Periodic Table of the Elements

Atomic number — 1
Element symbol — H
Element name — Hydrogen
Atomic weight — 1.008

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.07	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.87	23 V Vanadium 50.94	24 Cr Chromium 52.00	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.63	33 As Arsenic 74.92	34 Se Selenium 78.97	35 Br Bromine 79.90	36 Kr Krypton 83.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.95	43 Tc Technetium (99)	44 Ru Ruthenium 101.1	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
55 Cs Cesium 132.9	56 Ba Barium 137.3	57-71 Lanthanoid	72 Hf Hafnium 178.5	73 Ta Tantalum 180.9	74 W Tungsten 183.8	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium (210)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinoid	104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (271)	107 Bh Bohrium (272)	108 Hs Hassium (277)	109 Mt Meitnerium (276)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (280)	112 Cn Copernicium (285)	113 Nh Nihonium (278)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (293)	118 Og Oganesson (294)

57 La Lanthanum 138.9	58 Ce Cerium 140.1	59 Pr Praseodymium 140.9	60 Nd Neodymium 144.2	61 Pm Promethium (145)	62 Sm Samarium 150.4	63 Eu Europium 152.0	64 Gd Gadolinium 157.3	65 Tb Terbium 158.9	66 Dy Dysprosium 162.5	67 Ho Holmium 164.9	68 Er Erbium 167.3	69 Tm Thulium 168.9	70 Yb Ytterbium 173.0	71 Lu Lutetium 175.0
89 Ac Actinium (227)	90 Th Thorium 232.0	91 Pa Protactinium 231.0	92 U Uranium 238.0	93 Np Neptunium (237)	94 Pu Plutonium (239)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (252)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Source : "SCIENCE & TECHNOLOGY WEEK" (MEXT) https://stw.mext.go.jp

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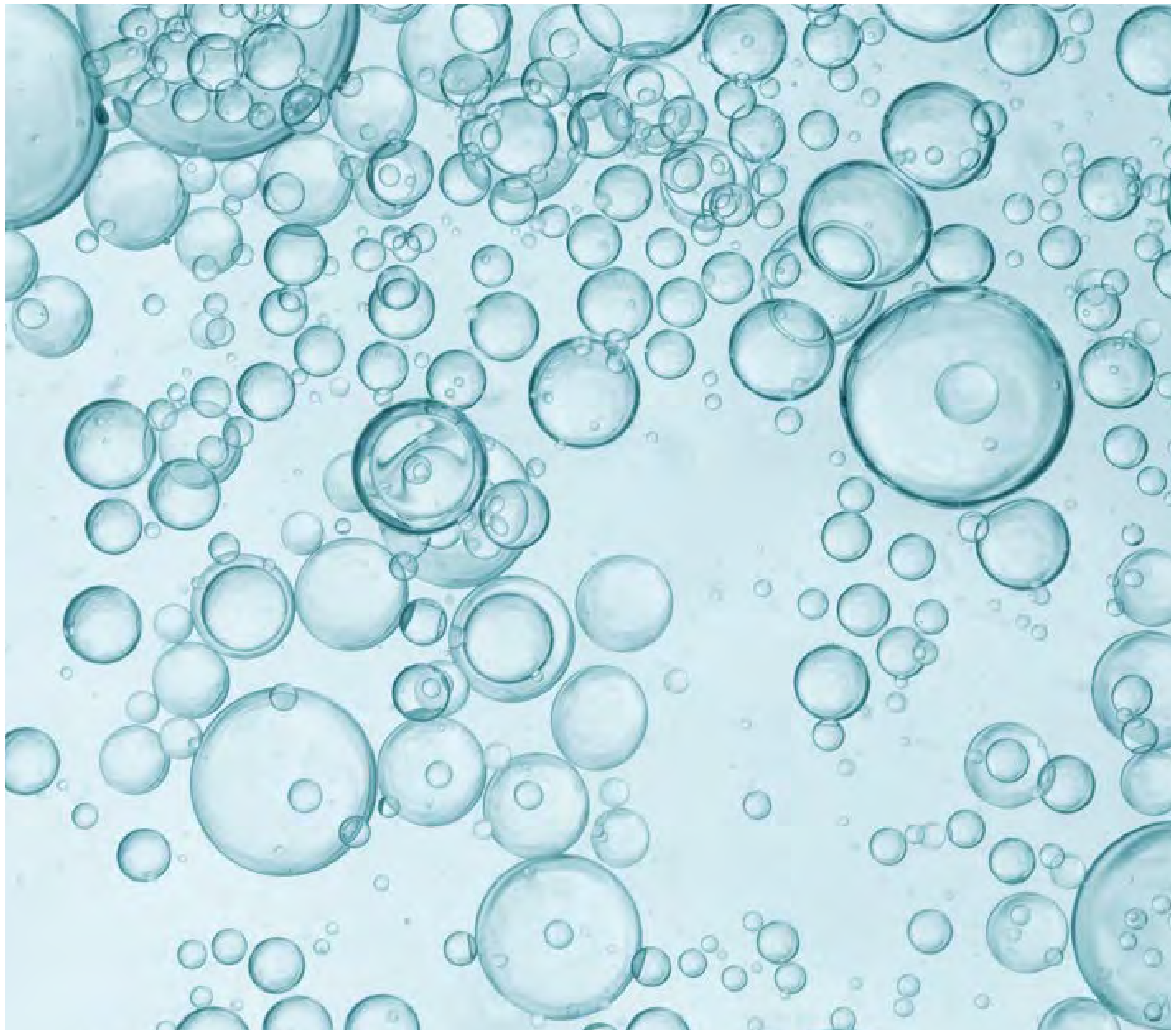
MITSUBISHI POWER

HYDROGEN POWER GENERATION HANDBOOK



Mitsubishi Power is a power solutions brand
of Mitsubishi Heavy Industries.

MOVE THE WORLD FORWARD MITSUBISHI HEAVY INDUSTRIES GROUP

INTRODUCTION

Hydrogen—atomic 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 CO_2 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.

Hydrogen is a clean energy source that does not emit CO_2 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.

INDEX

Notes on the Publication of the Revised Edition (second edition) of the *Hydrogen Power Generation Handbook*

Two year has passed since Mitsubishi Power published the first edition of the *Hydrogen Power Generation Handbook* in June 2019.
Since then, the drive towards a carbon-neutral society and hydrogen energy, which is expected to contribute to its realization, has been growing stronger.
In this revised edition (2nd edition), we introduce new trends and summarize hydrogen-related engineering information as a compendium at the end of the handbook. We hope this book will prove useful for all its readers.

Realizing a carbon-neutral society

Decarbonization with a power-generation technology that emits no CO_2.

The world faces a tipping point that could be called the "decarbonization revolution." Energy industries around the world have taken a major turn toward decarbonization, and the leaders of many countries have expressed their determination to achieve carbon neutrality.
At the same time, there is an urgent need for a stable supply of electricity to meet the increasing power demand due to population growth and economic development. Increasing supply of renewable energy such as wind and solar power also demand a stable power supply as they depend on natural conditions for their output.

In collaboration with other Mitsubishi Heavy Industries Group companies, Mitsubishi Power has set a course for energy transition-solutions for the expansion of renewable energy sources without compromising economic efficiency. Mitsubishi Power has also laid out a road map for technological development to achieve this goal. As a leading provider of power generation technologies and solutions, Mitsubishi Power is working to apply non-CO_2 emitting fuels such as hydrogen and ammonia to power generation for reducing CO_2 emissions and decarbonizing thermal power generation. We aim to achieve this through the further development of highly efficient power generation technologies and environmental technologies that we have fostered over the years.

The hydrogen power generation technology we introduce in this handbook replaces natural gas, the fuel for gas turbine combined cycle (GTCC) power generation, which currently emits the least amount of CO_2 among thermal power generation systems, with hydrogen, which does not emit any CO_2 during combustion. Mitsubishi Power's hydrogen power generation technology achieves a low cost of installation by maximizing the use of existing facilities and converting them for hydrogen power generation.

A 400MW class GTCC power 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.

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. In addition to supplying equipment, Mitsubishi Power is also involved in the entire fuel value chain, from the production, transportation, storage, and utilization of carbon-free hydrogen and ammonia. With our proven technological capabilities and our promotion of decarbonized energy, Mitsubishi Power will continue to contribute to the protection of the global environment and move the world closer to a carbon-neutral society.

Accelerating the shift to decarbonization.
Driving the potential of hydrogen generation.

Accelerated effort towards a Hydrogen Society

On October 14, 2020, the online Special Event of Hydrogen Energy Ministerial Meeting was held for concerned countries to work together to further promote the use of hydrogen on a global scale. Representatives from 23 different countries, regions, and international organizations, as well as representatives of companies participated in the event. Mitsubishi Power, a pioneer that is working on the practical application of hydrogen, sent its executive senior vice president assistant to the president, executive officer and CTO (at that time), Muyama to the event. His talk, titled "Hydrogen Power Generation towards Beyond Zero Society," stressed the importance of hydrogen power generation and introduced Mitsubishi Power's activities around the world.

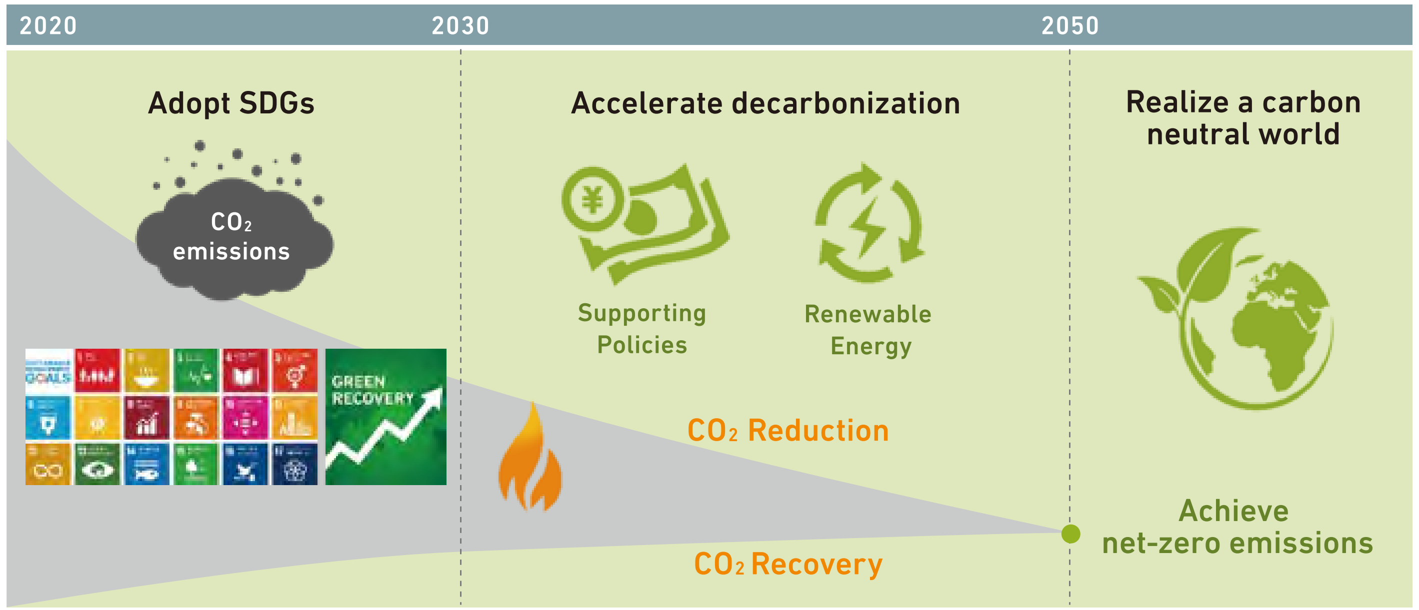
There are increasing number of examples of hydrogen application coming out of Europe. In January 2017, the Hydrogen Council, a global initiative to position hydrogen as the new energy was set up, which started with 13 world-leading companies in energy, transport, and manufacturing. As of January 2021, over 109 companies have joined the initiative. Mitsubishi Power is participating in the initiative as a supporting member.

The world is now aligned to become a Hydrogen Society

In 2019, the EU announced their action plan to achieve the carbon-neutral target by 2050. On October 26, 2020, Prime Minister Suga declared that by 2050, Japan aims to become a decarbonized nation with zero greenhouse gas emissions. A month earlier, President Xi Jinping of China announced that they aim to go carbon-neutral by 2060. And in January 2021, the new U.S. president, Joe Biden signed an executive order to rejoin the Paris Treaty. The world is now picking up the pace to achieving carbon-neutrality with increasing usage of hydrogen to produce CO_2 free energy.

The Roadmap towards a Carbon-Neutral Society

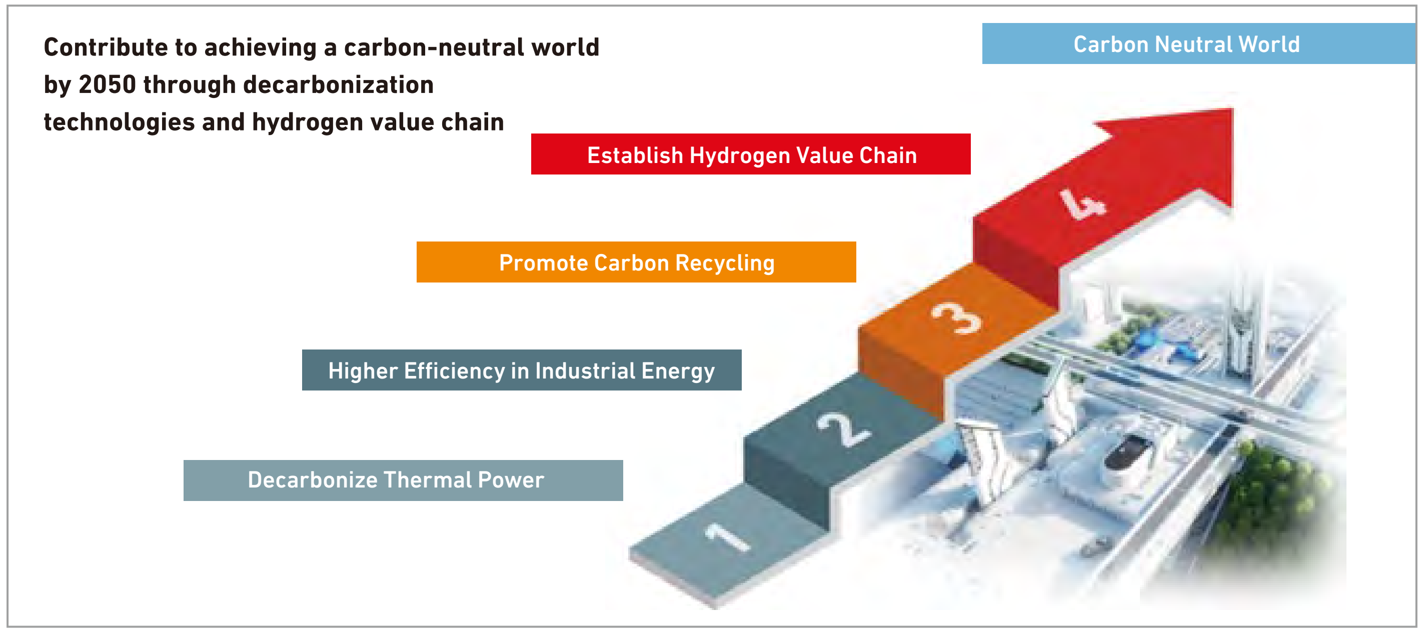
At present, the majority of energy production in the world relies on thermal power using an affordable, safe, and stable fossil fuel. To realize the carbon-neutral society in the future, Mitsubishi Power will continue to support the current power generating methods with a major focus of reducing CO_2 emissions and driving carbon capture. At the same time, it will continue to promote the use of renewable energy as well as mixed combustion of hydrogen or ammonia which produces no CO_2. In addition, Mitsubishi Power will continually increase the ratio of hydrogen to 100%, eventually removing all carbon emissions, enabling us to reach our goal.



The world will change to a carbon-neutral society by 2050 through the advancement of carbon reduction and capture technologies.

Energy Transition and Solution

Mitsubishi Heavy Industries (MHI) Group identifies the four steps to a carbon-neutral society as: "Decarbonization of Thermal Power Generation," "Efficient Energy Use in Industries," "Promoting Carbon Recycle," and "Developing the Hydrogen Value Chain." MHI aims to offer solutions for each step along the way. We are already a part of several large-scale global projects and continue to support their success.



Mitsubishi Power's Hydrogen Project

Converting Natural Gas Combustion Turbine into 100% Hydrogen Capable

Mitsubishi Power is taking part in the hydrogen conversion project at natural gas Gas Turbine Combined Cycle (GTCC) at the Magnum Power Plant in the Netherlands. The project aims to convert one of the three existing M701F gas turbines to a 100%-hydrogen firing device and ultimately drive demand for hydrogen amongst thermal power businesses. MHI Group also has the Carbon dioxide Capture and Storage (CCS) technology, essential for supplying carbon-free (blue) hydrogen, playing a vital role towards a hydrogen society.

Public-private green hydrogen strategy for the region

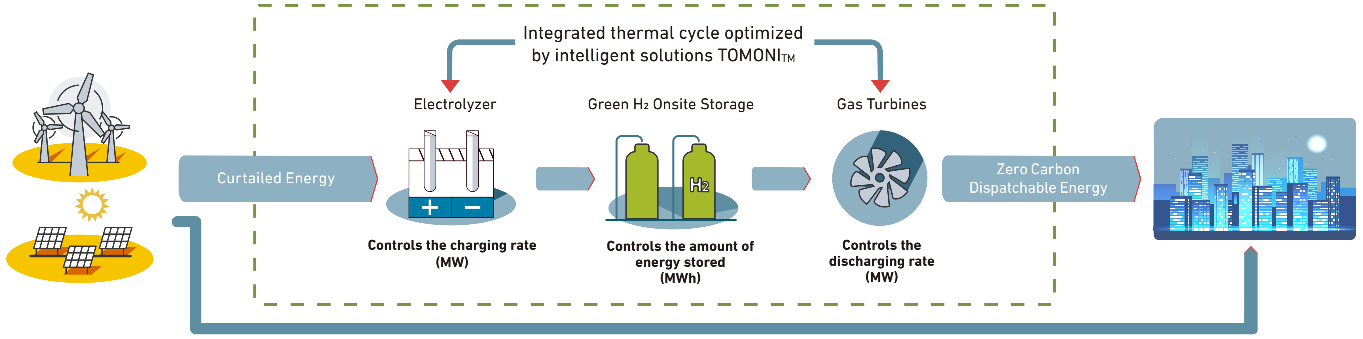
Mitsubishi Power is also instrumental in the launch of the Western Green Hydrogen Initiative (WGHI) in the Western Region of the U.S. In addition, two Canadian provinces are part of the Initiative supporting the green hydrogen strategy for the region that includes large-scale green-hydrogen storage. They expect to reinforce the reliability and independence of the energy across the Western region by actively adopting green hydrogen, creating jobs locally, avoiding creation of uneconomical grids, re-using existing infrastructure, and diversifying energy across multiple sectors are amongst other benefits.

Vattenfall's Magnum GTCC power plant

The world's first integrated green hydrogen solution

Mitsubishi Power has also begun providing the world's first integrated green hydrogen solution that includes power balancing and energy storage across multiple projects in the U.S. The integrated green hydrogen solutions are the Hydaptive™ integrated package and Hydaptive™ Storage package. The Hydaptive™ package provides renewable energy flexibility by acting as a near-instantaneous power balancing resource that greatly enhances the ability of a simple cycle or combined cycle power plant to ramp output up and down to provide grid balancing services. It integrates a hydrogen and natural gas fueled gas turbine power plant with electrolysis to produce green hydrogen using 100% renewable power and onsite storage of green hydrogen. Patent-pending TOMONI™ software and controls enable rapid load response by integrating operations of the gas turbines and the electrolysis plants. The Hydaptive™ Storage package combines the Hydaptive™ package with access to a large-scale off-site hydrogen production and storage infrastructure to sustain the supply of carbon-free green hydrogen, during the peak energy demand period. The two combined will solve the challenges faced by power plants operators and power transmission companies by integrating renewable energy, gas turbine, green hydrogen, and fuel storage technology, etc., to drive the momentum towards an 100% carbon-free power generation.

HYDAPTIVE™ STANDARD FLEXIBILITY PACKAGE

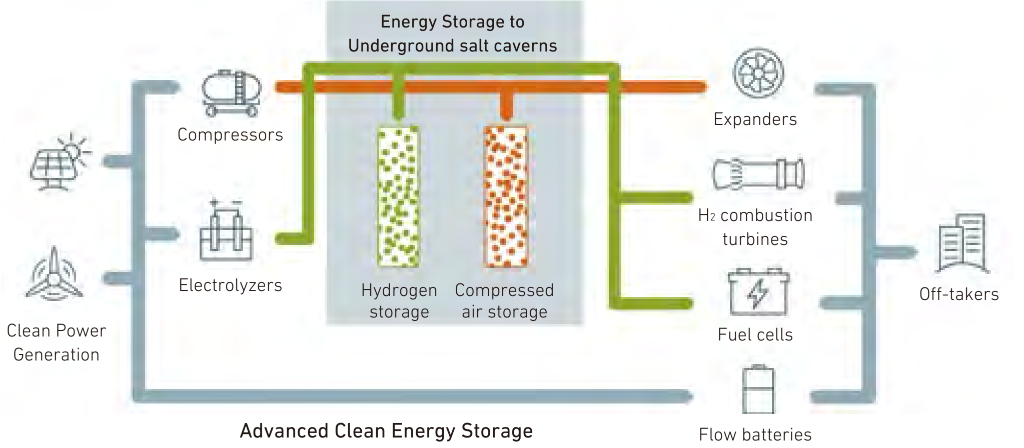


The Hydaptive™ package accelerates the path toward 100% carbon-free power generation

- Technology adapts as the grid needs larger amounts of energy storage
- Standard packages reduce the cost and complexity of decarbonization
- Integrated technology adds flexibility to existing dispatchable power generation

Storing green hydrogen in salt domes

Together with Magnum Development, Mitsubishi Power is driving the Advanced Clean Energy Storage Project. Using power generated from wind and solar power, the electrolyzer produces green hydrogen which is then stored in an underground salt dome controlled by Magnum Development. Hydrogen is then provided to the power plants as needed. The salt dome has the capacity to store the equivalent of 150GWh of energy.



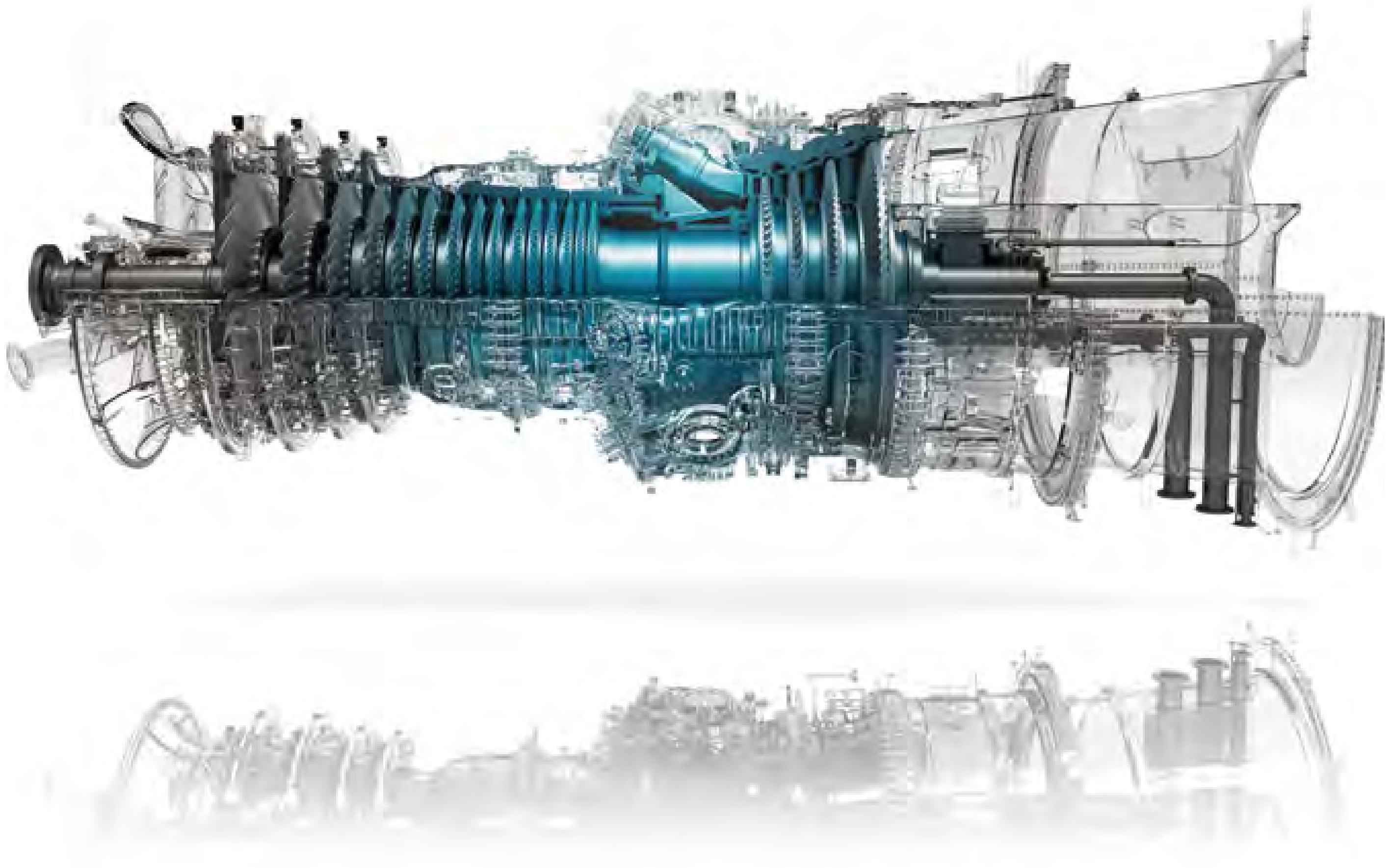
▨ Electricity
🟩 Hydrogen
🟧 Compressed air

Energy Storage Capacity	150GWh
Location	Utah, USA

This project was launched in May 2019. Renewable hydrogen will be stored in salt caverns owned by Magnum Development LLC and be delivered to power generation, industrial & transportation sectors.

Mitsubishi Power has cutting-edge hydrogen combustion technologies, and its hydrogen gas turbine requires minimum modification to the existing infrastructures at the power plants. In 2018, Mitsubishi Power had already achieved 30% hydrogen co-combustion and aims to make this 100% hydrogen by 2025. Large-scale hydrogen generation is a crucial piece in creating a truly sustainable society across the globe. Cost is a challenge today, however as technology evolves, we will continue to reduce the cost of green hydrogen. Mitsubishi Power is fully committed to playing a significant leadership role in addressing this global obligation and deliver technological advancements to attain a carbon-free hydrogen society.

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

Coping with the conflict between robust energy demand and global decarbonization

“Energy is the cornerstone of industry,” said Satoshi Tanimura—Chief Engineer, GTCC Business Division, Energy Transition & Power Headquarters, Energy Systems, Mitsubishi Heavy Industries, Ltd. —a leader in the development of hydrogen-fueled gas turbines that feature CO_2-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 CO_2 emissions. They want electricity, but they don’t want the attendant CO_2 emission. It’s the mission of engineers to pursue thermal power generation that emits zero CO_2.”

In Japan, the country’s primary energy is mainly converted into electricity, accounting for 46% of all energy. Thermal power accounts for 77% of the electricity supply volume with the fuel type break-down being as follows: LNG at 38%; oil and petroleum at 7%; and coal at 32% (as of 2018).

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 Tanimura. “CO_2 emissions per unit with gas turbine combined cycle (GTCC) plants, which combine gas and steam turbines, are less than half of those generated by coal-fired thermal power. But it doesn’t change the fact that CO_2 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 CO_2 reduction.”

A clear roadmap to the achievement of a hydrogen society

Satoshi Tanimura’s focus is on thermal power generation that does not emit CO_2. “Our 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 Tanimura. “That’s where Mitsubishi Power comes in—we conceived a hydrogen power generation system that utilizes existing gas turbine facilities.”

Tanimura 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 1600°C), and it offers a reduction of about 10% in CO_2 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 Tanimura had to overcome.

Successful 30% hydrogen combustion represents a major step toward a hydrogen society

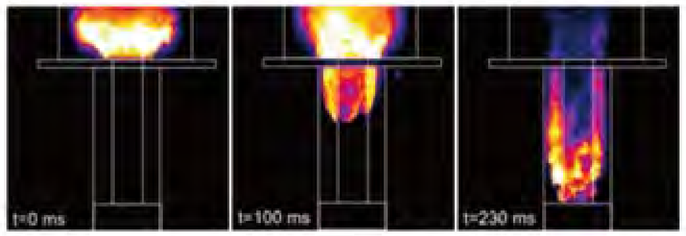
Easy-to-burn hydrogen and the struggle for safety
Hydrogen—atomic number 1—is the first element students learn about, and the lightest of all elements. Hydrogen is clean—when it burns, it produces only water. Conversely, it is a substance that is difficult to handle. It burns violently, so the idea of 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.

The type of fuel co-firing presents a challenge in terms of flashback prevention. Mitsubishi Power has successfully applied 100% hydrogen through a process called "diffusion combustion" where the fuel and air are put in the combustor separately. However, this technology results in a high NOx value. On the other hand, "Pre-Mix (DLN) combustion," where the fuel and air are mixed prior to being put into the combustor is possible with a low NOx count. However, fuel that contains hydrogen is prone to flashback. To resolve this, improvements were made to the swirler 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.



Source: University of Michigan at the 2014 University Turbine Systems Research Workshop

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 combusting 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 location and method of fuel burning, we continue to incorporate 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 CO_2-free power generation system and ultimately to the realization of a carbon-free society.

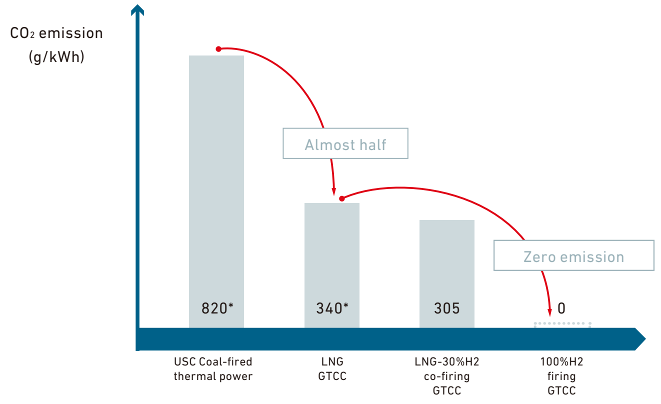
Of utmost importance to power plant operators—users of the gas turbine—are safety, stable supply, and cost. In providing a steady supply of electricity, naturally a stable supply of fuel is a requirement, along with the mitigation of outages, longer intervals between periodic inspections, and low operation 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 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 CO_2-free society—100% hydrogen thermal power generation
The values below are emissions per unit indicating CO_2 emission volume when generating 1kWh of electricity.

Standard coal-fired power generation: 863g-CO_2 /kWh
Ultra-supercritical (USC) coal-fired power generation: 820g-CO_2 /kWh
GTCC power generation: 340g-CO_2 /kWh
Hydrogen 30% mixed-combustion gas turbine: 305g-CO_2 /kWh



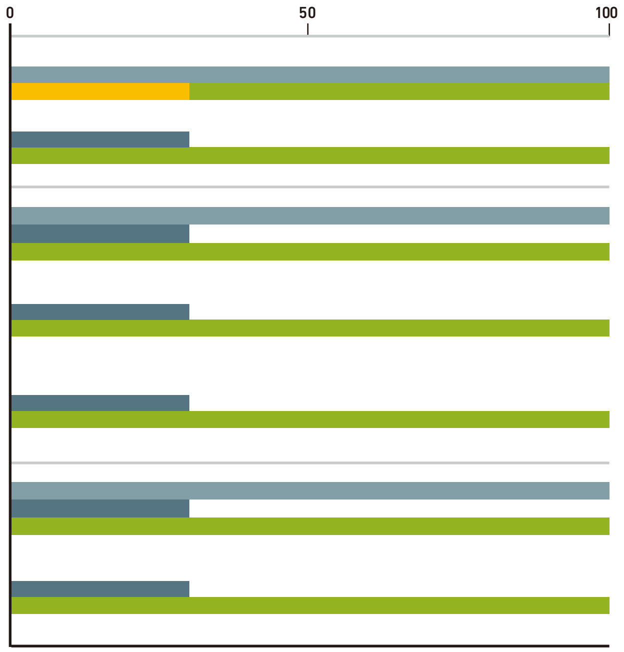
*Source: METI Web Site(https://www.meti.go.jp/committee/kenkyukai/energy_environment/jisedai_karyoku/001_haifu.html)

Development Status of Hydrogen Combustion Technology
As Mitsubishi Power has successfully achieved mixed-combustion power generation at 30% hydrogen, Satoshi Tanimura's next objective is CO_2-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 Tanimura. "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 pushes 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 jets 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 combustor, 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 the kind of challenges engineers are wrestling with in the battlefield of development.

GT Model		Combustor Type	H_2 (vol%)
H-25	60/50Hz	Diffusion Multi-Cluster (DLN*)	100 30→100 (target)
H-100	60/50Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)
M501F	60Hz	Diffusion Pre-Mix (DLN) Multi-Cluster (DLN)	100 30 100 (target)
M501GAC	60Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)
M501J M501JAC	60Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)
M701F	50Hz	Diffusion Pre-Mix (DLN) Multi-Cluster (DLN)	100 30 100 (target)
M701J M701JAC	50Hz	Pre-Mix (DLN) Multi-Cluster (DLN)	30 100 (target)



* DLN: Dry Low NOx

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; a supply source and way to transport the hydrogen to a pipe-less Japan must be considered; technology to extract hydrogen from the source material, and technology to collect and retain the CO_2 emitted during the process must be developed. 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 Tanimura, when taking a comprehensive perspective of the practical use of hydrogen. "In Japan, we simply assume we'll 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 CO_2 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.

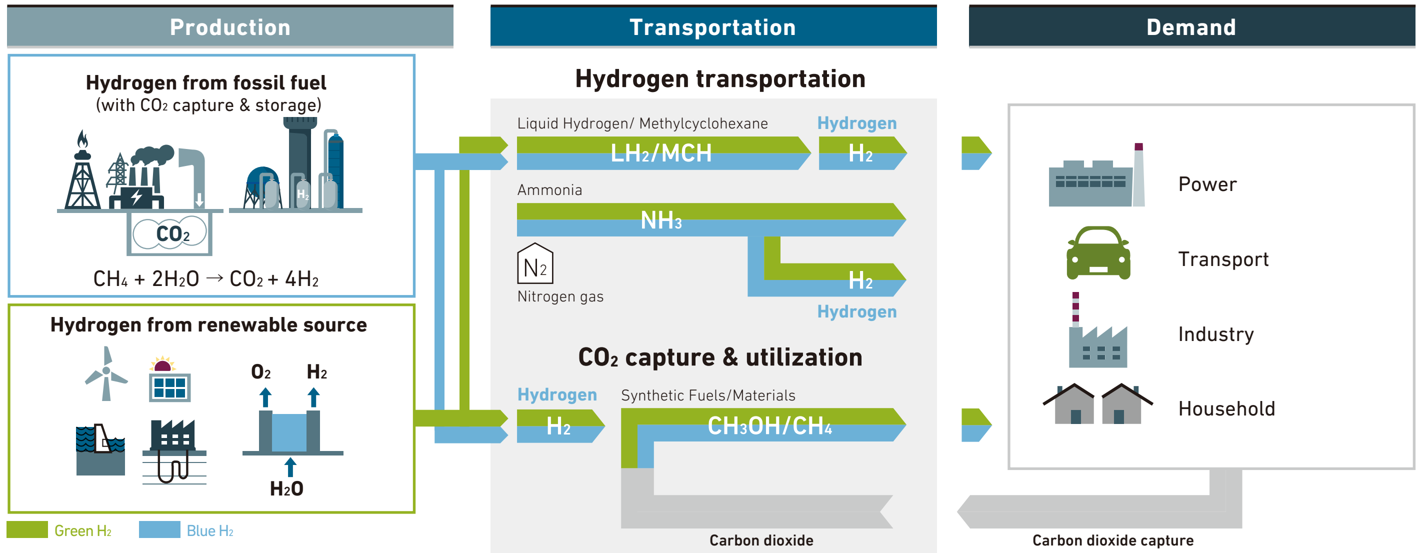
As engineers developing gas turbines, Tanimura and his colleagues have a clear understanding of the need for a comprehensive hydrogen usage plan. "In Japan, as we don't have a developed pipeline, naturally the transport of hydrogen constitutes a major issue," Tanimura said. "As of now, there are schemes 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, methyl cyclohexane (MCH), and ammonia (NH_3) 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 Tanimura.

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," Tanimura 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 60%, it requires 1.4 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 hydrogen. This is another reason hydrogen gas turbines will drive the forthcoming hydrogen society," he said.

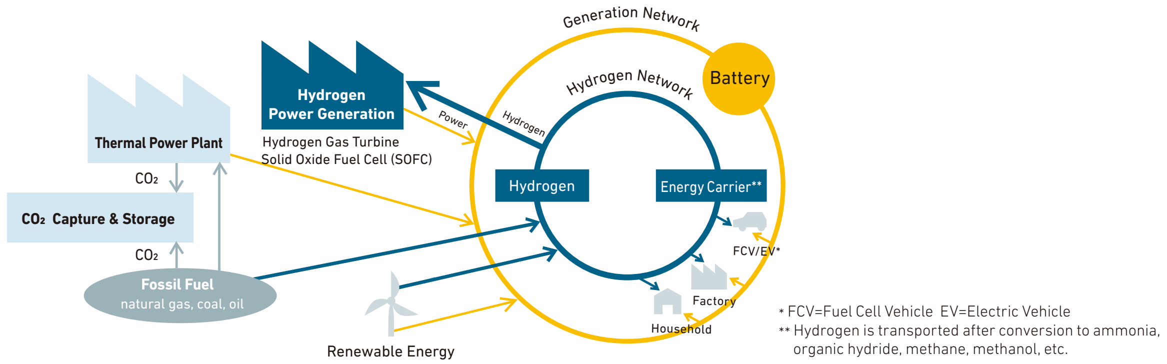
Human beings discovered fire and began using it purposefully about 500,000 years ago. And now we are about to obtain CO_2-free combustion technology that will turn into energy that supports society.

Tanimura and his colleagues remain dedicated to achieving 100% hydrogen combustion technology by 2025.

Overview of Global Hydrogen Supply Chain



The relation between Mitsubishi Power's hydrogen power generation technology and the hydrogen network



* FCV=Fuel Cell Vehicle EV=Electric Vehicle
** Hydrogen is transported after conversion to ammonia, organic hydride, methane, methanol, etc.

Satoshi Tanimura

Chief Engineer, GTCC Business Division,
Energy Transition & Power Headquarters, Energy Systems,
Mitsubishi Heavy Industries, Ltd.

An expert in gas turbine combustor development, from basic design to combustion adjustment, his focus. Tanimura joined Mitsubishi Heavy Industries in 1986 and was assigned to the Gas Turbine Engineering Department, where he pursued the development of large-scale gas turbine combustors and also served as an engineer. He worked on the development of a 1300°C-class gas turbine combustor, and spearheaded efforts to develop low-NOx technology for the 1500°C- and 1600°C-class models.

TECHNICAL REVIEW

As a leading provider in the fields of thermal power generation and environmental technology, Mitsubishi Power is developing high efficiency power generation technologies. This includes the field of gas turbine power generation technologies where Mitsubishi Power has made possible hydrogen-mixed combustion and is in the process of taking the technology to it's next phase. Energy market needs are diversifying and Mitsubishi Power is working to meet such decentralized needs. We will now introduce our large-scale hydrogen gas turbines, which have potential for mass consumption, and fuel cells that are able to efficiently employ a diverse array of fuel types including hydrogen as dispersion type power sources through the Mitsubishi Heavy Industries technical review.

Hydrogen Gas Turbine

- Development of Hydrogen and Natural Gas Co-firing Gas Turbine
  Hydrogen-mixed combustion technology in high efficiency gas turbines.
  Achievement of 10% reduction in CO_2 emissions compared to prior gas fired power generation.
- Hydrogen-fired Gas Turbine Targeting Realization of CO_2-free Society
  Hydrogen single fuel firing technology in high efficiency gas turbines.
  We lead the field in creating an international hydrogen supply chain to achieve a CO_2-free Hydrogen Society.
- Validation Results of 1650°C Class JAC Gas Turbine at T-point 2 Demonstration Plant
  Verification results of the 1650°C class JAC gas turbine, applying the combustor forced air-cooling system, ultra-thick TBC, and high pressure ratio compressor as its main technologies.

Fuel Cells

- Development of Next-Generation Large-Scale SOFC toward Realization of a Hydrogen Society
  Our fuel cell power generation technology meets today's decentralized energy source needs.
  We contribute to the realization of a "safe and sustainable energy environment based society."
- Efforts toward introduction of SOFC-MGT Hybrid System to the Market
  Development with the goal to achieve a Low Carbon Society.
  The 250kW class have been empiracally demonstrated. We have begun testing the 1MW class.

Source: Mitsubishi Heavy Industries Technical Review
Authors and affiliation names shown here are true and accurate at the time of writing

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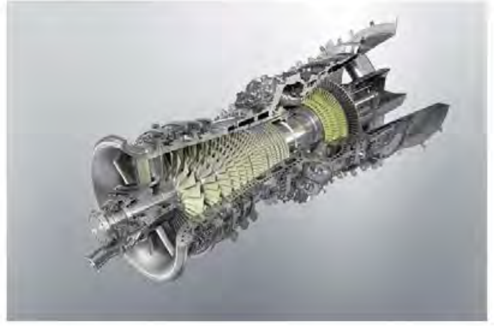
Mitsubishi Heavy Industries Technical Review Vol. 55 No. 2 (June 2018)

Development of Hydrogen and Natural Gas Co-firing Gas Turbine



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The nonuse 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 30 vol% of hydrogen. This co-firing makes it possible to reduce CO_2 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 40.5 GW annually since 2011 and is predicted to expand to a maximum of about 2,500 GW in 2030. 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 CO_2 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 CO_2, the amount of CO_2 generated during power generation can be reduced by replacing a part of the hydrocarbon components in the fuel with hydrogen.

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Figure 1 shows the hydrogen rich fuel operating experience in the MHI Group. Due to the fuel use of off gas (exhaust gas generated in refinery plants, etc.), the use results include fuels with various hydrogen content ratios. In addition, at the time of participation in World Energy NETWORK, the MHI Group succeeded in a combustion test of pure hydrogen fuel firing. However, these are results from small power generation facilities. In order to realize the full-scale introduction of hydrogen in the power generation field, large-scale and high-efficiency energy conversion methods are required like the current natural gas.

Therefore, the MHI Group is promoting the development of a large gas turbine capable of co-firing natural gas and hydrogen at the introduction stage of hydrogen infrastructure. This paper presents the outline and future prospects of technological development enabling hydrogen co-firing.

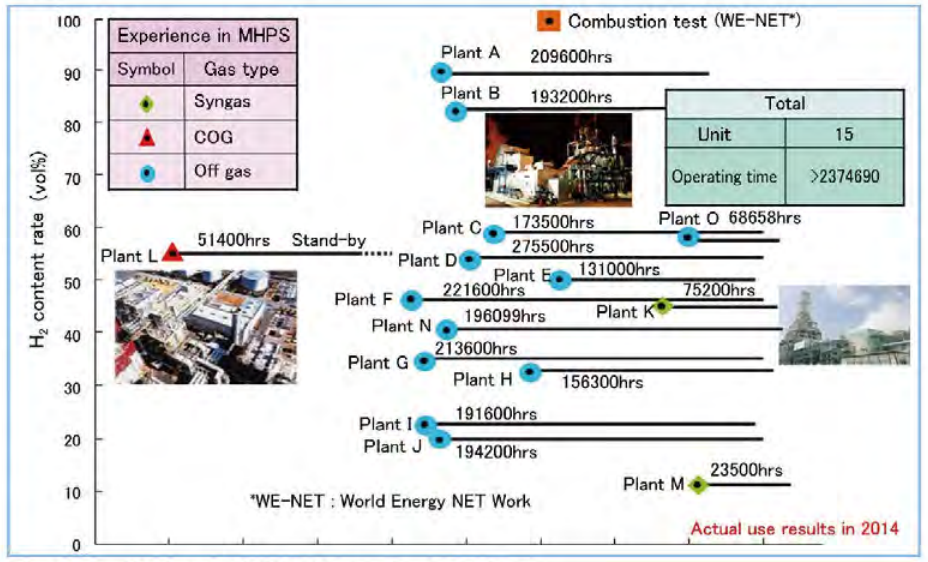


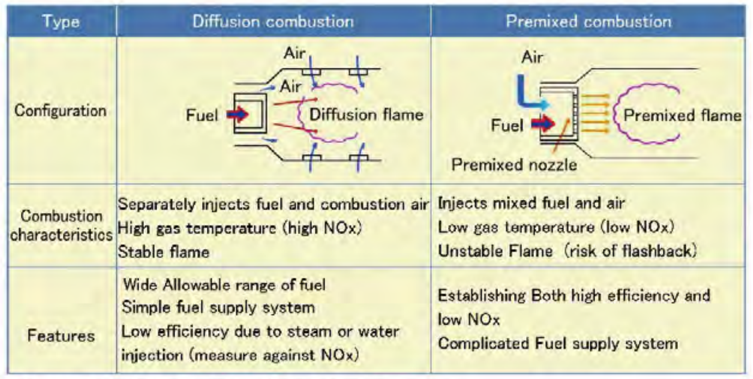
Figure 1 Hydrogen rich fuel operating experience

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 (hereinafter referred to as the combustion speed) is higher than the speed of the fluid (hereinafter 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.



Type	Diffusion combustion	Premixed combustion
Configuration		
Combustion characteristics	Separately injects fuel and combustion air High gas temperature (high NOx) Stable flame	Injects mixed fuel and air Low gas temperature (low NOx) Unstable Flame (risk of flashback)
Features	Wide Allowable range of fuel Simple fuel supply system Low efficiency due to steam or water injection (measure against NOx)	Establishing Both high efficiency and low NOx Complicated Fuel supply system

Figure 2 Comparison of combustion type

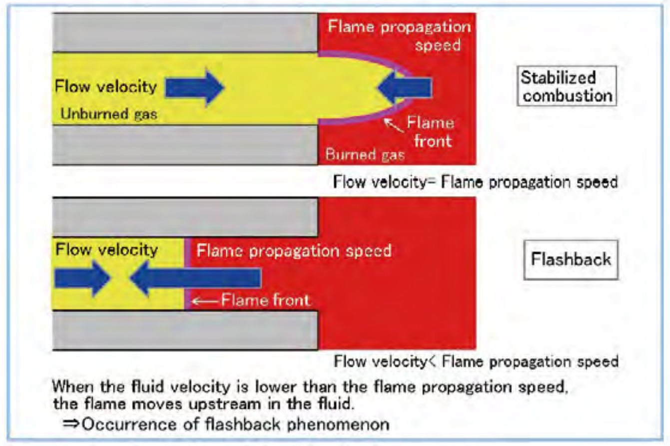


Figure 3 Overview of flashback phenomenon

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.

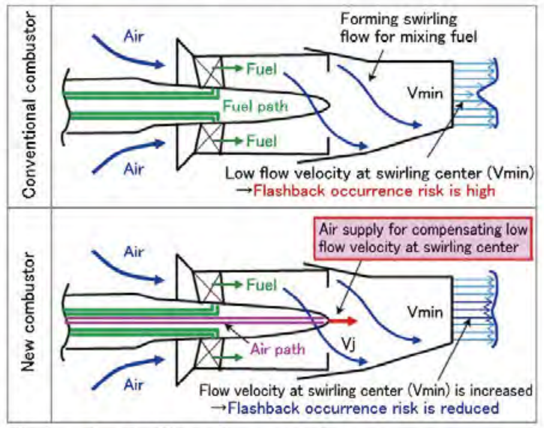


Figure 4 Outline of new combustor

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 φ5 μ I-type linear probe made of tungsten) for the flow velocity measurement and by achieving high time 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.

Figure 5 Photograph of air flow test equipment

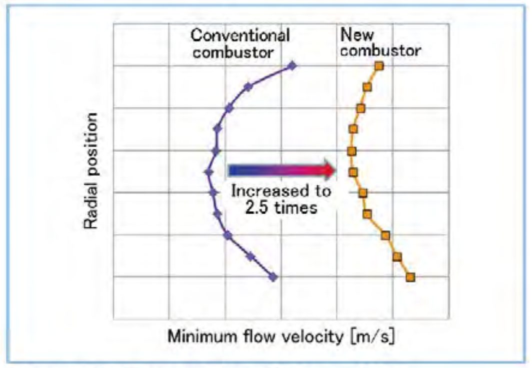


Figure 6 Comparison of flow velocity distributions in region close to swirling center

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 combustion test, an actual pressure combustion test facility at the Mitsubishi Hitachi Power Systems, Ltd. Takasago Plant was used. **Figure 7** gives the facility configuration of the actual pressure combustion test equipment. The high pressure and high temperature air used in the combustion test equipment is supplied by a two-shaft gas turbine and is guided to a test sector simulating the casing shape of the gas turbine (for one combustor) installed in the combustion test pressure vessel. The exhaust gas after combustion is discharged from the exhaust tower together with the exhaust gas of the compressor driving gas turbine. In order to simulate the fuel of the actual plant, hydrogen is added in the upstream part of the natural gas supply line and supplied to the actual pressure combustion test facility. Since hydrogen is added sufficiently upstream of the test facility, it is evenly mixed with natural gas before reaching the combustor.

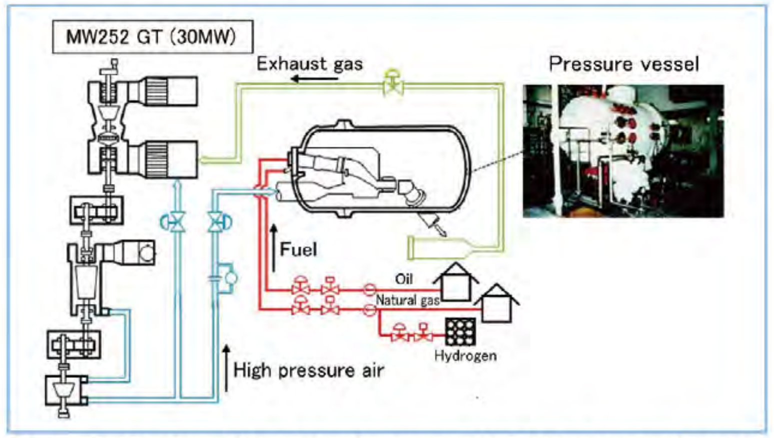


Figure 7 Configuration of actual pressure combustion test equipment

Figure 8 shows the change in NOx with respect to the hydrogen mixing ratio under conditions equivalent to the rated conditions of a turbine inlet temperature 1600-degree class gas turbine. It was confirmed that as the hydrogen mixing ratio increased, NOx tended to increase slightly. This is thought to be because of the fact that the combustion speed increased due to the mixing of hydrogen in the fuel and the flame position in the combustor moved upstream. However, it was confirmed that even under the conditions with the hydrogen mixing ratio of 30 vol%, NOx was within the operable range. **Figure 9** provides the change in combustion instability pressure level under the same conditions. It was confirmed that combustion instability pressure level was not significantly affected by the change in the hydrogen mixing ratio. From the above results, it can be considered that gas turbine operation under up to 30 vol% hydrogen co-firing conditions without the occurrence of flash back or a significant increase in the internal pressure fluctuation is made possible by applying the new combustor, even though there is an increase in NOx due to the increase in the hydrogen mixing ratio.

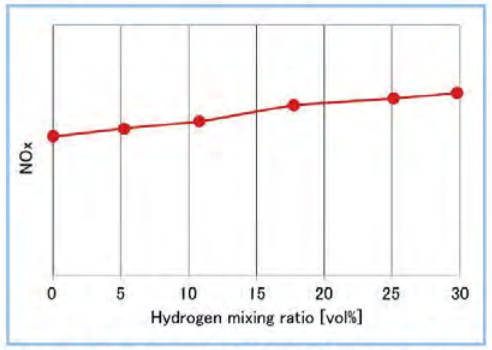


Figure 8 Change in NOx with respect to hydrogen mixing ratio

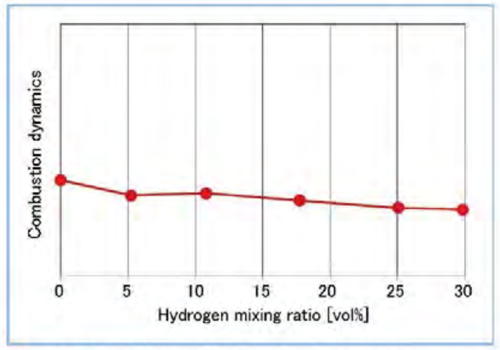


Figure 9 Change in internal pressure fluctuation level with respect to hydrogen mixing ratio

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 reselect 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 CO_2 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 to promote the development of a gas turbine that enables further higher concentration hydrogen co-firing for plant verification operation targeted to be implemented in fiscal 2025.

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Mitsubishi Heavy Industries Technical Review Vol. 55 No. 4 (December 2018)

Hydrogen-fired Gas Turbine Targeting Realization of CO_2-free Society

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HIDEFUMI ARAKI[*2] **NORIAKI SENBA**[*3]

SATOSHI TANIMURA[*4]

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 CO_2*-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 CO_2 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 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

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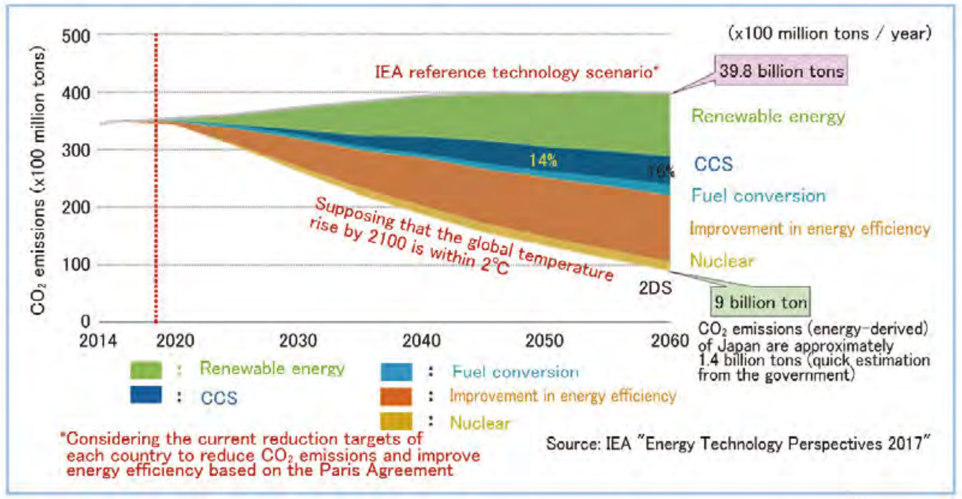
*3 Manager, Basic Engineering Department, Mitsubishi Heavy Industries Engineering, Ltd

*4 Senior Manager, Large Frame Gas Turbine Engineering Department, Gas Turbine Technology & Products Integration Division, generation with a turbine inlet temperature of 1,600°C), and the CO_2 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 CO_2 reduction amount from the present to 2060 in the IEA (International Energy Agency) report. The reduction of CO_2 emissions using renewable energy is estimated to account for about 30% of the total.



Source: IEA "Energy Technology Perspectives 2017"

Figure 1 Forecast of total global CO_2 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 CO_2 reduction amount to 2050. Together with carbon dioxide capture and storage (CCS), which collects CO_2 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.

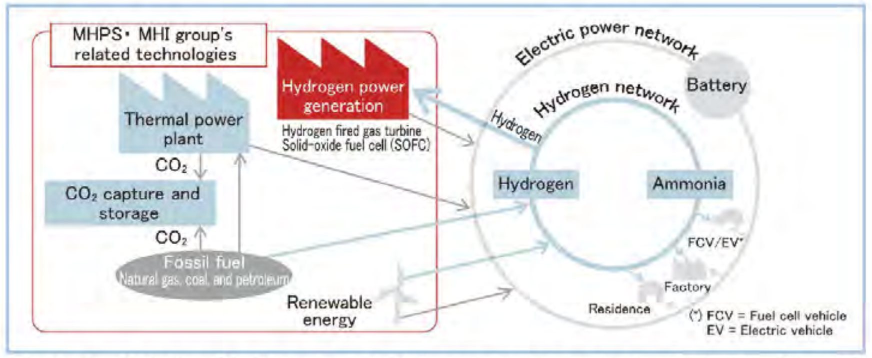


Figure 2 Relationship between our hydrogen power generation technologies and hydrogen network

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 hydro carbons 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.

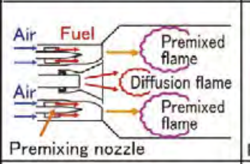
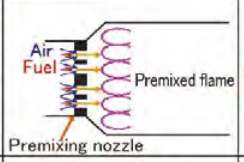
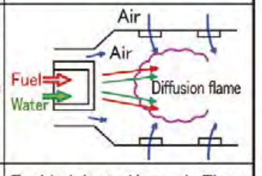
Combustor	Multi-nozzle combustor	Multi-cluster combustor	Diffusion combustor
Combustion method	Premixed flame combustion	Premixed flame combustion	Diffusion flame combustion
Structure			
NOx	Low NOx due to flame temperature uniformed by premixing nozzle	Low NOx due to flame temperature uniformed by small 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.

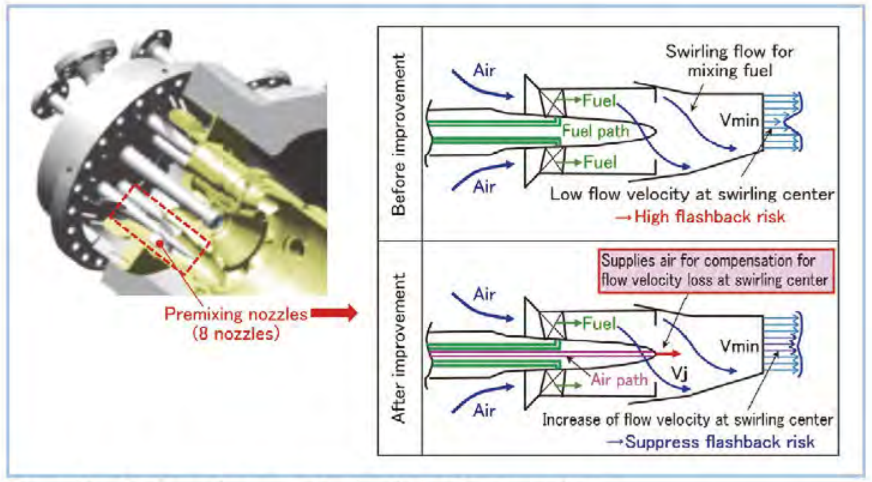


Figure 4 Outline of new combustor for hydrogen co-firing

(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)	- 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	- 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.

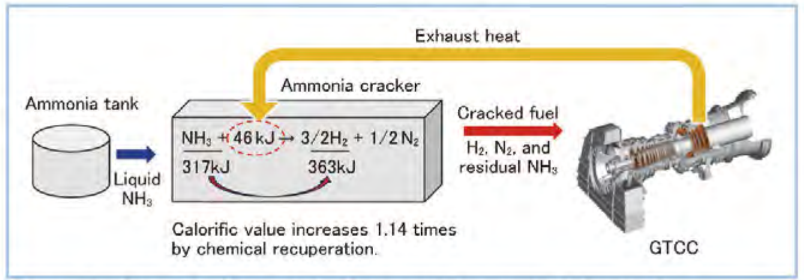


Figure 7 Concept of ammonia decomposition gas turbine cycle

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 CO_2 reduction by using CO_2-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	- 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 CO_2 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 CO_2 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.

Vattenfall' s gas power plant Magnum. (Photo: Koos Boertjens / Vattenfall)

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 CO_2-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 CO_2-free hydrogen society.

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Validation Results of 1650°C Class JAC Gas Turbine at T-point 2 Demonstration Plant

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Renewable energy has become more widespread in recent years. On the other hand, however, since the power supply capacity of renewable energy is not stable, the importance of gas turbine combined cycle (GTCC) power generation has further increased. For higher GTCC efficiency, a higher temperature of the gas turbine is important. Mitsubishi Power, Ltd. (Mitsubishi Power) developed the high-efficiency M501J gas turbine, which attained the world's first turbine inlet temperature of 1600°C, utilizing the development results from the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project in which it has participated since 2004. We have since steadily accumulated operating results. At T-point 2 in January 2020, we started test operation of the next-generation 1650°C class JAC gas turbine, which is based on the proven J-series and uses an enhanced air-cooled system for cooling the combustor, thicker TBC (thermal barrier coating) and a compressor with a high pressure ratio as its core technologies, all of which have been validated as individual elements at the T-point validation facility. Recently, the final confirmation of the integrity of equipment reliability, performance, etc., has been completed. This report presents the verification results.

1. Introduction

Since it has recently become very important to reduce CO_2 emissions, power supply by renewable energies such as wind power generation and solar photovoltaic power generation has been planned and carried out. However, such renewable energies are unstable and natural fluctuations are unavoidable, and present concerns such as sudden frequency and load fluctuations in the power system. Against this background, GTCC power generation, which is more efficient and more operable than conventional thermal power generation, is becoming more important in terms of global environmental conservation and a stable energy supply. For higher GTCC efficiency, a higher temperature of the gas turbine plays an important role. We developed the M701D, a 1150°C class large-capacity gas turbine, in the 1980s. This was followed by the M501F, which had a turbine inlet temperature of 1350°C and the M501G, which employed a steam-cooled combustor and had a turbine inlet temperature of 1500°C (**Figure 1**). Through these developments, we have verified the high plant thermal efficiency and reliability, as well as low emissions. From 2004, we participated in the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project to conduct research and development of the latest technology necessary for higher temperature and efficiency, and utilized the results of these efforts to develop the M501J, which attained the world's first turbine inlet temperature of 1600°C. Verification operation of the M501J GTCC started in 2011 at the gas turbine combined cycle power plant validation facility (T-point) located in Mitsubishi Power Takasago Works, and operating results have been steadily accumulated.

The J-series gas turbine adopts a 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 is expected. Therefore, we 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 one of its core technologies. In the spring of 2015, we completed the validation test of the entire system at T-point, and since then the system has been in operation for more than 10,000 hours. This core technology is applied to the next-generation JAC (J-Air-Cooled) high-efficiency gas turbine, which has achieved a high turbine inlet temperature of 1650°C. We have been proceeding with the construction of the second gas turbine combined cycle power plant validation facility (hereinafter referred to as T-point 2) located in Mitsubishi Power Takasago Works for long-term actual-equipment validation of the JAC gas turbine. T-point 2, which is state-of-the-art GTCC equipment with an output of 566 MW that combines the 1650°C next-generation JAC high-efficiency gas turbine and the newly-developed high-efficiency steam turbine, has been in test operation since January 2020 and achieved a combined rated output of 566 MW on April 2. We then carried out various tests and adjustments necessary to operate T-point 2 as a power plant, completed all the functional confirmations and started commercial operation on July 1. Due to the adoption of the JAC gas turbine, the power generation efficiency of the GTCC reached 64%. During test operation, in order to verify the underlying technology, we carried out thousands of temporary large-scale measurements in addition to measurement instruments, and monitored and evaluated them online. This report presents the development concept of the state-of-the-art high efficiency JAC gas turbine and the verification results obtained at the T-point 2 validation facility.

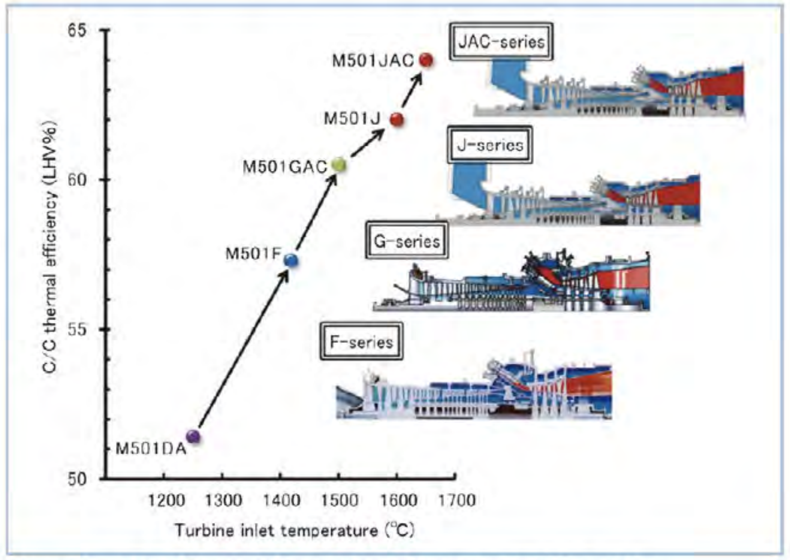

Figure 1 Developmental transition of large gas turbine series

2. Development and results of M501J gas turbine

The M501J achieves a turbine inlet temperature of 1600°C based on the component technologies already verified by the abundantly-proven F-series gas turbine and G-/H-series gas turbines, with turbine inlet temperature classes of 1400°C and 1500°C, respectively, in addition to the application of the development of the most advanced 1700°C class technology resulting from the national project. As a result of the increase of the turbine inlet temperature and the adoption of the latest component technology, the GTCC power generation end thermal efficiency has greatly increased in comparison with existing equipment. CO_2 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** lists the technological characteristics of the M501J.

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The development of the M501J gas turbine was carried out by conducting validation tests of each component at the basic design stage, reflecting the results in the detailed design and finally validating the actual operation of the entire gas turbine in the power generation plant validation facility. **Figure 3** depicts the appearance of the gas turbine combined cycle power plant validation facility (T-point) located in Mitsubishi Power Takasago Works. We carried out 2300 temporary measurements on the first model of the M501J and verified during test operation in 2011 that the performance, mechanical characteristics and combustion characteristics satisfied the target values before the shipping of the commercial product. We have received orders for 76 J-series gas turbines from Japanese and overseas customers and are shipping them as they become available. Up to now, 45 units have been put into commercial operation and a total operational time of more than 1,160,000 hours has been reached (**Figure 4**).

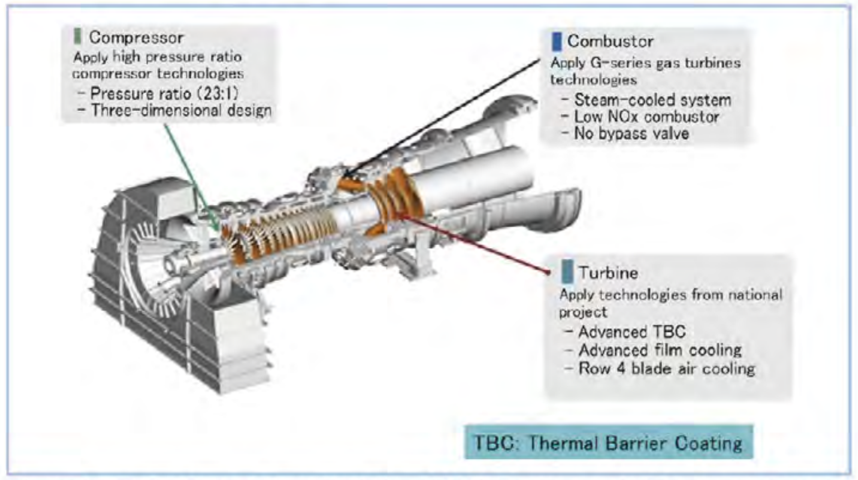


Figure 2 Technological characteristics of M501J series gas turbine components

①Gas turbine building
②Heat recovery steam generator
③Steam turbine building
④Air-cooled condenser

Figure 3 Gas turbine combined cycle power plant validation facility (T-point) in the Mitsubishi Power Takasago Works.

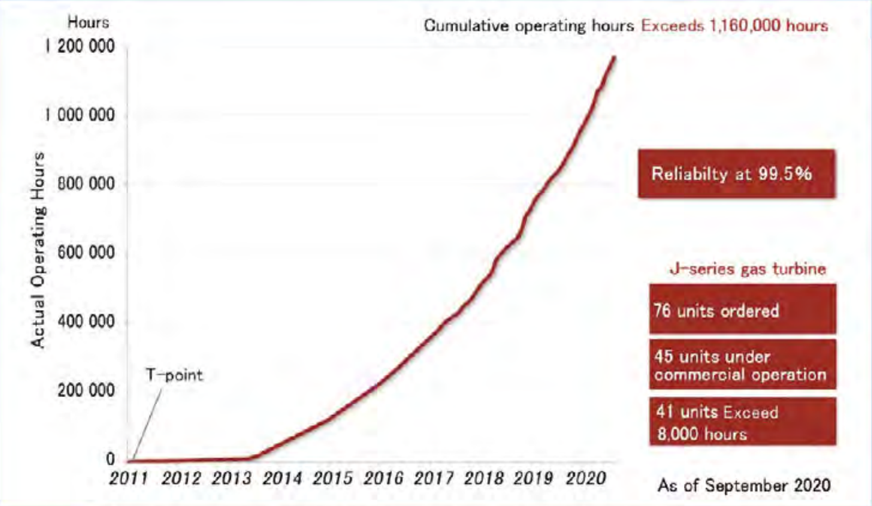
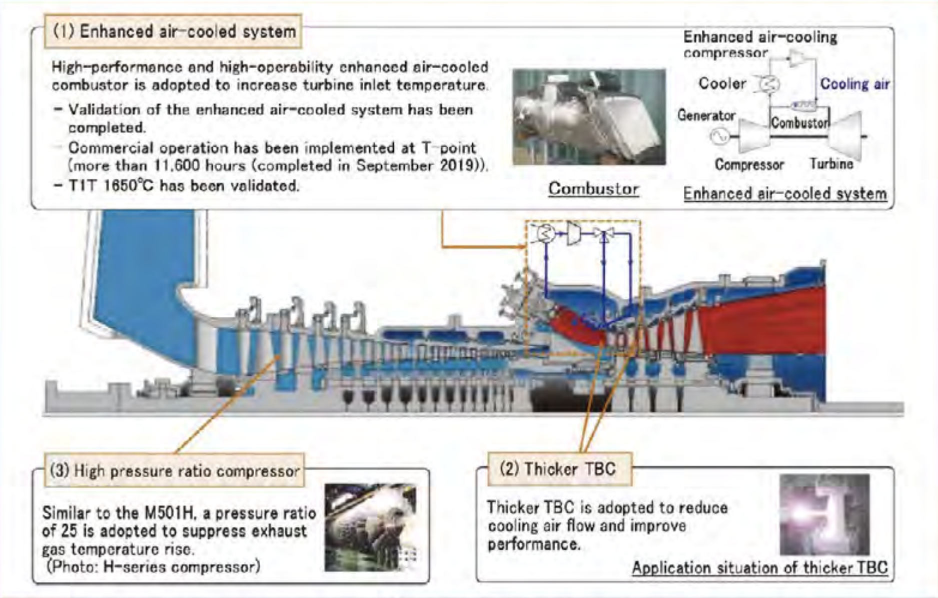


Figure 4 Operating results of M501J series gas turbine (including 50 Hz units)

3. Development concept of 1650°C class M501 JAC series gas turbine

We proceeded with the development of the next-generation 1650°C class JAC gas series turbine in order to further improve the efficiency and operability by applying to the proven M501J gas turbine the following validated component technologies: (1) an enhanced air-cooled system for cooling the combustor, (2) thicker TBC and (3) a compressor with a high pressure ratio.

The basic concept of this gas turbine is as follows (**Figure 5** and **Figure 6**). Validation of these individual component technologies was completed at the T-point validation facility and they were then applied to the 1650°C class JAC series gas turbine (**Table 1**).



High-performance and high-operability enhanced air-cooled combustor is adopted to increase turbine inlet temperature.
- Validation of the enhanced air-cooled system has been completed.
- Commercial operation has been implemented at T-point (more than 11,600 hours (completed in September 2019)).
- TIT 1650°C has been validated.

Similar to the M501H, a pressure ratio of 25 is adopted to suppress exhaust gas temperature rise.
(Photo: H-series compressor)

Thicker TBC is adopted to reduce cooling air flow and improve performance.

Figure 5 Development concept of 1650°C class JAC series gas turbine

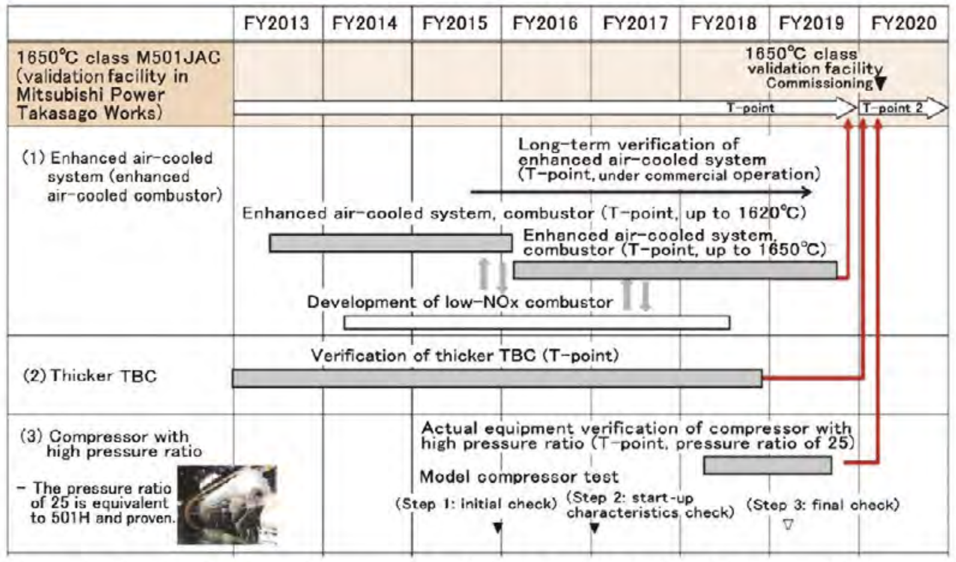


Figure 6 Application flow of component technology to 1650°C class JAC gas turbine

Table 1 Comparison of gas turbine performance (ISO, standard conditions)

	M501J	M501JAC
Frequency (Hz)	60	60
Pressure ratio	23	25
Gas turbine output (MW)	330	435
Gas turbine efficiency (%-LHV)	42	44
Combined cycle output (MW)	484	630
Combined cycle efficiency (%-LHV)	62	>64

(1) Adopting an enhanced air-cooled system to improve operability and increase the turbine inlet temperature in comparison to that of the J-series.

(2) Adopting thicker TBC developed based on the technology resulting from the national project to achieve both high performance and reliability despite the increasing turbine inlet temperature.

(3) Adopting a compressor with a high pressure ratio design equivalent to the H-series to suppress the increase of the exhaust gas temperature at the gas turbine outlet.

4. Validation of core technologies incorporated in 1650°C class M501 JAC gas turbine

This chapter describes the core component technologies incorporated in the JAC gas turbine and their long-term verification results.

4.1 Enhanced air-cooled system for cooling combustor

System overview

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, we devised an enhanced air-cooled system that is a technology for realizing air cooling of high-temperature gas turbines. By adopting this enhanced air-cooled system, air cooling of gas turbines even with a turbine inlet temperature of 1650°C can be realized, enabling an increase in combined power generation efficiency and the operability of the entire plant. In the spring of 2015, we completed the actual equipment validation test of the entire system at the T-point validation facility. An overview of the air-cooled system is presented below.

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 combustion area in the combustor (**Figure 7**).

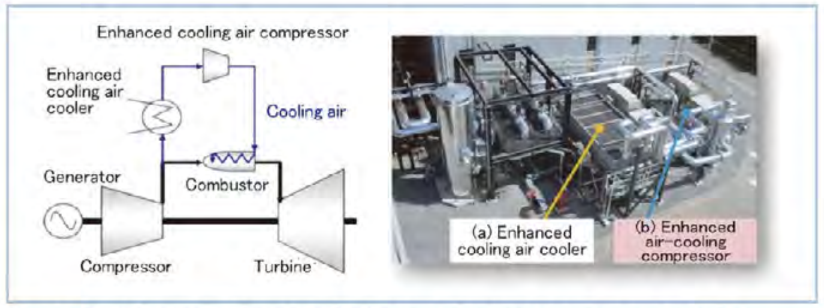


Figure 7 Schematic diagram of enhanced air-cooled system and T-point validation facility

The characteristics of the enhanced air-cooled system are described below.

(1) In contrast to the conventional steam-cooled system, which recovers all exhaust heat on the bottoming side, the enhanced air-cooled system recovers some exhaust heat on the topping side and can improve the efficiency of the system.

(2) Cooling performance equal to or higher than that of the 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 improving the efficiency of next-generation GTCC with an enhanced air-cooled system to develop a combustor that can be efficiently cooled 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.

Actual equipment validation of enhanced air-cooled system

In the spring of 2015, we validated the operability of the enhanced air-cooled system required for actual plants, namely the responsiveness to transient changes such as start/stop, load change and load rejection, using the T-point validation facility, and confirmed that there were no problems. The enhanced cooling air compressor operating point behavior during a gas turbine trip test was also tested and it was confirmed that the enhanced cooling air compressor could be stopped safely without entering a surging state at a trip from 100% load of the gas turbine.

This enhanced air-cooled system was operated and long-term validation was carried out at the T-point validation facility, and operating results of more than 10,000 hours have been accumulated.

4.2 Thicker TBC

Although the turbine inlet temperature of the 1650°C class JAC gas turbine can become 50°C higher than that of the J-series, thicker TBC is adopted to achieve both high performance and reliability. Generally, the durability decreases as the TBC is thickened, but the TBC developed based on the technology resulting from the national project has higher durability than before, making thicker TBC possible. Prior to application to the actual blade, for application validation of thicker TBC, coupon test pieces were sampled to check the microstructures and porosity, which was followed by thermal-cycle testing to confirm that there were no problems in terms of durability. In the actual equipment validation, thicker TBC was applied to the combustor, row 1 to 3 turbine vanes and blades, as well as the split ring segments, and the reliability was confirmed through long-term validation. **Figure 8** shows the thicker TBC applied to the row1 turbine vane.

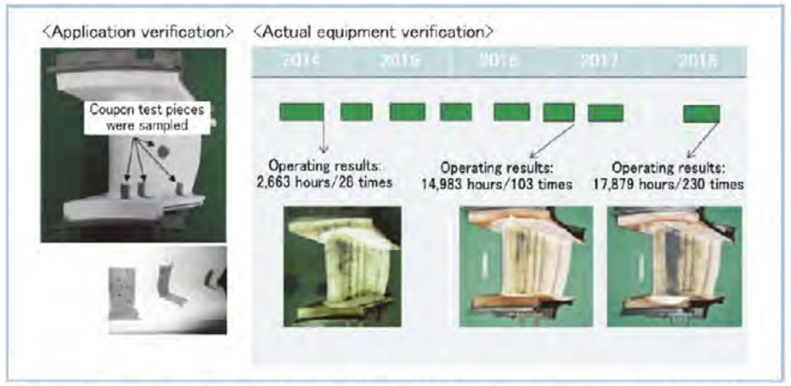


Figure 8 Verification results of thicker TBC on turbine row 1 vane at T-point

4.3 Compressor with high pressure ratio

The compressor of the 1650°C class JAC gas turbine has a high pressure ratio design equivalent to our H-series, which has a proven operational results and specifications that suppress the increase of the exhaust gas temperature resulting from an increase of the gas turbine inlet temperature by increasing the pressure ratio from the 23 adopted by the J-series to 25. As a large-air-flow compressor with a pressure ratio of 25, an H-series compressor with a pressure ratio of 25 was validated at the T-point validation facility in 2001. We also performed actual equipment validation of the compressor that was designed based on the J-series and had a pressure ratio of 25 at the T-point validation facility in May 2018. As a result, it was confirmed that the starting characteristics and aerodynamic performance were good.

5. Verification results of the 1650°C class M501 JAC gas turbine at T-point 2

T-point 2 is a state-of-the-art GTCC facility with an output of 566 MW that combines a 1650°C next-generation JAC high-efficiency gas turbine and a newly-developed high-efficiency steam turbine. The M501 JAC gas turbine was shipped and installed in the spring of 2019 and test operation at T-point 2 commenced in January 2020. In this test operation, first the gas turbine alone was operated and reached its rated load after 10 starts from the first ignition. After steam ventilation, the operability confirmation test was carried out by Combined Cycle (CC) operation, and after that, commercial operation began on July 1 (**Figure 9** and **Figure 10**). In test operation, we constantly monitored the start-up acceleration, no-load rated speed and state quantity during partial-load and rated-load operation of the gas turbine in order to make a final confirmation of the reliability, actual performance, exhaust gas emissions, etc., of the equipment. Next, functional tests and special tests required for actual commercial plants were completed.

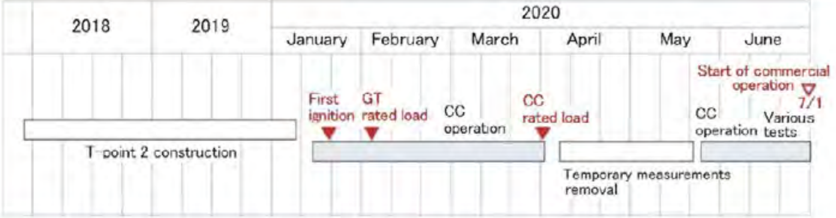


Figure 9 Test operation schedule at T-point 2

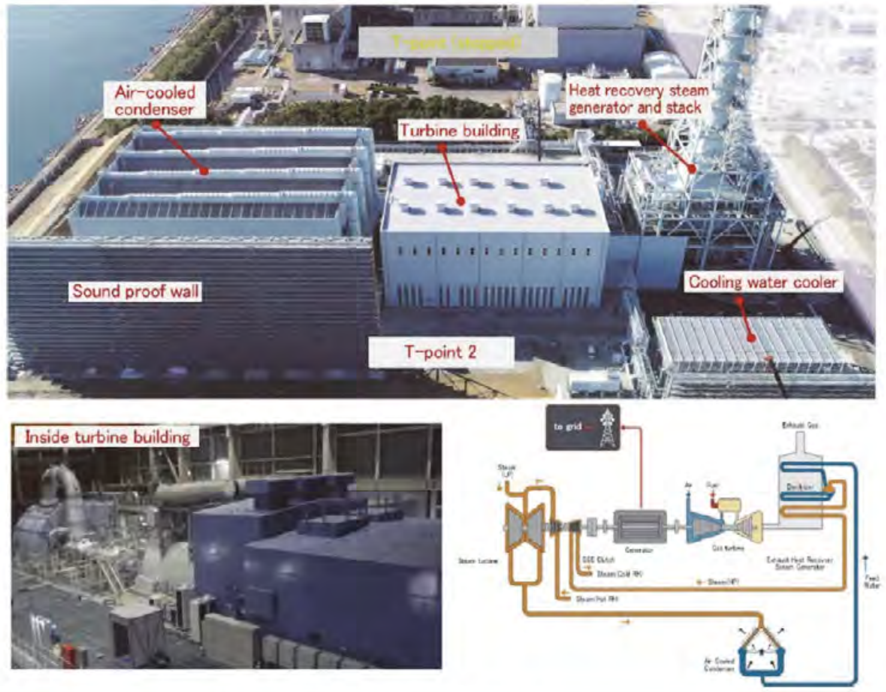


Figure 10 Overview of T-point 2 combined cycle plant

During test operation, more than 2,800 temporary large-scale measurements were conducted to evaluate the integrity in order to verify the technologies that are the basis of the JAC gas turbine. For the rotating parts, roughly 100 large-scale telemetric measurements were carried out to confirm the metal temperature and vibration stress integrity of the compressor rotors and turbine blades. This chapter presents the final confirmation results of the integrity of each component (**Figure 11**).

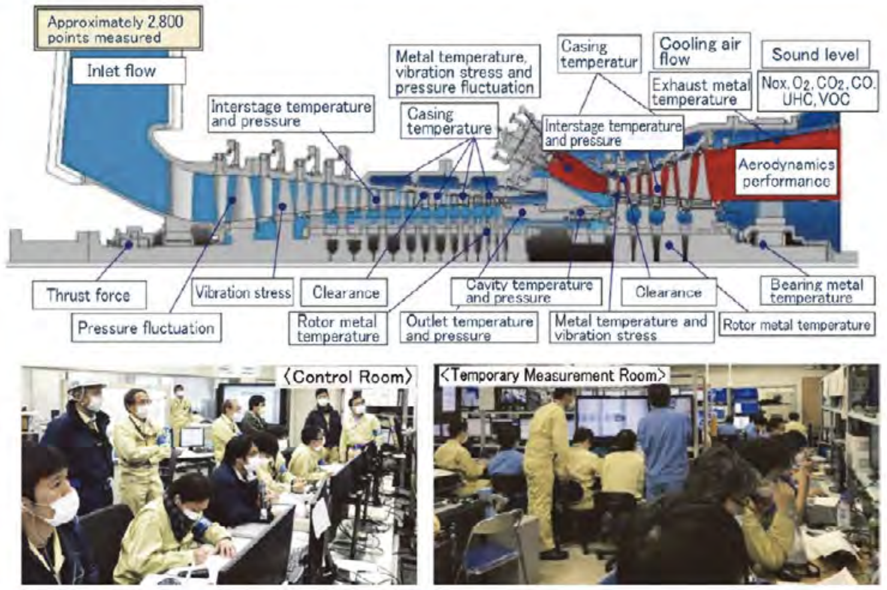


Figure 11 Implementation status of test operation and temporary measurements

5.1 Enhanced air-cooled combustor and enhanced air-cooled system

The enhanced air-cooled system had already been validated at the T-point validation facility, including its ability to follow transient changes. In addition, the metal temperature of the enhanced air-cooled combustor was measured in this test operation and its cooling performance in the actual equipment was finally validated. As a result, it was confirmed that the combustion casing metal temperature distribution was lower than the design allowance value, so there were no problems in terms of cooling performance (**Figure 12**). It was also confirmed that there were no particular problems with the combustion vibration characteristics and exhaust gas emissions, and stable operation was possible under partial- to rated-load conditions.

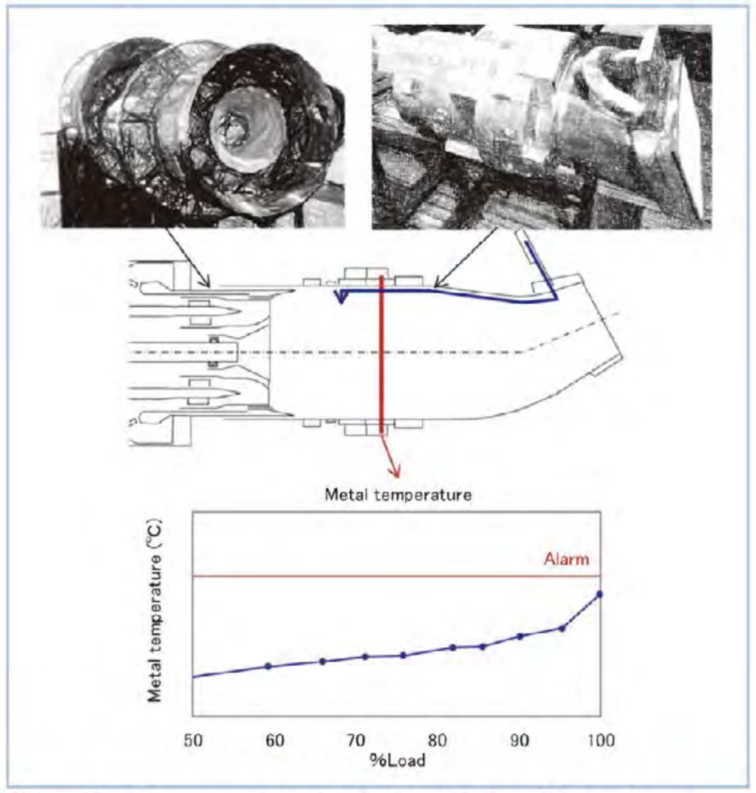


Figure 12 Measurement results of enhanced air-cooled combustor metal temperature

The JAC gas turbine uses a system that enables clearance control during under-load operation based on the enhanced air-cooled system. This system uses two cooling air supply methods: one causes cooling air to bypass the turbine blade ring and introduces it directly into the combustor and the other causes cooling air to pass through the turbine blade ring in advance to supply it to maximize the performance by reducing the turbine clearance during load operation. These two systems can be switched by the switching valve (three-way valve) even during load operation. The former can handle operation with large load fluctuations by opening the clearance (Flexible Mode). On the other hand, the latter can close the clearance during load-hold operation and maximize the performance of steady operation (Performance Mode). **Figure 13** shows the behavior of the clearance when the three-way valve is switched during load operation. It was finally confirmed that this system can improve operability more than before while maximizing performance.

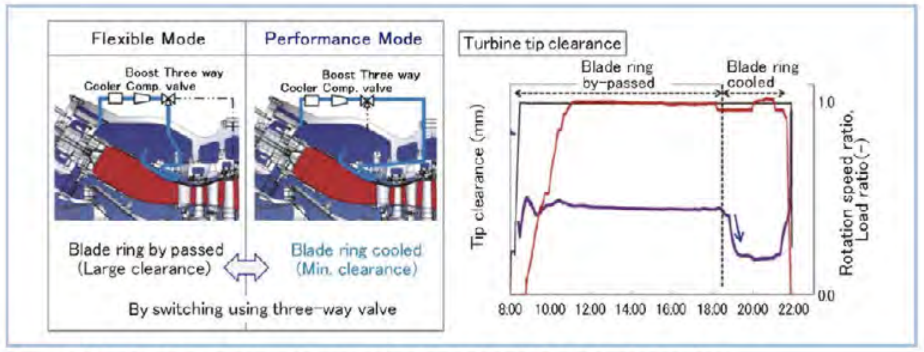


Figure 13 Turbine clearance control using enhanced air-cooled system

5.2 Turbine blade metal temperature

The turbine inlet temperature of the 1650°C class JAC gas turbine can become 50°C higher than that of the J-series and adopts thicker TBC to achieve both high performance and reliability. As mentioned above, the integrity of the thicker TBC has been verified and confirmed at T-point over the long term. **Figure 14** shows the specially measured metal temperature distribution of the JAC turbine row 1 vane to which the TBC is applied in order to optimize the cooling design. It was confirmed that although turbine row 1 vane was subjected to the strictest heat load and its cooling structure was complicated, there were no local high temperature parts, all parts were below the design allowance temperature and the integrity was maintained under the condition of an inlet gas temperature of 1650°C. The integrity was also confirmed in the inspection after about 2000 hours of operation.

For the turbine row 1 blade, in addition to confirmation of the blade surface metal temperature and vibration stress using telemetric measurements, pyrometric measurement, which has been introduced at T-point, was carried out. The pyrometer was inserted into the gas path from the standby position through the insertion hole provided in the combustor casing and the turbine row 1 vane to confirm the integrity of the blade surface temperature distribution around the leading edge of the blade surface, which was subjected to a particularly high heat load. The integrity was also confirmed in the inspection after about 2000 hours of operation (**Figure 15**).

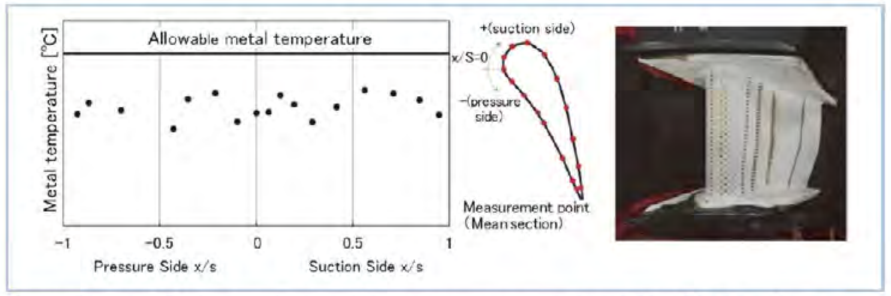


Figure 14 Metal temperature distribution measurement results of turbine row 1 vane and inspection results after operation

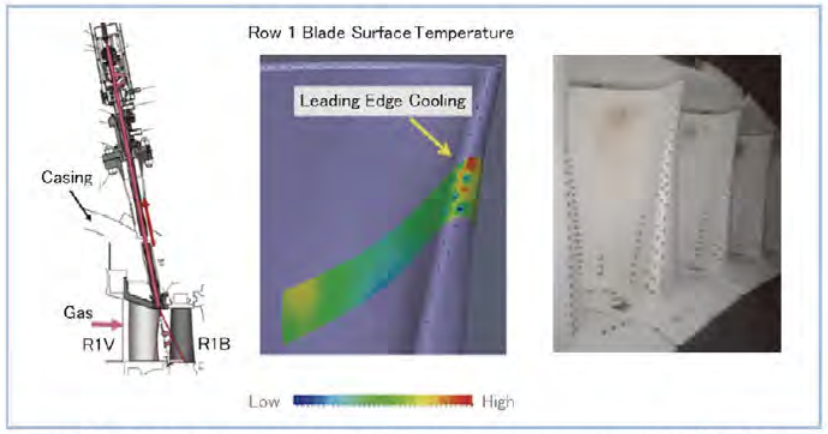


Figure 15 Surface temperature distribution measurement results of turbine row 1 blade and inspection results after operation

5.3 High pressure ratio compressor

The compressor of the 1650°C class JAC gas turbine has a pressure ratio that was increased from 23 to 25. However, since a high pressure ratio compressor has a design in which the outlet flow path area is relatively narrow, there is a concern that the flow rate will decrease and the rotating stall will relatively deteriorate during startup with a low pressure ratio. As mentioned above, an H-series compressor with a similar pressure ratio of 25 was validated, as was a compressor with a pressure rate of 25 based on the J-series in May 2018 at T-point. Detailed temporary measurements were also carried out for the JAC-series, and it was final-confirmed that the starting characteristics, blade vibration stress and aerodynamic performance were favorable (**Figure 16**).

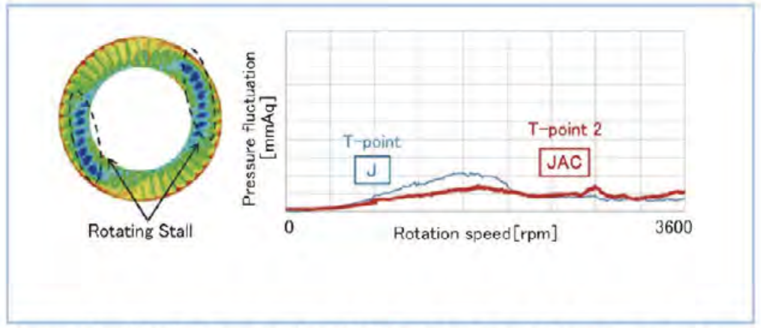


Figure 16 Verification results of JAC gas turbine high pressure ratio compressor

6. Conclusion

For higher GTCC efficiency, a higher temperature of the gas turbine plays an important role. Mitsubishi Power has participated in the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project since 2004. We utilized the results of these efforts to develop the high-efficiency M501J gas turbine, which attained the world's first turbine inlet temperature of 1600°C, and have since steadily accumulated operating results. In order to further improve the efficiency and operability of GTCC, we developed the next-generation 1650°C class JAC gas turbine, which is based on the proven J-series and uses an enhanced air-cooled system for cooling the combustor, thicker TBC and a compressor with a high pressure ratio as its core technologies, and completed the validation of the individual elements at the T-point validation facility.

We had been proceeding with construction of the second gas turbine combined cycle power plant validation facility (T-point 2) in our Takasago Works for long-term verification of the JAC gas turbine. We started its test operation in January 2020, carried out as many as about 2,800 temporary large-scale measurements and made final confirmation of the integrity of the JAC series equipment, such as the reliability and performance during 1650°C operation. At T-point 2, the combined rated output reached 566 MW on April 2 and all the functional confirmations as a power generation facility were completed. Commercial operation commenced on July 1. Since then, operational hours and the number of starts continue to be accumulated.

Verified JAC gas turbines have been shipped to commercial power plants in North America, etc., one after another. Hydrogen co-firing is planned for a GTCC power generation project in Utah in the United States. By incorporating the combustor technology we developed independently, we aim to start the operation of the JAC gas turbine with a hydrogen co-firing rate of 30% and to realize 100% hydrogen-fired operation in the future.

The long-term verification operation at T-point 2 is carried out from our RMC (remote monitoring center). We aim to improve the reliability of not only major equipment such as gas turbines, but also the entire plant including auxiliary equipment, validate various applications included in the "TOMONI" digital solution, such as shortening the startup time and automatically optimizing operating parameters, and realize autonomous operation in the future.

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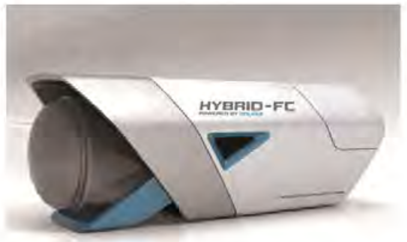
Development of Next-Generation Large-Scale SOFC toward Realization of a Hydrogen Society



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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, MHI has been conducting demonstration tests at Tokyo Gas Co., Ltd.'s Senju Techno Station and the operation was started in March 2013. The pressurized-type SOFC-MGT hybrid system brought about by combining the 200-kW-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 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 CO_2, one of the major greenhouse effect gases, it is necessary to combine decentralized 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 indispensably 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's 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 member, 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.

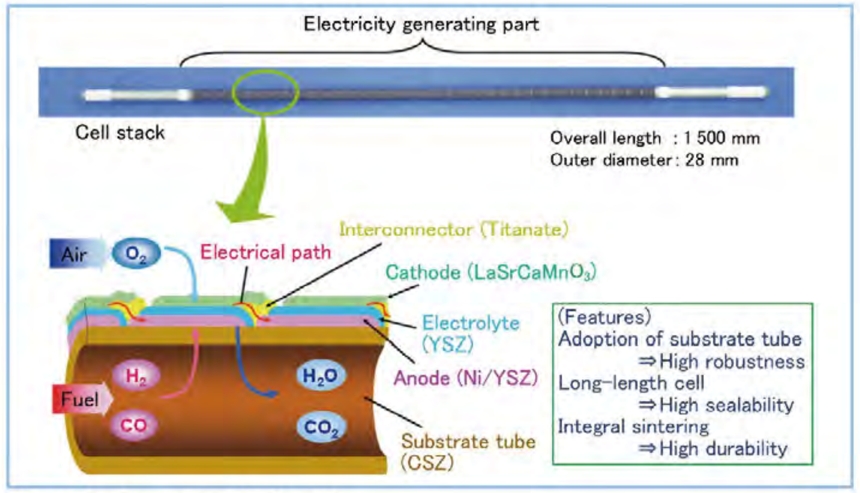

Figure 1 Structure of cell stack

MHPS has been developing our 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 30% 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**).

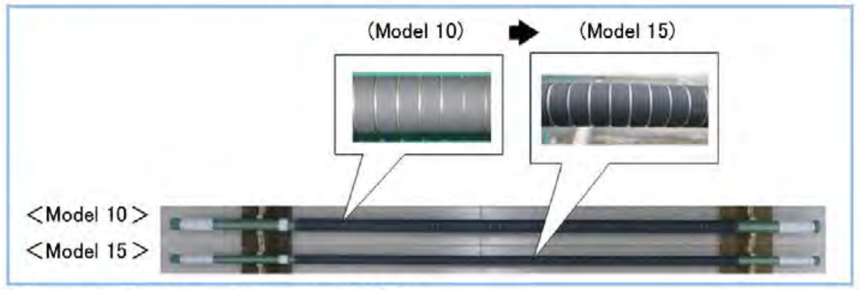

Figure 2 Tubular cell stack for SOFC

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**).

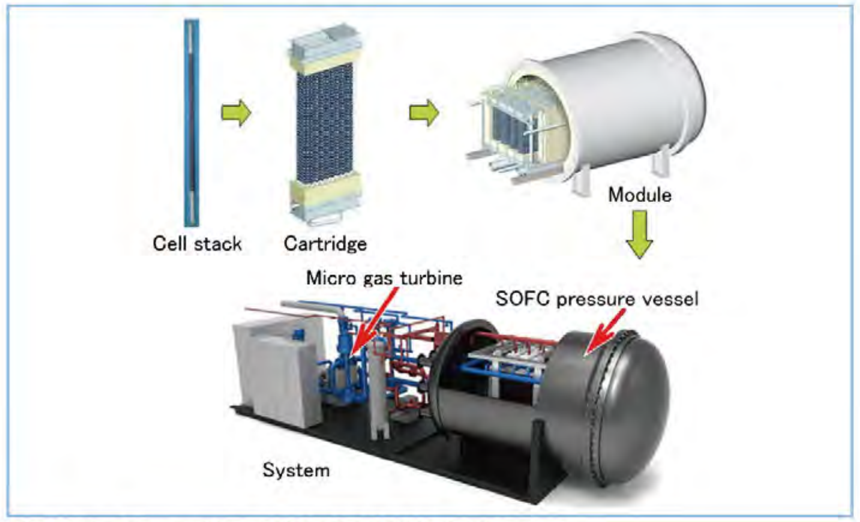

Figure 3 Composition of SOFC-MGT hybrid system

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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 accompanied 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 generating 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**).

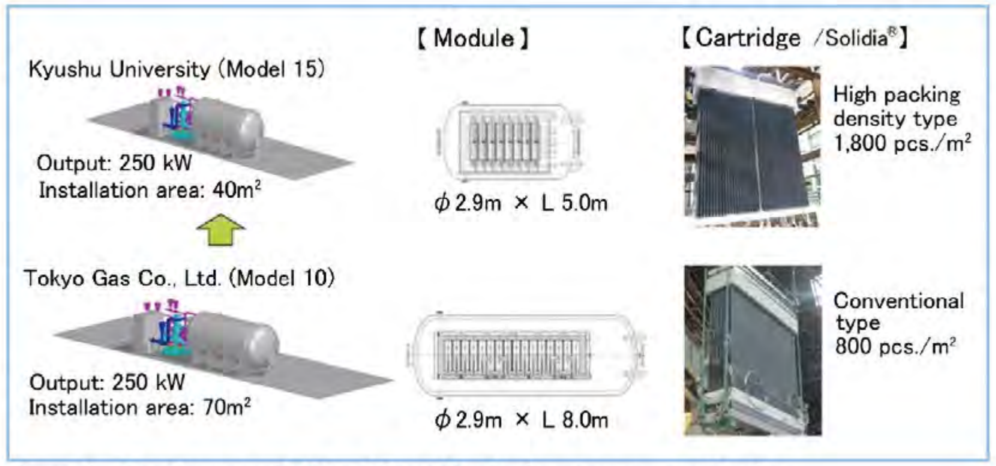


Figure 4 Development of cell stack/cartridge for low-cost mass production

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.

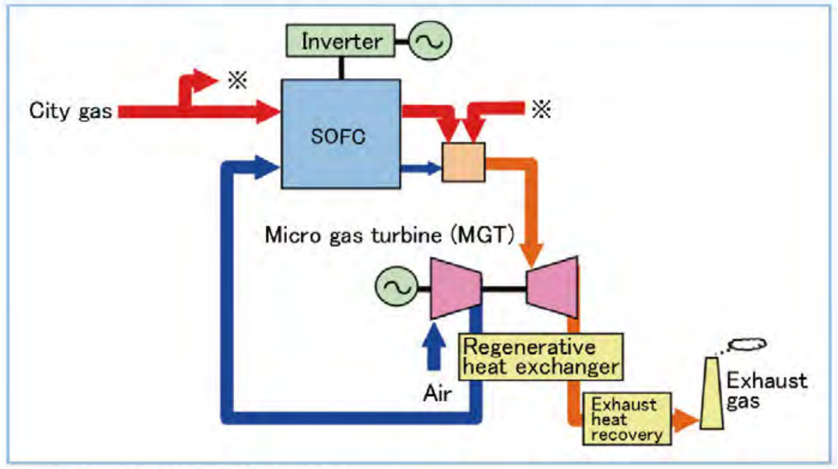
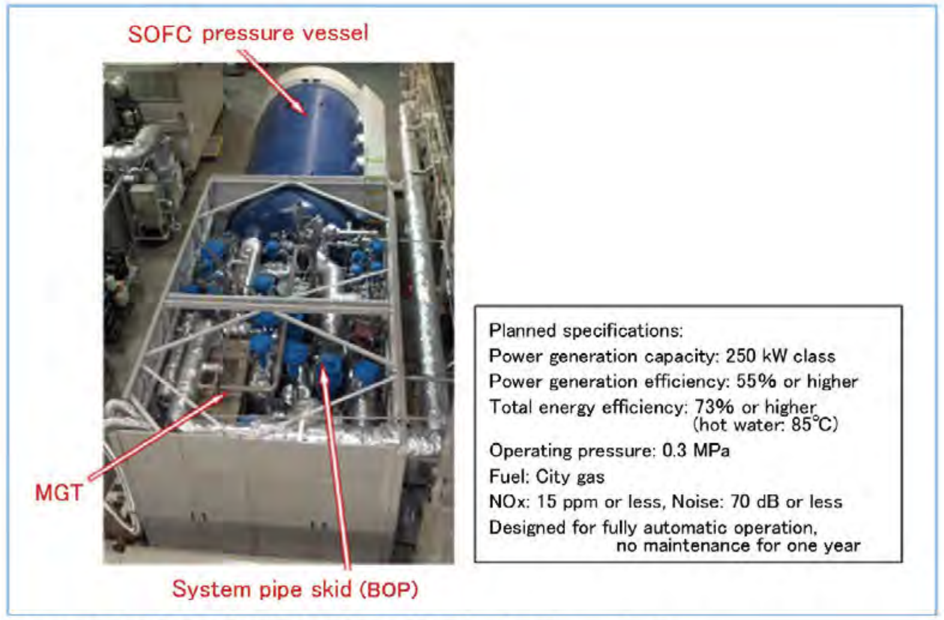


Figure 5 SOFC-MGT hybrid system

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**).



Planned specifications:
Power generation capacity: 250 kW class
Power generation efficiency: 55% or higher
Total energy efficiency: 73% or higher (hot water: 85°C)
Operating pressure: 0.3 MPa
Fuel: City gas
NOx: 15 ppm or less, Noise: 70 dB or less
Designed for fully automatic operation, no maintenance for one year

Figure 6 Model 10 SOFC-MGT hybrid system for demonstration

With this demonstration system, we pinpointed problems toward promotion of initial introduction of the SOFC-MGT hybrid system and the examination of deregulation for promotion of its introduction. At present, in particular, because the SOFC-MGT hybrid system is a pressurized system with a fuel gas pressure of 100 kPa or more and is rated as a power generation system that has to be monitored at all times, we are targeting the necessary reconsideration of the regulation requirements for continuous monitoring so that the system would be diffused in earnest. Therefore, we obtained the technical data necessary for deregulation including the grounds for system safety design and the system long-term durability test data, as well as the operation data such as emergency measures on assumed starting and stopping, load change and system problems and verified the system's reliability and safety.

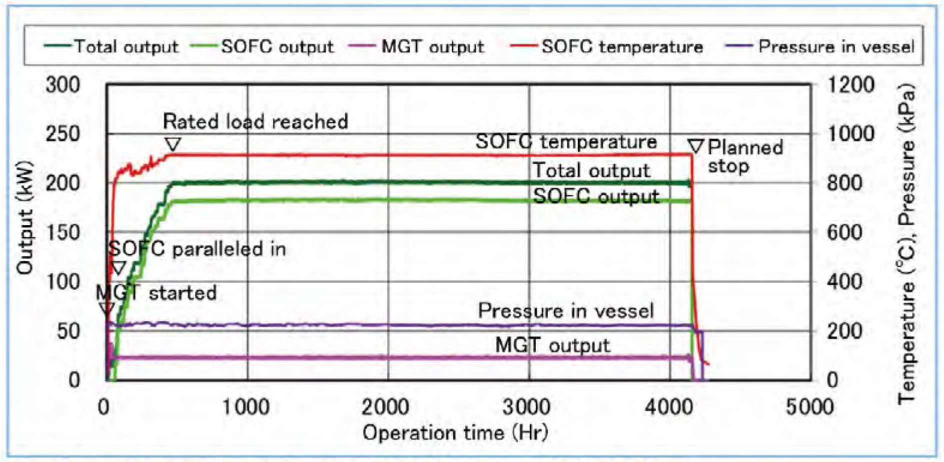


Figure 7 Result of durability test for SOFC-MGT hybrid system

We conducted the evaluations of various kinds of examinations and test data and the deregulation activities, receiving cooperation from the Fuel Cell Commercialization Conference of Japan, Japan Gas Association and Japan Electrical Manufacturers' Association and other entities.

For the system's long-term durability, continuous operation for over 4,100 hours was conducted till the planned shutdown. As a result, no time deterioration was observed under the condition of a constant rated load, and the voltage degradation rate was stable at 0% in 1,000 hours (**Figure 7**).

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 Ito Campus of Kyushu University (Nishi-ku, 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-academia collaboration toward earnest diffusion of SOFC.

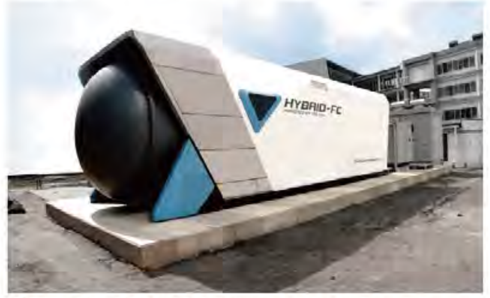


Figure 8 SOFC-MGT hybrid system for demonstration delivered to Kyushu University

Table 1 Specifications of the system

		250 kW SOFC-MGT hybrid system
Appearance		
Rated output	(kW)	250
Net efficiency	(%-LHV)	55
Total heat efficiency	(%-LHV)	73 (hot water), 65 (steam)
Dimensions of the unit	(m)	12.0 x 3.2 x 3.2
Operation		For cogeneration

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 proactively introduce 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®)

Toward 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 monoxide 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)).

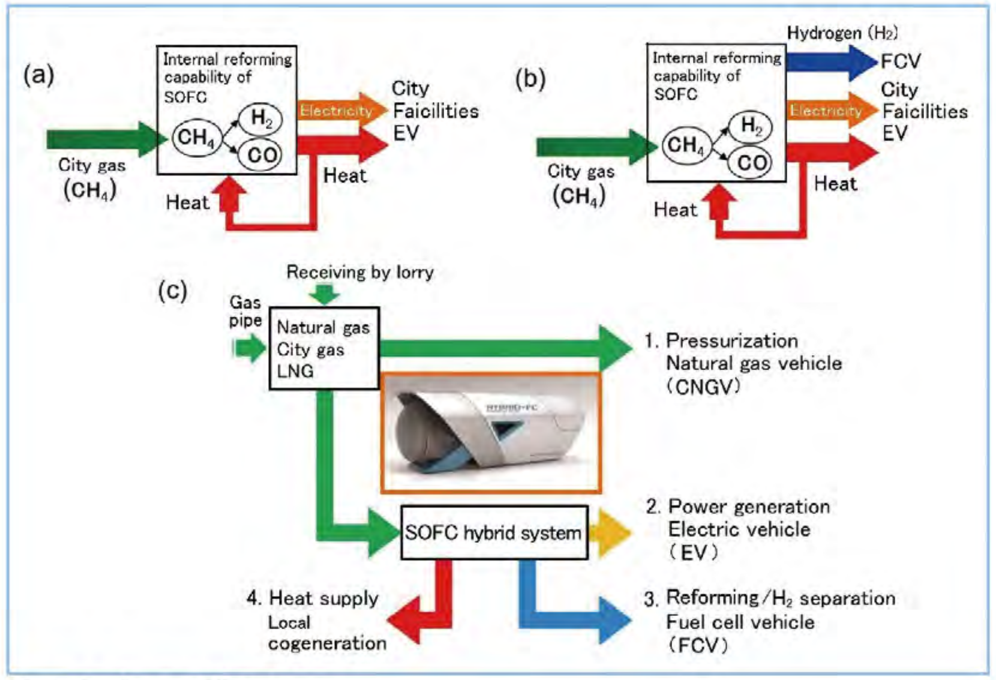


Figure 9 Image of Quatrogen
(a) Supply of electricity and heat by conventional SOFC
(b) Hydrogen production by internal reforming
(c) Application to a hydrogen station.

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 CO_2 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.

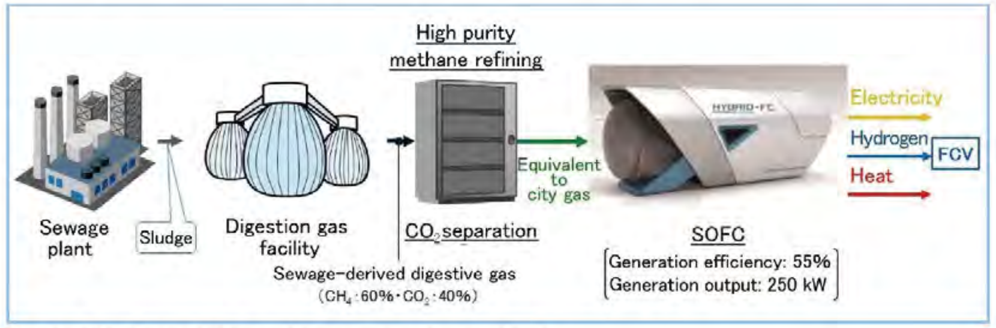


Figure 10 Image of digestive gas power generation

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."

Mitsubishi Heavy Industries Technical Review Vol. 55 No. 4 (December 2018)

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

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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 system to the market started in 2017. Furthermore, since fiscal 2016, in another NEDO commissioned project, the verification of the 1 MW class system, which features 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 CO_2 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 grids 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 best 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 fuel 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 (IGFC) 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**).

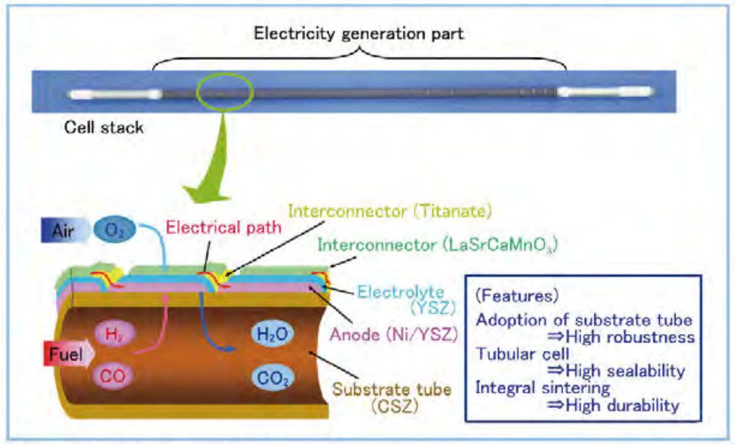

Figure 1 Structure of cell stack

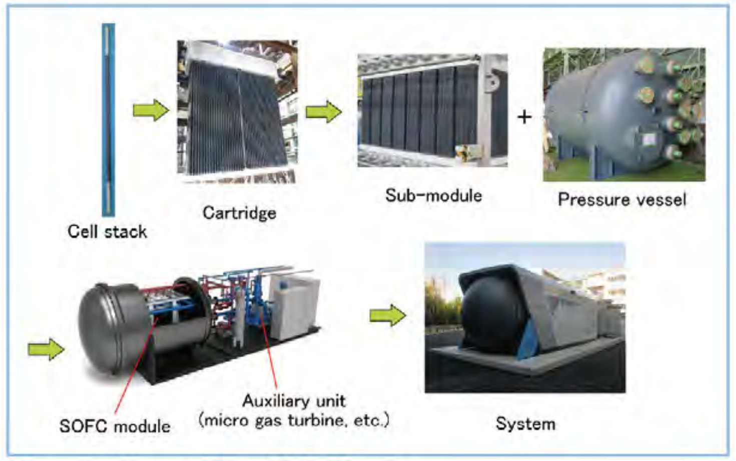

Figure 2 Composition of hybrid system

This system consists of the SOFC, Micro Gas Turbine (MGT), recycle blower, etc. Power is generated in the two stages of the 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**).

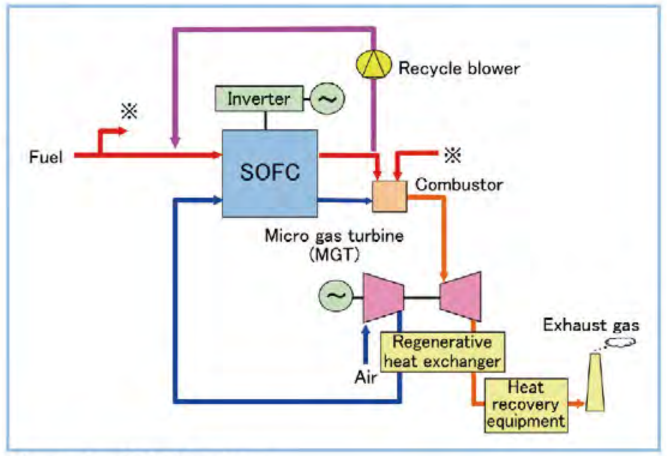

Figure 3 Hybrid system

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3. 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., Senju Techno Station of Tokyo Gas Co., Ltd. and Technology Center of Taisei Corporation (**Figure 4**).

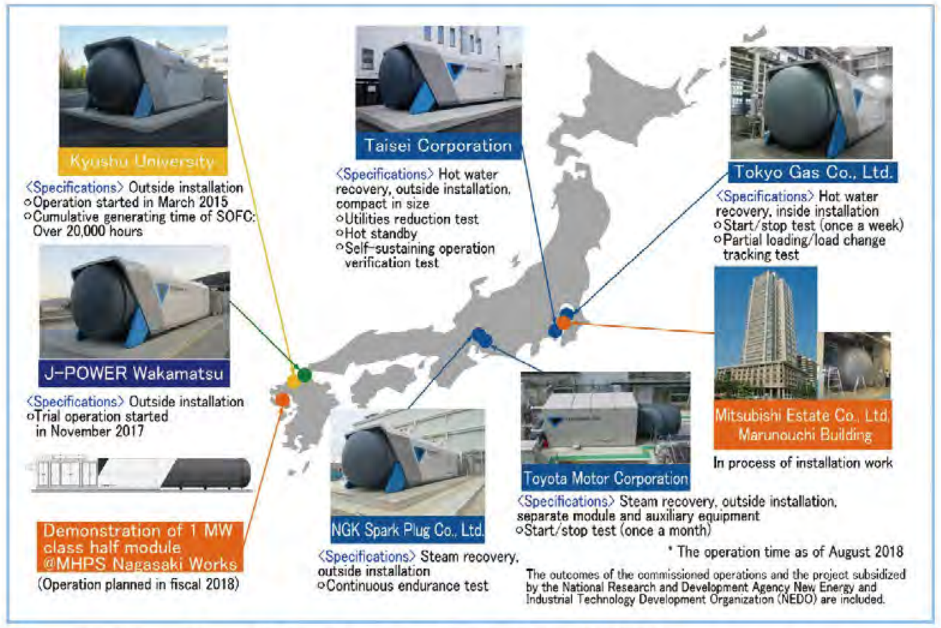


Figure 4 Operation and planning status for the fuel cell SOFC

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 Taisei 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, and 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 MHPS 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, which is half the number of units required for 1 MW class, is used 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.

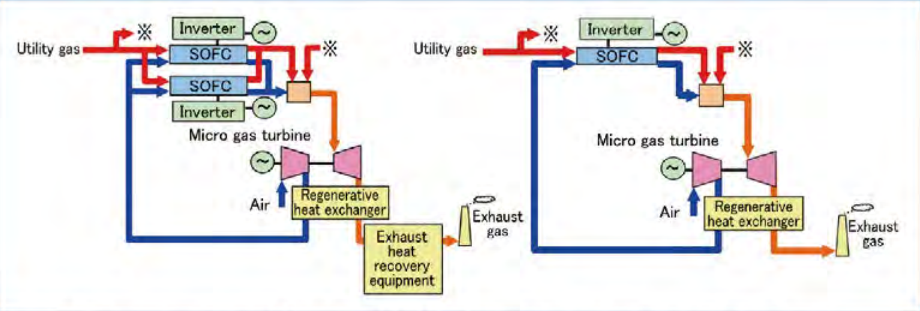


Figure 5 Compositions of the actual 1MW class unit and the demonstration unit

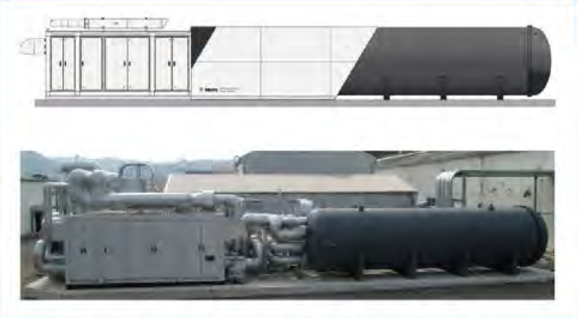
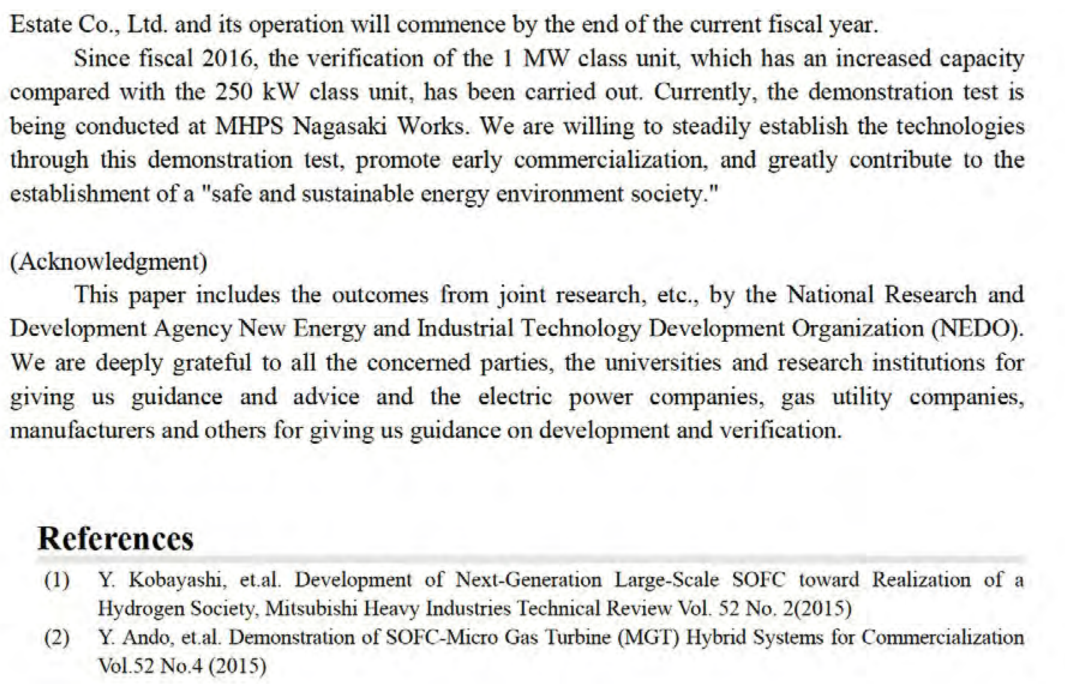


Figure 6 State of the installed half-module demonstration 1MW class unit

5. Conclusion

MHPS positions the SOFC hybrid power generation system as a key effective technology for making the reduction of CO_2 emissions and the 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 Marunouchi 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 MHPS 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)

This paper includes the outcomes from joint research, etc., by the National Research and Development Agency New Energy and Industrial Technology Development Organization (NEDO). We are deeply grateful to all the concerned parties, the universities and research institutions for giving us guidance and advice and the electric power companies, gas utility companies, manufacturers and others for giving us guidance on development and verification.

References

(1) Y. Kobayashi, et.al. Development of Next-Generation Large-Scale SOFC toward Realization of a Hydrogen Society, Mitsubishi Heavy Industries Technical Review Vol. 52 No. 2(2015)

(2) Y. Ando, et.al. Demonstration of SOFC-Micro Gas Turbine (MGT) Hybrid Systems for Commercialization Vol.52 No.4 (2015)

Compendium

In this section, we list the characteristics of hydrogen and information pertaining to engineering for your use. We also provide information about ammonia, which is seen as a potential hydrogen energy carrier from the *Mitsubishi Heavy Industries Technical Review*.

Contents

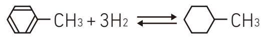
1. Basic Data

	Hydrogen H_2	Methane CH_4	Ammonia NH_3	Air	Nitrogen N_2	Carbon Dioxide CO_2
Molecular Weight	2.016	16.04	17.03	28.97	28.02	44.01
Density (gas) kg/Nm³	0.08987	0.717	0.771	1.2932	1.2506	1.977
Specific Heat Cp kJ/(kg·K) [25℃,1atm]	14.306	2.2317	2.1645	1.0063	1.0413	0.85085
Heat Capacity Ratio Κ (-) [25℃,1atm]	1.4054	1.3062	1.316	1.4018	1.4013	1.2941
Gas Constant R J/(kg·K)	4124.3	518.4	488.2	287.0	296.7	188.9
Freezing Point ℃ [1atm]	-259.14	-182.76	-77.7	-	-209.86	-56.6
Boiling Point ℃ [1atm]	-252.87	-161.49	-33.4	-	-195.8	-78.5 (rise)

2. Transport Property

	Liquid Hydrogen H_2	Compressed Hydrogen H_2 (350 atm)	Compressed Hydrogen H_2 (700 atm)	Methane CH_4 (liquid)	Ammonia NH_3 (liquid)	Natural Gas (LNG 13A)	Propane C_3H_8 (liquid)	Methylcyclohexane C_7H_{14} (MCH*)
Molecular Weight	2.016	2.016	2.016	16.04	17.03	18.36	44.1	98.18
Hydrogen Content (weight %)	100	100	100	25.13	17.76	23.77	18.29	6.16
Hydrogen Density (kg-H_2/m³)	70.8	23	39	108.1	120.0	103.0	107.0	47
Boiling Point (℃)	-252.87	-	-	-161.49	-33.4	-161.49 (Methane) Varies by composition	-42.07	101.05
Other properties	High hydrogen density No recycling required High purity	High inflammable Highly combustible Explosive		-	High hydrogen density No recycling required Can be used directly	Composition (%) Methane CH_4: 89.60 Ethane C_2H_6: 5.62 Propane C_3H_8: 3.43 Butane C_4H_{10}: 1.35	-	Normal temperature and pressure Petroleum infrastructure Available for use

* Carrying hydrogen using the difference of hydrogen between MCH toluene (C_7H_8) (molecular weight 92) and MCH (C_7H_{14}) (molecular weight 98)



3. Combustion Property

Fuel Name	Hydrogen H_2	Methane CH_4	Ammonia NH_3	Propane C_3H_8
Density [kg/Nm³]	0.08987	0.717	0.771	2.02
Boiling Point (@hPa) [℃]	-252.87	-161.49	-33.4	-42.1
Low-heating Value* [MJ/kg]	120.4	50.2	18.6	46.6
Low-heating Value [MJ/Nm³]	10.82	35.99	14.34	93.67
Heat Equivalent Ratio* [-]	0.10～7.17	0.50～1.69	0.63～1.40	0.51～2.51
Maximum Combustion Potential* [m/s]	2.91	0.37	0.07	0.43
Minimum Self-ignition Temperature* [℃]	500	537	651	432
Generated CO_2 [g/MJ]	0	54.8	0	64.4
Generated H_2O [g/MJ]	74.8	44.8	85.4	35.1

* Source: Journal of the Combustion Society of Japan Vol 58, Issue 183, (2016), 41-48

4. Comparison of Heat Required to Produce 1mol of Hydrogen

	Method	Thermochemical Equation	Heat Required to Produce 1mol of Hydrogen
(1)	**Methane Pyrolysis**	CH_4 (g) + 74.4kJ = $2H_2$ (g) + C	37.2kJ/mol
(2)	**Methane Reforming**	① CH_4 (g) + H_2O (g) + 205.7kJ = CO (g) + $3H_2$ (g) ② CO (g) + H_2O (g) = H_2 (g) + CO_2 (g) + 41.2kJ ⇒ CH_4 (g) + $2H_2O$ (g) = CO_2 (g) + $4H_2$ (g) - 164.5kJ (=①+②)	41.1kJ/mol
(3)	**Ammonia Decomposition**	NH_3 (g) + 46.1kJ = $3/2H_2$ (g) + $1/2N_2$ (g)	30.7kJ/mol
(4)	**MCH Dehydrogenation**	$C_6H_{11}CH_3$ + 202.5kJ = $C_6H_5CH_3$ + $3H_2$ (g)	67.5kJ/mol

5. Conversion Tables

5-1. Unit Conversion Table

Energy

	Per Million British Thermal Units (MmBtu)	Per British Thermal Unit (Btu)	Kilowatt Hour (kWh)	Megajoule (MJ)	Kilocalorie (kcal)	Tonne of Oil Equivalent (toe)
Per Million British Thermal Units (MmBtu)	1	1.000 x 10^{6}	2.931 x 10^{2}	1.055 x 10^{3}	2.519 x 10^{5}	2.519 x 10^{-2}
Per British Thermal Unit(Btu)	1.000 x 10^{-6}	1	2.930 x 10^{-4}	1.055 x 10^{-3}	2.519 x 10^{-1}	2.519 x 10^{-8}
Kilowatt Hour (kWh)	3.412 x 10^{-3}	3.412 x 10^{3}	1	3.6	8.598 x 10^{2}	8.598 x 10^{-5}
Megajoule (MJ)	9.478 x 10^{-4}	9.478 x 10^{2}	2.777 x 10^{-1}	1	2.388 x 10^{2}	2.388 x 10^{-5}
Kilocalorie (kcal)	3.968 x 10^{-6}	3.968	1.163 x 10^{-3}	4.186 x 10^{-3}	1	1.000 x 10^{-7}
Tonne of Oil Equivalent (toe)	3.968 x 10^{1}	3.968 x 10^{7}	1.163 x 10^{4}	4.186 x 10^{4}	1.000 x 10^{7}	1

Volume

	Cubic Meter (m^3)	Cubic Feet (cf)	US Gallon (US gal)	US Barrel (bbl)	Liter (litre)
Cubic Meter (m^3)	1	3.531 x 10^{1}	2.641 x 10^{2}	6.29	1 x 10^{3}
Cubic Feet (cf)	2.831 x 10^{-2}	1	7.480	1.781 x 10^{-1}	2.831 x 10^{1}
US Gallon (US gal)	3.785 x 10^{-3}	1.336 x 10^{-1}	1	2.38 x 10^{-2}	3.785
US Barrel (bbl)	1.589 x 10^{-1}	5.614	42	1	1.589 x 10^{2}
Liter (litre)	1 x 10^{-3}	3.531 x 10^{-2}	2.641 x 10^{-1}	6.289 x 10^{-3}	1

Mass

	Kilogram (kg)	Ton (t)	UK Ton (UK ton)	US Ton (US ton)	Pound (lb)
Kilogram (kg)	1	1.000 x 10^{-3}	9.842 x 10^{-4}	1.102 x 10^{-3}	2.204
Ton (t)	1 x 10^{3}	1	9.842 x 10^{-1}	1.102	2.20462 x 10^{3}
UK Ton (UK ton)	1.016 x 10^{3}	1.016	1	1.120	2.240 x 10^{3}
US Ton (US ton)	9.071 x 10^{2}	9.071 x 10^{-1}	8.928 x 10^{-1}	1	2 x 10^{3}
Pound (lb)	4.535 x 10^{-1}	4.535 x 10^{-4}	4.464 x 10^{-4}	5 x 10^{-4}	1

5-2. Hydrogen Cost Simple Conversion Table

H_2 Cost		$\$/\mathrm{Nm}^3$	€/Nm^3	Yen/kg	$\$/\mathrm{kg}$	€/kg	Yen/MmBtu	$\$/\mathrm{MmBtu}$	€/MmBtu	Yen/MJ	$\$/\mathrm{MJ}$	€/MJ	Yen/kWh-th	$\$/\mathrm{kWh\text{-}th}$	€/kWh-th
30.00	**Yen/Nm^3**	0.286	0.240	336	3.20	2.69	2,480	23.6	19.8	2.35	0.0224	0.0188	8.5	0.0805	0.0677

- The conversion table was made based on the Japanese government's target of 30 yen/ Nm^3 by around 2030 and the following presuppositions.

0.08932 kg/Nm^3 1,055 MJ/MmBtu
12.77 MJ – HHV/Nm^3 3.6 MJ/kWh-th

- Exchange rate: ¥105/US $ ¥125/€

6. Gas Turbine Lineup

Mitsubishi Power gas turbines made with cutting-edge technology

Small and medium capacity gas turbines (41 MW to 116 MW)

H-25-series
H-100-series

Large capacity gas turbines (114 MW to 574 MW)

For 60 Hz

- M501J-series
- M501G-series
- M501F-series
- M501D-series

For 50 Hz

- M701J-series
- M701F-series
- M701G-series
- M701D-series

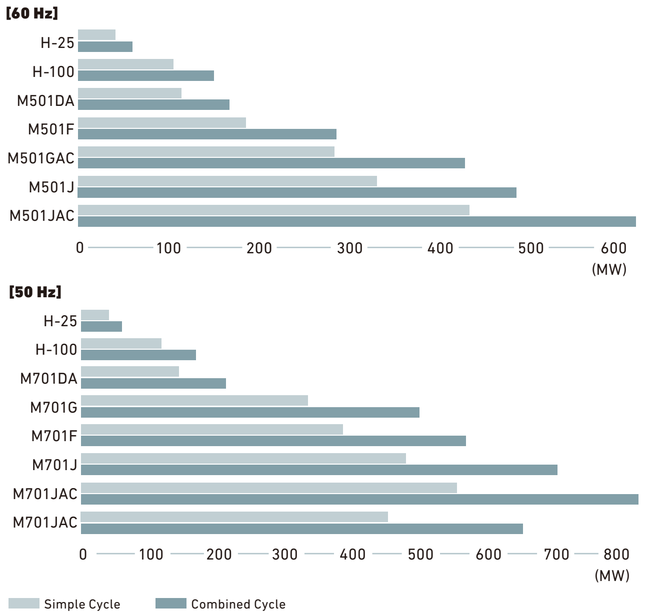
Aero-Derivative Gas Turbines (30 MW to 140 MW)

- FT8® MOBILEPAC®
- FT8® SWIFTPAC®
- FT4000® SWIFTPAC®

Powering the world with a full range of gas turbines

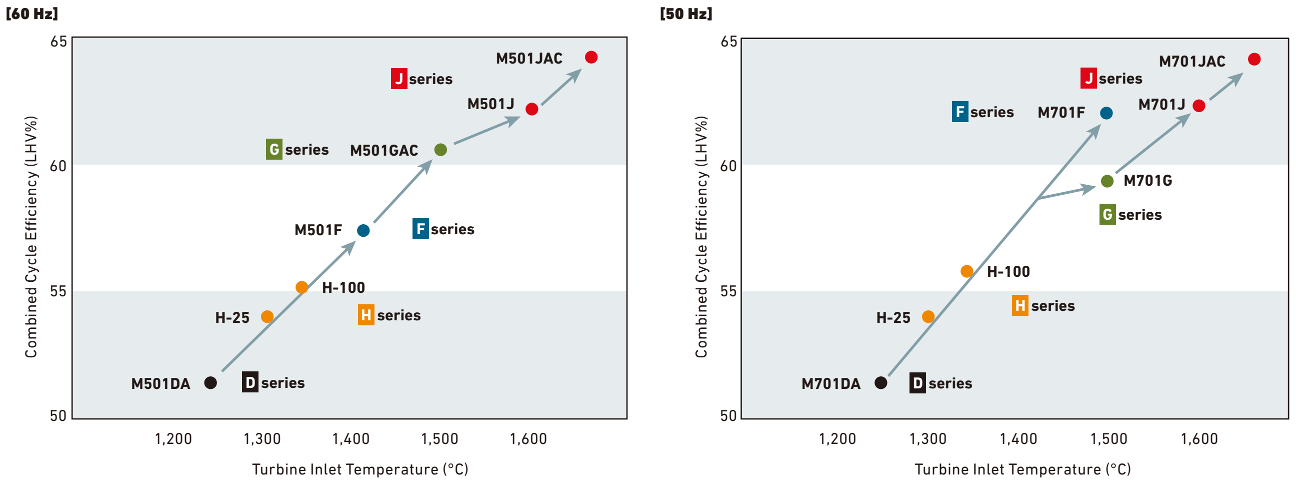
To meet the power demands of industries and societies around the world, Mitsubishi Power produces a wide range of gas turbines from the 30 MW to the 574 MW class for power generation and industrial use. These turbines drive the development and supply of highly-efficient, clean energy around the world. In fact, Mitsubishi Power has delivered more than 1,600 gas turbines to customers in more than 50 countries worldwide.

Gas Turbine and Combined Cycle Output



- (ISO, 1 GT + 1 ST, GAS FUEL)

Thermal Efficiency of Combined Cycle Systems



Performance

Simple Cycle Specs

	ISO Base Rating (kW)	LHV Heat Rate		Efficiency (%-LHV)	Pressure Ratio	Turbine Speed (rpm)	Exhaust Flow (kg/s)	Exhaust Temp (°C)
		(kJ/kWh)	(Btu/kWh)					
50Hz / 60Hz								
H-25*	41,030	9,949	9,432	36.2	17.9	7,280	114	569
50Hz								
H-100*	116,450	9,400	8,909	38.3	18	3,000	296	586
M701DA	144,090	10,350	9,810	34.8	14	3,000	453	542
M701G	334,000	9,110	8,630	39.5	21	3,000	755	587
M701F	385,000	8,592	8,144	41.9	21	3,000	748	630
M701J	478,000	8,511	8,067	42.3	23	3,000	896	630
M701JAC	448,000	8,182	7,755	44.0	25	3,000	765	663
M701JAC	574,000	8,295	7,826	43.4	25	3,000	1,024	646
60Hz								
H-100*	105,780	9,421	8,930	38.2	18.4	3,600	293	534
M501DA	113,950	10,320	9,780	34.9	14	3,600	354	543
M501F	185,400	9,740	9,230	37.0	16	3,600	468	613
M501G	267,500	9,211	8,730	39.1	20	3,600	612	601
M501GAC	283,000	9,000	8,531	40.0	20	3,600	618	617
M501J	330,000	8,552	8,105	42.1	23	3,600	620	635
M501JAC	435,000	8,182	7,755	44.0	25	3,600	764	645

Mechanical Drive Specs

	ISO Base Rating		LHV Heat Rate		Efficiency (%-LHV)	Pressure Ratio	Turbine Speed (rpm)	Exhaust Flow (kg/s)	Exhaust Temp (°C)
	(hp)	(kW)	(kJ/kWh)	(Btu/hp-hr)					
H-100*	144,350	107,650	9,256	6,542	38.9	18.4	3,600	293	534
H-100*	160,780	119,900	9,266	6,549	38.9	20.1	3,000	315	552

Aero-Derivative Gas Turbine Specs

	ISO Base Rating (kW)	LHV Heat Rate		Efficiency (%-LHV)	Turbine Speed (rpm)	Exhaust Flow (kg/s)	Exhaust Temp (°C)
		(kJ/kWh)	(Btu/kWh)				
50Hz							
FT8®	28,528	10,376	9,834	34.7	3,000	92	496
FT4000®	70,154	8,908	8,443	40.4	3,000	183	431
FT4000®	140,500	8,896	8,431	40.5	3,000	367	431
60Hz							
FT8®	30,941	9,825	9,312	36.7	3,600	92	491
FT4000®	71,928	8,686	8,232	41.5	3,600	183	422
FT4000®	144,243	8,661	8,209	41.6	3,600	367	422

Notes: (1) All ratings are defined at ISO standard reference conditions: 101.3kPa. 15°C and 60% RH.
(2) All ratings are at generator terminals and are based on the use of natural gas fuel.
** without inlet and exhaust losses*

Combined Cycle Specs

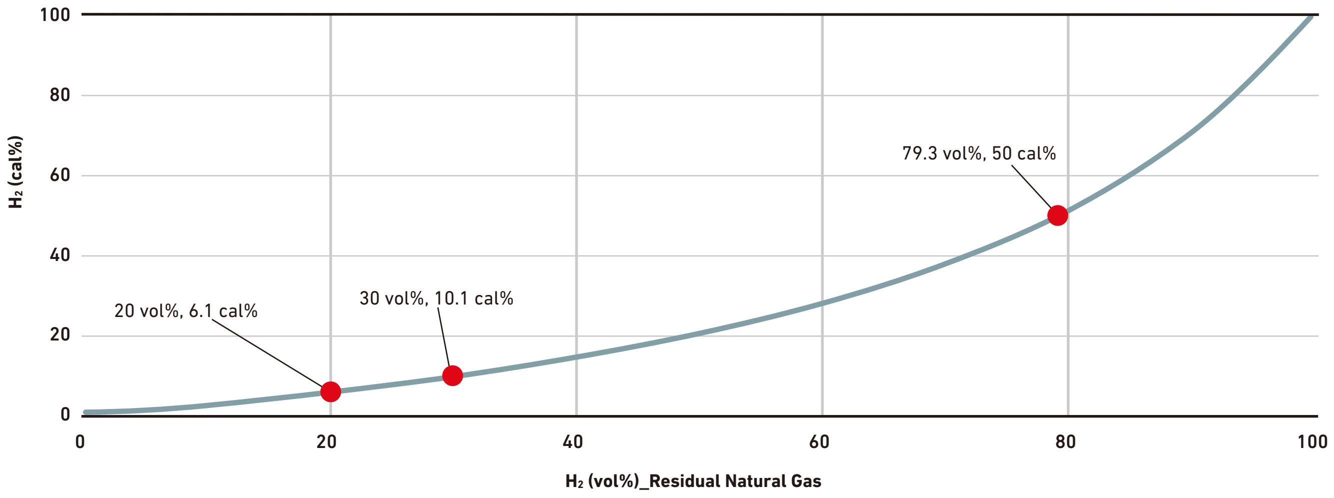
	Plant Output (kW)	LHV Heat Rate		Plant Efficiency (%)	Gas Turbine Power (kW)	Steam Turbine Power (kW)	Number & Type Gas Turbine
		(kJ/kWh)	(Btu/kWh)				
50Hz / 60Hz							
MPCP1(H-25)	60,100	6,667	6,319	54.0	39,600	20,500	1×H-25
MPCP2(H-25)	121,400	6,606	6,261	54.5	79,200	42,200	2×H-25
50Hz							
MPCP1(H-100)	171,000	6,272	5,945	57.4	112,700	58,300	1×H-100
MPCP2(H-100)	346,000	6,207	5,884	58.0	225,400	120,600	2×H-100
MPCP1(M701DA)	212,500	7,000	6,635	51.4	142,100	70,400	1×M701DA
MPCP2(M701DA)	426,600	6,974	6,610	51.6	284,200	142,400	2×M701DA
MPCP3(M701DA)	645,000	6,947	6,585	51.8	426,300	218,700	3×M701DA
MPCP1(M701F)	566,000	5,807	5,504	62.0	379,300	186,700	1×M701F
MPCP2(M701F)	1,135,000	5,788	5,486	62.2	758,600	376,400	2×M701F
MPCP1(M701G)	498,000	6,071	5,755	59.3	325,700	172,300	1×M701G
MPCP2(M701G)	999,400	6,051	5,735	59.5	651,400	348,000	2×M701G
MPCP1(M701J)	701,000	5,779	5,477	62.3	472,300	228,700	1×M701J
MPCP1(M701JAC)	650,000	<5,625	<5,332	>64.0	441,700	208,300	1×M701JAC
MPCP1(M701JAC)	840,000	<5,625	<5,332	>64.0	570,900	269,100	1×M701JAC
60Hz							
MPCP1(H-100)	150,000	6,534	6,193	55.1	102,500	47,500	1×H-100
MPCP2(H-100)	305,700	6,418	6,083	56.1	205,000	100,700	2×H-100
MPCP1(M501DA)	167,400	7,000	6,635	51.4	112,100	55,300	1×M501DA
MPCP2(M501DA)	336,200	6,974	6,610	51.6	224,200	112,000	2×M501DA
MPCP3(M501DA)	506,200	6,947	6,585	51.8	336,300	169,900	3×M501DA
MPCP1(M501F)	285,100	6,305	5,976	57.1	182,700	102,400	1×M501F
MPCP2(M501F)	572,200	6,283	5,955	57.3	365,400	206,800	2×M501F
MPCP1(M501G)	398,900	6,165	5,843	58.4	264,400	134,500	1×M501G
MPCP2(M501G)	800,500	6,144	5,823	58.6	528,800	271,700	2×M501G
MPCP1(M501GAC)	427,000	5,951	5,640	60.5	280,800	146,200	1×M501GAC
MPCP2(M501GAC)	856,000	5,931	5,622	60.7	561,600	294,400	2×M501GAC
MPCP3(M501GAC)	1,285,000	5,931	5,622	60.7	842,400	442,600	3×M501GAC
MPCP1(M501J)	484,000	5,807	5,504	62.0	326,200	157,800	1×M501J
MPCP2(M501J)	971,000	5,788	5,486	62.2	652,400	318,600	2×M501J
MPCP1(M501JAC)	630,000	<5,625	<5,332	>64.0	431,900	198,100	1×M501JAC
MPCP2(M501JAC)	1,263,000	<5,608	<5,315	>64.2	863,800	399,200	2×M501JAC

7. Fuel Consumption by Gas Turbine Type

Gas Turbine Type	Catalog Performance		Hydrogen		Natural Gas	
	ISO Base Rating (kW)	Efficiency (%-LHV)	(ton/hour)	(Nm^3/hour)	(ton/hour)	(Nm^3/hour)
50Hz / 60Hz						
H-25	41,030	36.2	4	45,000	9	12,000
50Hz						
H-100	116,450	38.3	10	112,000	24	30,000
M701F	385,000	41.9	28	312,000	72	90,000
M701J	478,000	42.3	34	379,000	88	110,000
M701JAC	448,000	44.0	31	345,000	79	99,000
M701JAC	574,000	43.4	40	445,000	103	128,000
60Hz						
H-100	105,780	38.2	9	101,000	22	28,000
M501F	185,400	37.0	16	178,000	39	49,000
M501J	330,000	42.1	24	267,000	61	76,000
M501GAC	283,000	40.0	22	245,000	55	69,000
M501JAC	435,000	44.0	30	334,000	77	96,000

- Atmospheric temperature 15°C base (ISO standard)
- Fuel consumption when 100% hydrogen-fired is estimated based on the performance of a natural gas-fired system.

8. Co-firing of Hydrogen and Natural Gas:
The Relation between Volume Fraction and Thermal Ratio



9. Hydrogen Production Process

	Common name for hydrogen	Origin & Production Method	Mitsubishi Heavy Industries Group's Related Products & Technologies
Carbon-free Hydrogen	■ Green	Renewable Electricity → Electrolysis $H_2O \rightarrow H_2 + \frac{1}{2}O_2$	Wind Turbines Water Electrolyzer
	■ Pink	Nuclear Heat → Pyrolysis/Electrolysis $CH_4 \rightarrow 2H_2 + C$	High-temperature Gas-cooled Reactor
	■ Turquoise	Fossil Fuel → Pyrolysis $CH_4 \rightarrow 2H_2 + C$	Methane Pyrolysis Technology
	■ Blue	Fossil Fuel → Reforming & CO_2 Capture $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	Natural Gas Reforming Apparatus Coal Gasifier CO_2 Capture Technology
Conventional Hydrogen (CO_2 emission)	■ Gray	Fossil Fuel → Reforming (CO_2 release into the atmosphere) $CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	Natural Gas Reforming Apparatus Coal Gasifier

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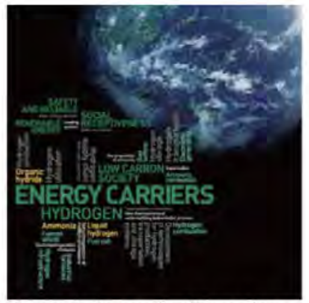
CO_2-Free Energy (Ammonia)



Strategic Innovation Promotion Program (SIP) Energy Carriers(1)

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NORIAKI SENBA[*4] **HIROMITSU NAGAYASU**[*5]

In order to abide by the Paris Agreement, it is necessary for CO_2 emissions to be reduced to net zero in the second half of this century, and in other words, fuel that emits no CO_2 (CO_2-free fuel) is in demand. Among such fuel, ammonia is a portable fuel which is easy to carry, and it can be easily produced from natural gas. In addition, the capture and storage of CO_2 emitted in the production of ammonia prevent the emission of CO_2. The production of ammonia has a long history, and it is now distributed at relatively low prices throughout the world. The use of ammonia by direct combustion is also becoming feasible through research on Energy Carriers in the Strategic Innovation Promotion Program (SIP). We hope that a system for using CO_2-free fuel will be developed and such fuel will be used to prevent global warming.

1. Introduction

(1) Paris Agreement and zero CO_2 emissions target

In December 2015, the Paris Agreement was adopted. The general objective of the Paris Agreement is to cap the increase in the global average temperature at 2°C above pre-industrial levels. In addition, in consideration for countries especially vulnerable to climate change, it stipulates that efforts to limit the temperature increase to 1.5°C should be pursued.

To that end, the long-term goal that total global greenhouse gas emissions should be limited to the amount that the ecological system could absorb in the second half of this century was set. This goal is intended to reduce greenhouse gas emissions by human activities to substantially zero.

In order to abide by the Paris Agreement, CO_2 emissions reduction in every field, the reduction of CO_2 emissions to zero in the second half of this century and the introduction of methods for reducing CO_2 in the atmosphere known as negative emission technologies, are necessary.

(2) Need for CO_2-free fuel

In recent years, the introduction of renewable energy such as solar power and wind power has been promoted, and the ratio of renewable energy used in the electric power sector will further increase. In the future, the need for CO_2-free fuel will be diversified, for example, for use in time zones that cannot be covered by renewable energy, for the load adjusting function of electric power, for uses as heat sources of general industries where it is difficult to use renewable energy and for use in fields such as transportation where CO_2 capture and storage cannot be applied.

In Japan, the study of the use of hydrogen energy has been promoted since the WE-NET Project was carried out. Recently, the use of hydrogen has been studied for the purpose of preventing global warming rather than enhancing energy security.

For the transportation of hydrogen, the use of liquefied hydrogen, organic hydride and ammonia has been studied. If the production of hydrogen without the emission of CO_2 is made possible, the remaining challenge is how to transport and use hydrogen in economical ways.

In any case, the provision of inexpensive and CO_2-free fuel will be demanded in various fields in the future.

(3) SIP Energy Carriers

We have conducted research and development on liquefied hydrogen, organic hydride and ammonia as "Energy Carriers" in the Strategic Innovation Promotion Program (SIP). The research and development of the production of carriers (i.e., production from petroleum, natural gas and coal and production from renewable energy), transportation and utilization (i.e., use as hydrogen and direct use of ammonia) have been conducted in the 5-year plan since fiscal year 2014. In the production of CO_2-free fuel such as hydrogen and ammonia from fossil fuel such as petroleum, natural gas and coal, CO_2 capture and storage (CCS) is indispensable. We also conducted testing and research for the inexpensive production of hydrogen through the electrolysis of water using electric power and high-temperature heat produced from renewable energy. **Figure 1**(1) shows an overview of testing and research on energy carriers.

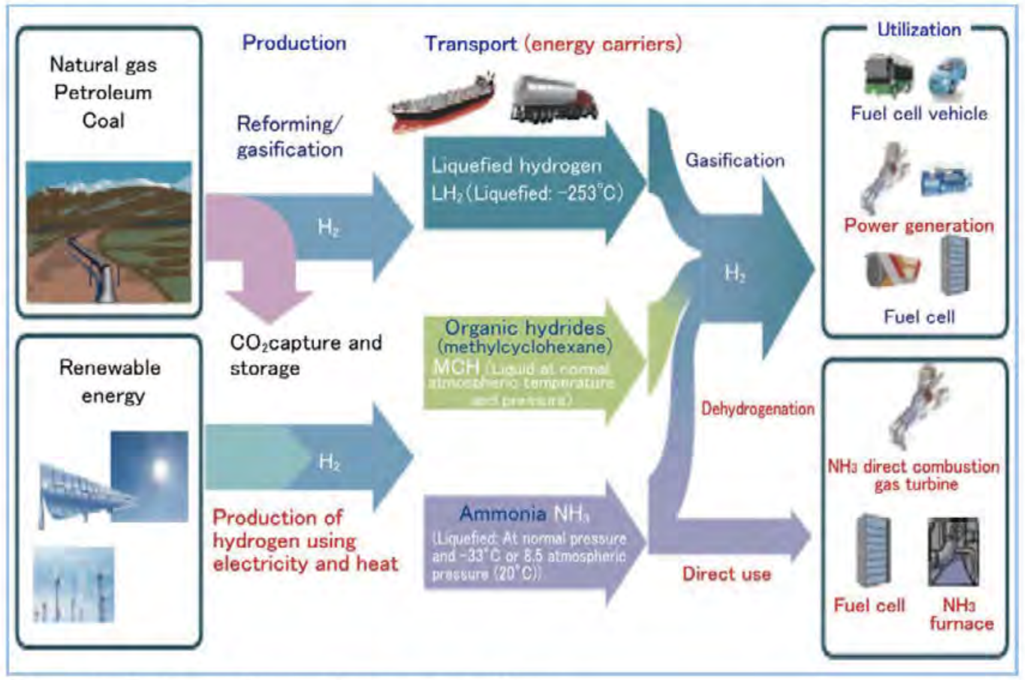

Figure 1 Testing and research on energy carriers

2. Efforts for SIP Energy Carriers

(1) Testing and research on energy carriers as fuel

Testing and research on Energy Carriers(1) have been conducted in the 5-year plan from FY2014 to FY2018 and three methods for carrying hydrogen have been evaluated.

a. High-temperature solar heat supply system
b. Hydrogen production using heat
c. Development of ammonia synthesis process using CO_2-free hydrogen
d. Basic technology for hydrogen station using ammonia
e. Ammonia fuel cell
f. Ammonia direct combustion
g. Development of hydrogen supply technology using organic hydride
h. Development of cargo loading/unloading system for liquid hydrogen and the relevant rules for operation
i. Development of hydrogen engine technology

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j. Safety assessment of energy carrier

This research on hydrogen production and the utilization of hydrogen/ammonia was conducted with the aim of evaluating which methods (including hydrogen transportation methods) are desirable, and to represent Japan's trailblazing development of hydrogen utilization technology ahead of other countries. In the latter half of the 5-year plan, research mainly focused on the direct use of ammonia, and testing and research on ammonia direct combustion in gas turbines, reciprocating engines, boilers and industrial furnaces and direct ammonia use in solid oxide fuel cells (SOFC) were conducted. In July 2017, ammonia mixed combustion testing was conducted at a coal-fired power plant of Chugoku Electric Power Co., Inc. Through this testing and research, the prospect of putting ammonia direct combustion into actual use was obtained, which was a significant outcome of testing and research on energy carriers.

(2) Evaluation of three methods

Japan has few petroleum, natural gas and coal resources, all of which have been conventionally used for fuel. Even if renewable energy is introduced to the fullest extent possible, it is said that it cannot cover all the energy required in Japan. Therefore, it is absolutely necessary to produce CO_2-free fuel from overseas energy sources or import it. In the case of the transport of materials such as fuel in large amounts, the most economical method for liquid or gaseous fuel is to use pipelines, but when transporting over long distances or across the ocean, it must be liquefied and transported by ship.

The liquefying temperature of hydrogen is very low at -253°C and the amount of power required for liquefying it is very large. Furthermore, it is not easy to maintain the temperature at -253°C.

Ammonia becomes a liquid at -33°C and under atmospheric pressure. On the other hand, when ammonia is pressurized, it becomes a liquid at 8.5 atm and at ambient temperature, providing the advantages of ease of handling and its usability as a direct fuel. Concerning organic hydride, methylcyclohexane produced by adding hydrogen to toluene can be transported at ambient temperature and under atmospheric pressure, but a large amount of energy is required for extracting hydrogen from methylcyclohexane.

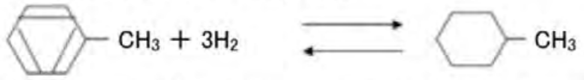
Based on the physical and chemical properties of ammonia and the fact that it is currently distributed throughout the world, the conclusion was reached on "Energy Carriers" in the SIP that ammonia can play an important role as a CO_2-free fuel.

Table 1(2) presents a comparison of the physical properties of compressed hydrogen, liquefied hydrogen, methylcyclohexane and ammonia.

Table 1 Physical properties of NH3 and major energy carriers

	Hydrogen content (weight %)	Hydrogen density (kg・H_2/m^3)	Boiling point (°C)	Hydrogen release enthalpy change* (kJ/molH_2)	Other properties**
Ammonia	17.8	121	-33.4	30.6	Acutely toxic, corrosive
Methylcyclohexane (MCH)	6.16	47.3	101	67.5	Inflammable, irritant
Liquefied hydrogen	100	70.8	-253	0.899	Highly inflammable, highly combustible, explosive
Compressed hydrogen (350 atm)	100	23.2	–	–	
Compressed hydrogen (700 atm)	100	39.6	–	–	

* Carrying hydrogen using the difference of hydrogen between MCH toluene (C7H8) (molecular weight 92) and MCH (C7H14) (molecular weight 98)



* Hydrogen release enthalpy change: Energy required in extraction of hydrogen

** The descriptions in "Other properties" were excerpted from the summary of "Hazardous information" in the MSDS. For the exact properties of each material, see the MSDS for each material.

(3) Effectiveness of ammonia

The physical properties of ammonia are almost the same as those of LPG, and ammonia can be transported using LPG vessels. At present, the production of ammonia amounts to 180 million tons/year globally. About 80% of the production volume is used in fertilizer such as urea, and about 10%, which is 18 million tons/year, is internationally distributed.

At the present time (October 2018), the price of ammonia on an FOB basis in the Gulf of Mexico region in the U.S. is 250US$/T. This price is converted to 14.3US$ in terms of 1 million BTU (MMBTU), which is equal or slightly higher in terms of calorific value compared with the price of crude oil of 70US$/BBL (13.5 US$/MMBTU) (WTI price).

As with LPG, ammonia becomes a liquid when it is pressurized at ambient temperature and it is a portable fuel that is easy to handle in final use.

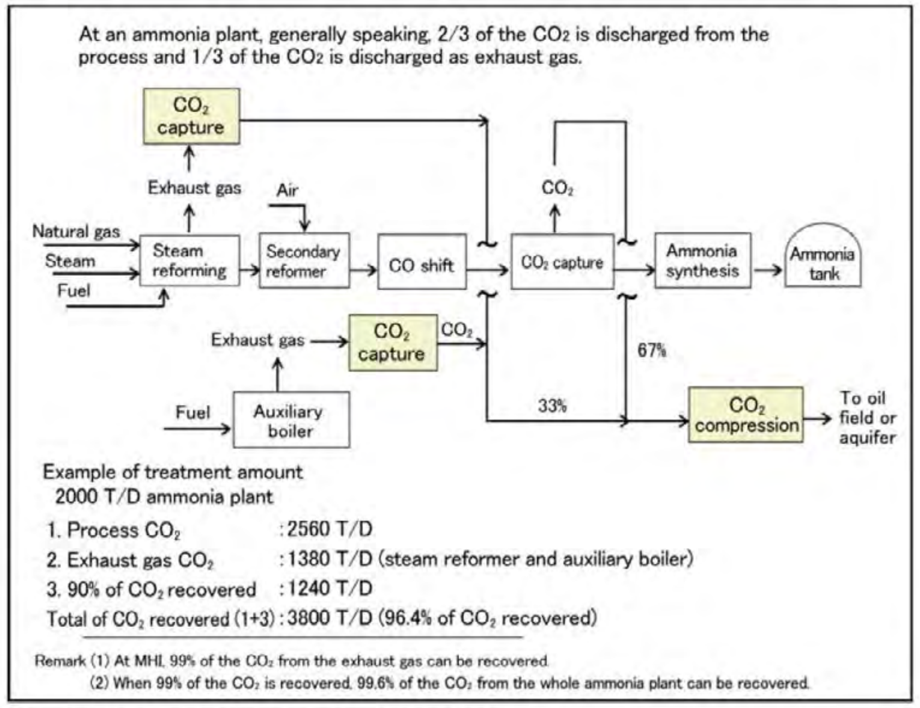
In particular, when it is used as a fuel for transportation, its ease of transportation at ambient temperature is a significant advantage. However, ammonia is toxic and emits an odor when it leaks, and if it is used near ordinary households, it may cause problems. Therefore, it is considered that ammonia will mainly be used in controlled areas such as in power plants, factories and cargo vessels.

3. Production method of CO_2-free ammonia

In 1913, Germans Haber and Bosch commercialized the process for synthesizing ammonia from hydrogen and nitrogen using an iron-based catalyst, and today the method is used in the production of ammonia. Mitsubishi Heavy Industries Engineering, Ltd. (MHIENG) has delivered many ammonia plants to various countries around the world since 1958. In current ammonia synthesis, natural gas is generally used as a feed stock.

By passing natural gas through a catalyst while heating it together with steam using a steam reformer, the natural gas is converted into hydrogen and CO. After that, air is injected, and the oxygen in the air is used for further combustion to convert the remaining methane into hydrogen and CO, and at the same time, nitrogen is supplied. Steam is added to the CO, which is converted into CO_2 and hydrogen using a catalyst. After that, the CO_2 is separated to produce hydrogen and nitrogen, and then ammonia is synthesized from the hydrogen and the nitrogen.

Figure 2 depicts the balance of CO_2 at a 2000 T/D-scale plant which is a standard ammonia plant. At the ammonia plant, about 2/3 of the CO_2 is separated from the process system, and about 1/3 of the CO_2 is discharged from the exhaust gas of the steam reformer and the auxiliary boiler. By capturing the CO_2 from this flue gases and storing it underground together with the CO_2 from the process system or using it for Enhanced Oil Recovery (EOR), this ammonia plant emits no CO_2. Thus, an ammonia fuel system that does not emit CO_2 can be established.



At an ammonia plant, generally speaking, 2/3 of the CO_2 is discharged from the process and 1/3 of the CO_2 is discharged as exhaust gas.

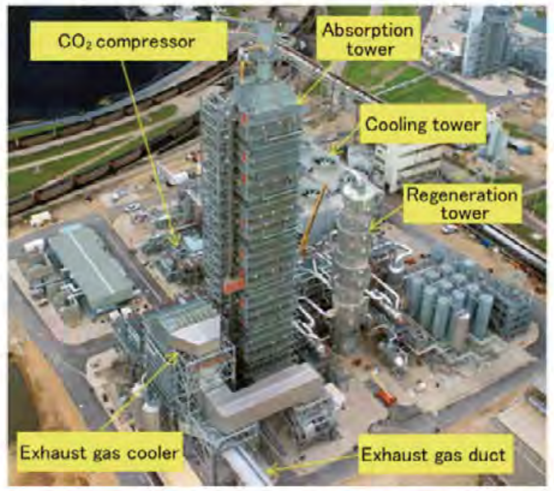
Example of treatment amount
2000 T/D ammonia plant

1. Process CO_2	:2560 T/D
2. Exhaust gas CO_2	:1380 T/D (steam reformer and auxiliary boiler)
3. 90% of CO_2 recovered	:1240 T/D
Total of CO_2 recovered (1+3)	:3800 T/D (96.4% of CO_2 recovered)

Remark (1) At MHI, 99% of the CO_2 from the exhaust gas can be recovered.
(2) When 99% of the CO_2 is recovered, 99.6% of the CO_2 from the whole ammonia plant can be recovered.

Figure 2 CO_2 balance at an ammonia plant

MHIENG delivered the world's largest CO_2 recovery system to a coal-fired power plant in Texas in the U.S. in January 2017, where the recovered CO_2 is used for EOR at the West Ranch oil field and crude oil is recovered, and CO_2 are stored in an oil reservoir. **Figure 3** gives an overview of the facility for recovering CO_2 from the coal-fired power plant.



NRG Energy, Inc. and JX Nippon Oil & Gas Exploration Corporation
Photo of Petra Nova project

Figure 3　Facility for recovering CO_2 from a coal-fired power plant

Since 2011, in Alabama in the U.S., MHIENG has conducted CO_2 capture from a coal-fired power plant and a demonstration test for storing the captured CO_2 in an aquifer (implemented by SECARB[※1]) jointly with Southern Company. **Figure 4** illustrates an overview of the CO_2 capture and storage project. As such, CO_2 capture and storage has been conducted on a commercial basis, and the technologies for CO_2 capture from exhaust gas at ammonia plants and the production of CO_2-free ammonia have already been established.

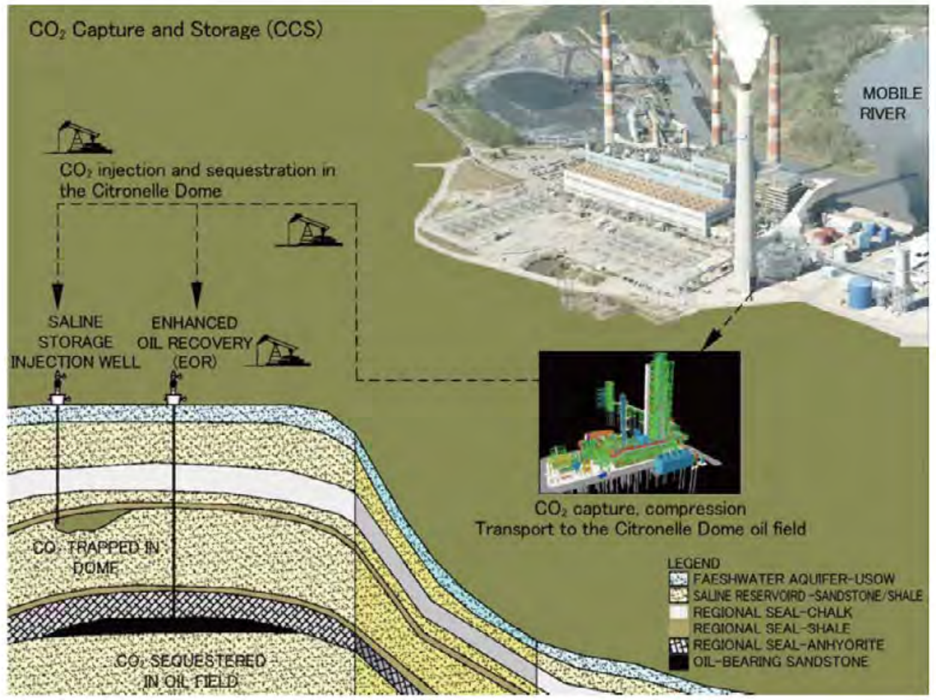


Figure 4　Overview of CO_2 capture and storage project

CO_2 from the process system can be stored as it is a total of 90% of the CO_2 from flue gas can be captured by the CO_2 recovery technology with which MHIENG has a significant amount of experience (KM CDR Process®[※2] developed in cooperation with Kansai Electric Power Co., Inc.), and the captured CO_2 is stored together with CO_2 from the process. As a result, 96% of the CO_2 generated in the production of ammonia can be stored. If 99% is captured from exhaust gas, 99.6% of the CO_2 can be stored, allowing the production of ammonia with almost no CO_2 emissions into the atmosphere.

There is another CO_2-free ammonia synthesis method in which electricity produced from renewable energy is used to electrolyze water and separate nitrogen in the air for the synthesis of ammonia. At present, inexpensive natural gas is produced in massive amounts in various places around the world, and therefore ammonia can be produced at a much lower cost by synthesis from natural gas compared with the use of renewable energy.

[※1] The Southeast Regional Carbon Sequestration Partnership

[※2] KM CDR Process® is a registered trademark of Mitsubishi Heavy Industries Engineering, Ltd. in Japan, the U.S., European Union (EUTM), Norway, Australia and China.

4. History of use of ammonia as fuel

Some people may not be familiar with the use of ammonia as fuel, but looking back to the Second World War, 100 ammonia-powered buses were used in Belgium.

At that time, diesel fuel could not be procured, and out of necessity, ammonia was used as fuel.

In another example from 1959 to 1968, the X-15 manned jet fighter of the U.S. Air Force used ammonia as fuel, and it reached a record speed of Mach 6.7 at an altitude of 107960m. The temperature was very low at an altitude of 100,000 meters, and it is assumed that the fact that ammonia does not solidify at low temperatures was the reason it was chosen as fuel.

5. Conclusion

CO_2-free fuel is strictly intended to prevent global warming. In order to achieve the target of +2°C or lower based on the Paris Agreement, global CO_2 emissions must be reduced to 1/2 by 2050, and advanced countries must reduce CO_2 emissions by 80%. To that end, CO_2-free fuel that can be used everywhere will become more important. MHIENG has already established commercial CO_2-free ammonia production technology and is ready to provide it at any time.

However, ammonia is more expensive than coal or LNG on the basis of its calorific value, and it is more expensive than even crude oil. For ammonia to be widely used as CO_2-free fuel, it seems that some political incentive is necessary in the early stages of introduction.

We are grateful to the people involved with the promotion of the research and development of "Energy Carriers" in the Strategic Innovation Promotion Program (SIP) who were helpful in writing this article.

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