measure for improving the Japanese energy situation.

MHPS has focused on developing the high-efficiency SOFC hybrid power generation system with a very wide range of power output. The system covers everything from medium-capacity (250 kW class) distributed power sources to large-capacity centralized power sources including Gas Turbine Fuel Cell (GTFC) combined cycle and Integrated Coal Gasification Fuel Cell (ICFC) combined cycle technologies, which are advocated by the "Council for promoting the early achievement of next-generation thermal power generation" of the Ministry of Economy, Trade and Industry.

2. Composition of SOFC-MGT hybrid system

Figure 1 illustrates the structure of a cell stack which is a power generation element of tubular type SOFC. On the outer surface of the substrate tube, which is a structural member made
of ceramics, an element (laminated anode, electrolyte, and cathode) reacting to generate power is formed and an electron-conductive ceramic interconnector connects these elements in series. Several hundred cell stacks are bound to form a cartridge, and several cartridges are contained in a pressure vessel. This is called an SOFC module (Figure 2).

![Figure 1 Structure of cell stack](image)

![Figure 2 Composition of hybrid system](image)

This system consists of the SOFC, Micro Gas Turbine (MGT), recycle blower, etc. Power is generated in the two-stage system of SOFC and MGT. Furthermore, when a waste heat recovery device is installed on the exhaust gas line, it can be utilized as a co-generation system that supplies steam or hot water at the same time (Figure 3).

![Figure 3 Hybrid system](image)

13. Efforts with 250 kW class

In fiscal 2015, under the NEDO-subsidized project “Technical demonstration of commercial system using solid oxide fuel cells,” demonstration tests under an actual load environment were started toward introduction to the market. The demonstration sites consist of four bases: Motomachi Plant of Toyota Motor Corporation, Komaki Plant of NGK Spark Plug Co., Ltd., Sendai Techno Station of Tokyo Gas Co., Ltd., and Technology Center of Taiyo Corporation (Figure 4).

![Figure 4 Operation and planning status for the fuel cell SOFC](image)

In this subsidized project, the respective main subjects/verification items have been set at each site and the demonstration tests are being carried out. The details of the demonstration test at each site are as described below. At each site, the effects of changes in power demand and start/stop operation on the performance and durability are assessed.
- The demonstration system for Toyota Motor Corporation: The start/stop operation test (once a month) is continuing.
- The demonstration system for NGK Spark Plug Co., Ltd.: The continuous durability test is continuing.
- The demonstration system for Tokyo Gas Co., Ltd.: The start/stop operation test (once a week) was conducted 31 times.
- The demonstration system for Taiyo Corporation: The self-sustaining function verification test was completed.

Based on the results of the demonstration tests, the introduction of the 250 kW class system to the market commenced in 2017. The results of the demonstrations at the four sites have been reflected in the models to be introduced to the market. The first commercial system was delivered to the Marunouchi Building owned by Mitsubishi Estate Co., Ltd. and its operation will commence by the end of the current fiscal year. As of August 2018, the installation of the main body has been completed.

For the NEDO Research and Development Project "Research on coal gas application for fuel cell module" which was implemented by Electric Power Development Co., Ltd. (J-POWER), the 250 kW class system was delivered to Wakamatsu Laboratory of J-POWER in fiscal 2017.
4. Status of Demonstration of 1 MW class SOFC-MGT hybrid system

Concerning GTFC, in which SOFC and a gas turbine are combined, the "Technology Roadmap for Next-Generation Thermal Power Generation" developed by the government and private sector committee in July 2015 indicates that the commercialization and mass production of the small-size GTFC (1 MW class) will be promoted to reduce the cost of SOFC. Demonstration projects using small- and medium-sized GTFC (100,000 kW class) will be conducted toward the establishment of the technologies around 2025.

In fiscal 2016, under the NEDO commissioned project "Gas turbine fuel cell combined cycle (GTFC) technology development", the verification of the small-sized GTFC (output: 1 MW class, operating pressure: 0.6 MPa class), which has a capacity/pressure condition closer to the small- and medium-sized GTFC (output: 100,000 kW class, operating pressure: 1.0 to 1.5 MPa class) compared with the conventional unit (output: 250 kW class, operating pressure: 0.2 MPa class) started at MBPS Nagasaki Works, toward introduction to the market. In the actual 1 MW class system, two SOFC module units will be installed. In this research and development project, only one SOFC module unit is half the number of units required for 1 MW class, to conduct the test, and is called a half module (Figure 5).

As of September 2018, the installation of the half module demonstration unit has been completed and the half module unit is being adjusted in the trial operation before power generation (Figure 6). In the future, the demonstration operation of the half module unit will be conducted to study the system specifications of an actual 1 MW class unit with its marketability being considered.

![Diagram: Compositions of the actual 1MW class unit and the demonstration unit](image)

![Diagram: State of the installed half-module demonstration 1MW class unit](image)

5. Conclusion

MBPS positions the SOFC hybrid power generation system as a key effective technology for making the reduction of CO₂ emissions and a stable supply of power compatible.

The 250 kW class demonstration units were installed at four sites in Japan in fiscal 2015, and the demonstration was conducted toward introduction to the market and its stable operation was verified. Based on the results, the system's introduction to the market started in fiscal 2017. The first commercial unit has already been delivered to the Minagishi Building owned by Mitsubishi Estate Co., Ltd. and its operation will commence by the end of the current fiscal year.

Since fiscal 2016, the verification of the 1 MW class unit, which has an increased capacity compared with the 250 kW class unit, has been carried out. Currently, the demonstration test is being conducted at MBPS Nagasaki Works. We are willing to steadily establish the technologies through this demonstration test, promote early commercialization, and greatly contribute to the establishment of a "safe and sustainable energy environment society."

(Acknowledgment)

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References