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DEVELOPMENT OF HYDROGEN-FIRED GAS TURBINE COMBUSTOR

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ABSTRACT

The introduction of hydrogen energy is an effective option to obtain sustainable development of economic activity while helping prevent global warming. In order to realize a sustainable society, the Mitsubishi Heavy Industries Ltd. (MHI) Group is promoting research and development of hydrogen gas turbine technologies with the support of the New Energy and Industrial Technology Development Organization (NEDO). The purpose of this paper is to outline the activities and future prospects of hydrogen firing technology. As the first step to accelerate the hydrogen use by thermal power plant, hydrogen co-firing combustor was developed which can enable the use of existing facilities without large-scale modifications. Using a modified combustor, a co firing (30 vol.% of hydrogen with natural gas) test has been successfully completed without occurrence of flashback or a significant increase in the internal pressure fluctuation. This co-firing capability results in a reduction in carbon dioxide (CO_2) emissions by 10% when compared to conventional natural gas thermal power plant. As the next step, for 100% hydrogen firing, modifications of a different combustor developed for Integrated coal Gasification Combined Cycle (IGCC) plants is in progress. The elemental burner combustion tests at elevated pressures demonstrated that the modified burner achieved stable combustion and showed the possibility of suppressing NOx emissions.

NOMENCLATURE

CO_2	Carbon Dioxide
COG	Coke Oven Gas
DLN	Dry Low NOx
GTCC	Gas Turbine Combined Cycle
IGCC	Integrated coal Gasification Combined Cycle
NOx	Nitrogen Oxides
MHI	Mitsubishi Heavy Industries, Ltd
MPW	Mitsubishi Power, Ltd
NEDO	New Energy and Industrial Technology Development Organization

INTRODUCTION

An implementation of renewable energy is ongoing in order to suppress global warming. Since 2011, wind power generation has increased 40GW annually and is predicted to further expand to a maximum of about 2,110 GW and supply up to 20% of total electricity by 2030 (Fried et al., 2016). However, the balancing between supply and demand of the electrical grid will be an issue because, regardless of the actual demand, the amount of electricity generation by renewable energy fluctuates depending on the climate, weather conditions, and, the time of the day (day and night). Therefore, construction of the system to store the surplus electric energy and absorb the output fluctuation is indispensable for the efficient use of renewable energy. In particular, when the fluctuation cycle is long and a significant amount of energy capacity is required, such as the fluctuation between seasons, it is effective to apply this excess energy to produce and store hydrogen (Bielmann et al, 2011). This stored hydrogen can be used when renewable energy does not meet the electricity demand.

One of the promising power generation systems to effectively utilize hydrogen fuel is the gas turbine. Conventional gas turbines generally use natural gas as a fuel. Since CO_2 generation in the combustion of fossil fuels is one of the major factors of global warming, there is a movement to regulate its emission worldwide. Combustion of hydrogen does not generate CO_2, therefore, the amount of CO_2 emitted from gas turbines can be reduced by replacing natural gas with hydrogen as fuel.

The MHI Group has been developing gas turbine combustion technologies in three types: diffusion, multi nozzle, and multi cluster as shown Figure 1 (Miyamoto et al., 2018). Figure 2 shows MPW hydrogen-rich fuel operating experiences with diffusion combustors (Inoue et al., 2018). The MHI Group has been actively developing hydrogen-rich fuel firing for large scale gas turbine used in thermal power plants. For many years, refinery by-product gas (called off-gas), COG and synthesis gas have been used to generate power worldwide. The experience accumulated while burning these gases with various hydrogen content ratios in MPW gas turbines has served as the technical foundation for the current hydrogen combustion R&D activities. However, most of those plants applied diffusion type combustors (Nose et al., 2018), and required additional water or steam injection for NOx emission control; known as "wet" control approach. This approach reduces NOx emissions at the expense of reduced efficiency. In order to achieve high efficiency, DLN technology should be adopted. As the first step in promoting the hydrogen use, the MHI Group focused on the development of technology for multi nozzle DLN combustor for hydrogen co-firing using existing gas turbine facilities without the large-scale modification. As the next step, for 100 vol.% hydrogen combustion, the modification of multi cluster DLN combustor developed for IGCC is in progress.

This paper outlines the current progress and future prospect of technological development enabling hydrogen firing technology.

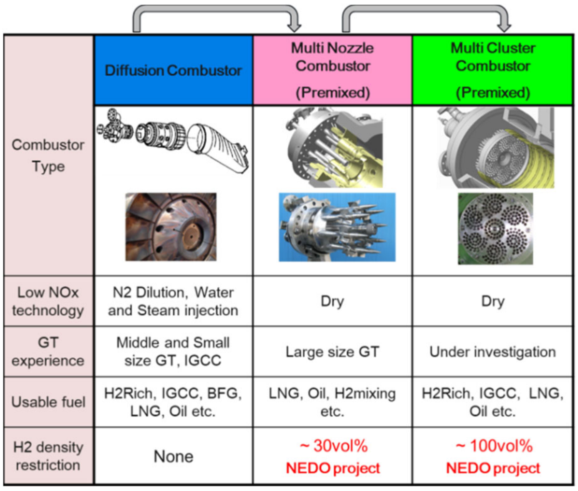

Fig. 1 Comparison between combustor types.

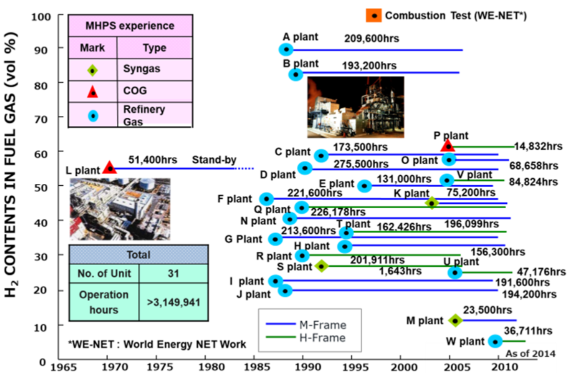

Fig. 2 Hydrogen rich fuel operating experiences with diffusion combustors.

CHALLENGES OF HYDROGEN COMBUSTION

The Dry Low NOx (DLN) combustor installed in MPW large gas turbine adopts the premixed combustion method to reduce NOx (nitrogen oxides, a known cause of acid rain). Figure 3 compares the main characteristics between the premixed combustion and the diffusion combustion. Since premixed combustion can reduce the local flame temperature compared with diffusion combustion, NOx emission can be reduced without steam/water injection. For this reason, premixed combustion is a technology currently widely applied in low NOx combustors. However, the stable combustion range for the premixed combustion is narrower than that of the diffusion combustion, moreover there is a higher risk of flashback.

Figure 4 provides sketches of flashback (Benim and Syed, 2014). Flashback is a phenomenon in which a flame moves upstream in the fluid when the flame speed is higher than the flow velocity. If flashback occurs inside the gas turbine combustor, there is a possibility of damaging upstream combustor parts. Therefore, it is important to prevent the flashback from occurring.

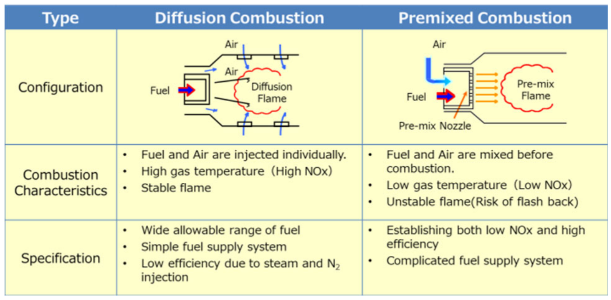

Fig. 3 Comparison of diffusion and premixed combustion.

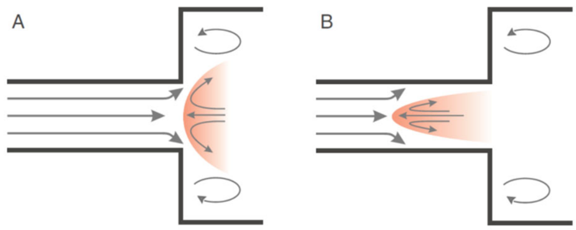

Fig. 4 Sketches of a stable flame (A) and a flame with flashback (B).

Table 1 Combustion properties of hydrogen and methane.

		Unit	H2	CH4
Lower Heating Value		kJ/m3	9883	32870
		kJ/kg	120.0	50.0
Flammability Limit	Upper	vol%	4.0	5.0
	Lower	vol%	75.0	15.0
Specific Gravity(25°C / Air = 1)		-	0.0695	0.554
Minimum Ignition Energy		mJ	0.018	0.2
Quenching Distance		mm	0.6	2.0
Diffusion Coefficient(0°C / 1atm)		mm2/s	61.1	19.6
Stoichiometric Air-Fuel Ratio		m3/m3	2.4	9.5
Laminar Burning Velocity		cm/s	291	37

In order to outline the issues and challenges in the use of hydrogen fuel, properties of hydrogen and methane, which are fuels that can be burned in a gas turbine, are compared in Table 1 (Ichikawa et al, 2019; Lewis and von Elbe, 1987). Important properties related to combustion characteristics are described in this section.

Minimum ignition energy / Ignition delay

The minimum ignition energy of hydrogen is about 1/10 of that of methane. The ignition delay time of hydrogen is about two orders of magnitude shorter than that of methane (Beerer et al, 2008).

These properties increase the risk of flashback and auto ignition of fuel-air mixture inside premixers.

Laminar burning velocity

Figure 5 shows the calculated laminar burning velocity of hydrogen and methane under typical gas turbine operating conditions. The laminar burning velocity was calculated using Chemkin-Pro with PREMIX code (ANSYS, 2016). GRI-Mech 3.0 (Smith et al., 1999) was used as the detailed chemical kinetic mechanism.

The maximum laminar burning velocity of methane is about 60 cm/s under the condition slightly exceeding the equivalence ratio Φ =1.0. On the other hand, the maximum laminar burning velocity of hydrogen increases even when the equivalence ratio exceeds 1.0, and the maximum value is more than 1000 cm/s at Φ =1.7. Figure 6 shows the difference of laminar burning velocity between hydrogen and methane as a function of adiabatic flame temperature. In the range of gas turbine operating conditions, the laminar burning velocity of hydrogen is several times faster than that of methane. Therefore, when hydrogen is mixed with natural gas fuel, the risk of flashback is higher compared with natural gas only.

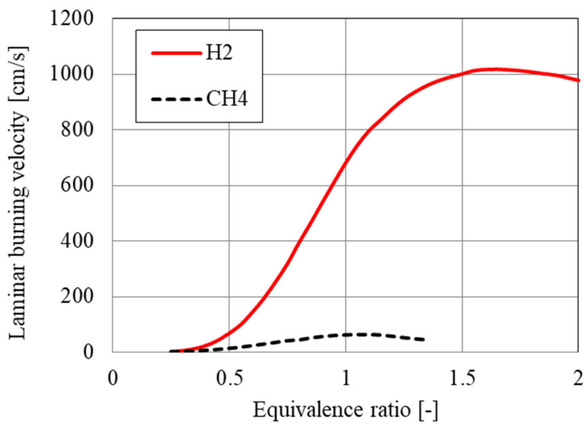

Fig. 5 Laminar burning velocities of hydrogen and methane at relevant gas turbine conditions.

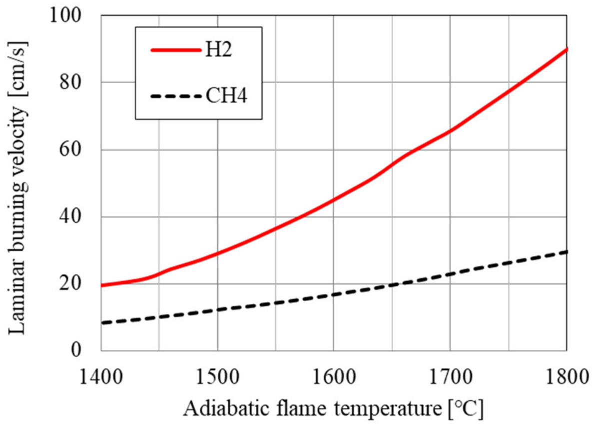

Fig. 6 Comparison of laminar burning velocities as a function of adiabatic temperature.

Quenching distance

Figure 7 shows the quenching distances of hydrogen and hydrocarbons (Lewis and von Elbe, 1987). The minimum quenching distance of hydrogen is about 0.06 cm, which is very small in comparison with hydrocarbons. Therefore, the hydrogen flame has a high possibility of propagating upstream in the wall boundary layer where hydrocarbon flames cannot exist. Since the combustion phenomena in the vicinity of the wall surface are affected by heat loss to wall that inhibits all reactions with high activation energies due to an insufficient temperature level , it is necessary to consider not only pressure and gas temperature conditions but also the other influencing factors such as wall temperature and wall material.

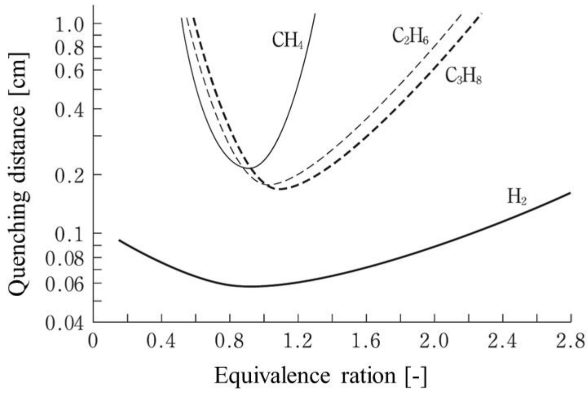

Fig. 7 Quenching distances of hydrogen and hydrocarbons.

As described in this section, the flame characteristics of hydrogen are very different from that of methane which is the main component of typical gas turbine natural gas fuel. In particular, in order to stably operate the gas turbine, it is necessary to develop a technology to deal with the increase in the flame speed.

MODIFICATIONS TO REALIZE HYDROGEN AND NATURAL GAS CO-FIRING

Since the flame speed of hydrogen is faster than that of natural gas, hydrogen co-firing may increase the risk of flashback, which typically result in damage of upstream parts inside the combustor. On the other hand, for hydrogen co-firing, large-scale modification of existing facilities is not realistic from the viewpoint of economic efficiency. Thus, hydrogen co-firing combustors which enables the use of existing facilities without large-scale modification has been developed.

In this section, the basic concept and verification result of hydrogen co-firing combustor are presented.

Basic concept of the improved nozzle

Figure 8 shows the schematic of the MPW gas turbine DLN combustor. The DLN combustion system consists of one central pilot nozzle and several main swirler nozzles for premixed flame around the pilot nozzle. The swirling flow promotes the mixing of fuel and air. Several articles (Kroner et al., 2007; Dam et al., 2011; Kroner et al., 2002) reported that in order to prevent the occurrence of flashback in such a swirling flow, it is necessary to increase the flow velocity at the core portion of the swirling flow beyond the flame speed.

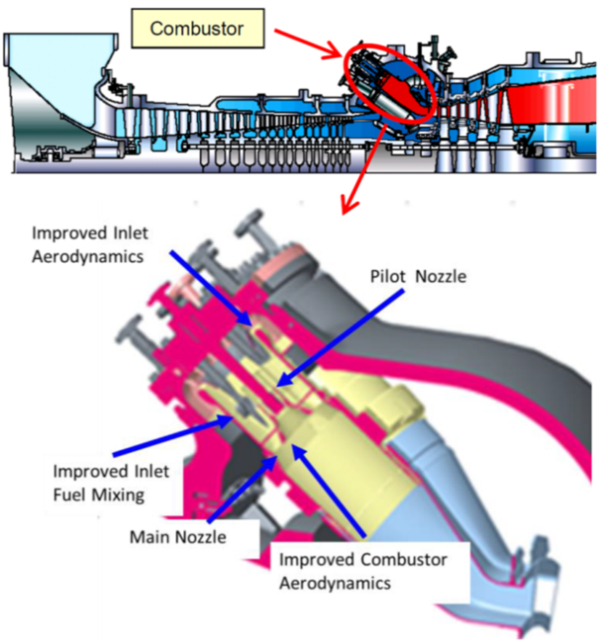

Fig. 8 Schematic of MPW gas turbine DLN combustor.

Figure 9 illustrates the outline of the original combustor nozzle and a modified combustor nozzle introduced with the purpose of decreasing the risk of flashback caused by hydrogen co-firing. The combustion air supplied from the compressor to the interior of the combustor passes through the swirler and it becomes a swirling flow. Fuel is supplied from small holes on the blade surface of the swirler and mixes rapidly with the surrounding air due to the swirling flow effect. A region with a low flow velocity exists in the vortex core of the swirling flow. The flashback phenomenon in the swirling flow is caused by the flame propagating upstream in the vortex core where the flow velocity is low. In the modified combustor nozzle, air is injected from the tip of the nozzle in order to increase the flow velocity in the vortex core. The injected air eliminates the low flow velocity region of the vortex core and thus reduce the occurrence of flashback.

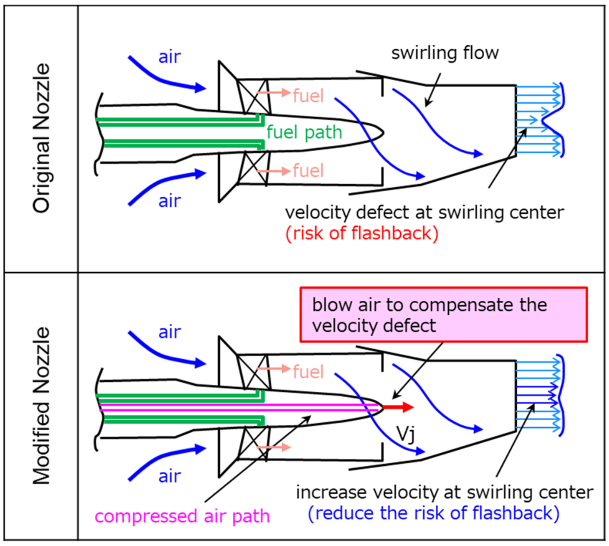

Fig. 9 Conceptual diagrams of original and improved nozzles.

Verification by air flow test

In order to verify the modified combustor concept, the flow velocity distribution was measured in an air flow test. Figure 10 shows a photograph of the flow test facility. The vortex core position might be not fixed in the turbulent flow.. For this reason, in the flow velocity measurement, it was necessary to perform measurement at the moment when the flow velocity lowers while the vortex core passes through the measurement point. Therefore, by applying a hot wire current meter (Kanomax 7000 Ser and φ5 μm I-type linear probe made of tungsten) for the flow velocity measurement and achieving high time resolution, it was possible to evaluate the instantaneous minimum flow velocity at the measurement position.

Figure 11 compares the flow velocity distributions of the original combustor and the modified combustor in the swirling regions. Focusing on the minimum flow velocity, which affects the occurrence of the flashback phenomenon, it was confirmed that flow velocity of the modified combustor was higher than that of the original combustor in the swirling center. Since the modified combustor injected only a small amount of air from a small hole at the tip of the nozzle, its effect on the flow velocity distribution in the region other than the vicinity of the swirling center was limited.

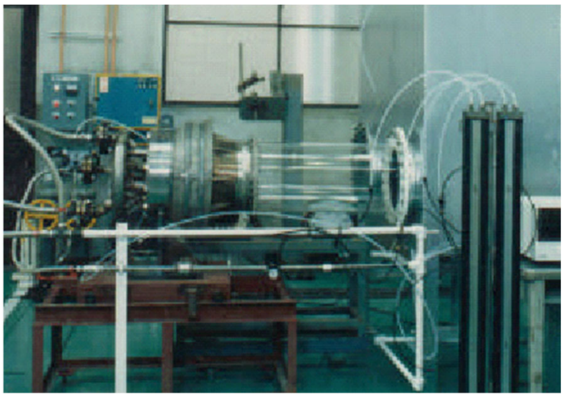

Fig. 10 Photograph of flow test facility.

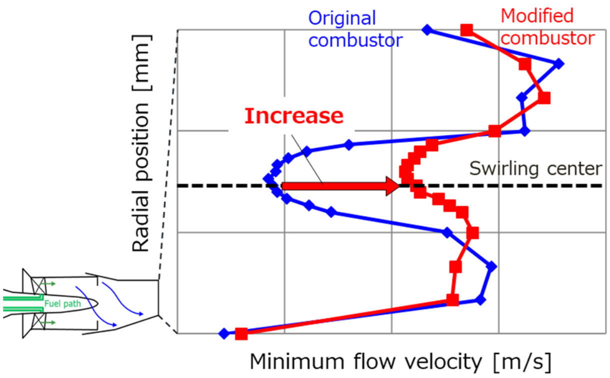

Fig. 11 Comparison of flow velocity distributions in swirling regions.

Verification by actual pressure combustion rig test

Important combustion characteristics of a gas turbine combustor include NOx and combustion dynamics. NOx is regulated on the amount of emissions to prevent the air pollution. Combustion dynamics needs to be kept below a threshold level in order to operate gas turbines stably. Since both NOx and combustion dynamics are affected by the pressure conditions, testing under the actual gas turbine pressure conditions is necessary. Therefore, in order to evaluate these combustion characteristics of the modified combustor with hydrogen co-firing, actual pressure combustion rig tests were conducted. Combustion rig testing was completed at high pressure at Mitsubishi Power Takasago Works (Figure 12). The high pressure and high temperature air used in the combustion rig test was supplied by a two-shaft gas turbine and is guided to a test sector simulating the casing shape of the gas turbine installed in the pressure vessel. In order to simulate the hydrogen content fuel of the actual plant, hydrogen was added in the natural gas supply line and supplied to the combustor. Hydrogen was added sufficiently upstream of the test facilities to ensure even mixing with natural gas before reaching the combustor.

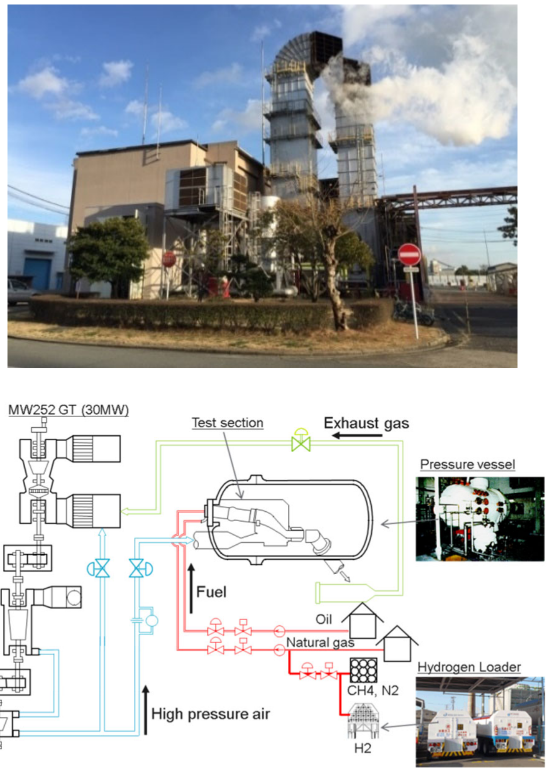

Fig. 12 Configuration of actual pressure combustion test facilities.

The combustion test was performed successfully for a 30 vol.% hydrogen-natural gas mixture. The addition of hydrogen decreased CO_2 emissions by 10% compared with natural-gas-fired power plant. The test was performed at actual condition corresponding to the turbine inlet temperature and pressure of a J-Series gas turbine. Figure 13 shows the NOx emissions with respect to the hydrogen mixing ratio. The results show a slight increase in NOx emissions with hydrogen addition, while it was still maintained within the operable range throughout the tested hydrogen mixing ratios. The slight increase in NOx may be attributed to the upstream shift of the flame position in the combustor due to the increased flame speed with hydrogen addition. Figure 14 shows the combustion dynamics level, which was not significantly affected by the hydrogen mixing ratio up to 30 vol.%. These test results demonstrate the capabilities of the modified combustor, which enables the gas turbine operation up to 30 vol.% hydrogen co-firing conditions without the occurrence of flashback or combustion dynamics (MPW, 2018).

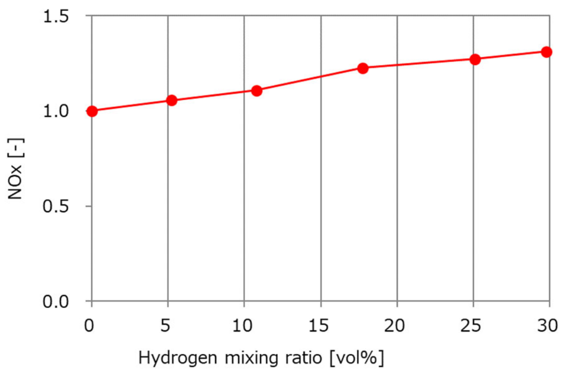

Fig. 13 NOx with respect to hydrogen mixing ratio.
(Normalized by 0 vol.% hydrogen condition)

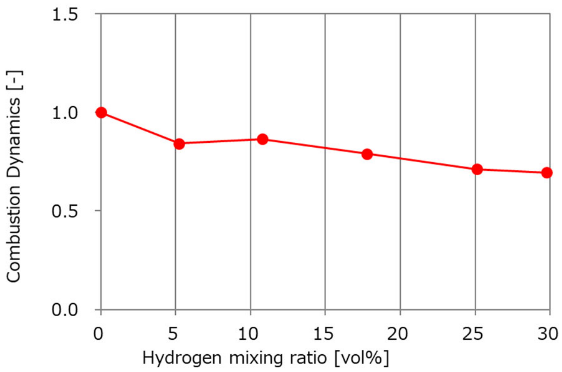

Fig. 14 Combustion dynamics
with respect to hydrogen mixing ratio.
(Normalized by 0 vol.% hydrogen condition)

MODIFICATIONS REQUIRED TO REACH HIGHER HYDROGEN CONTENT

Having tested 30 vol.% hydrogen co-firing, the next step is to aim at 100 vol.% hydrogen firing. In order to operate gas turbine power generation stably for a long period with 100 vol.% hydrogen firing, the prevention of flashback becomes the top priority. In the improvement of the original premixed combustor for natural gas firing as described above, it was difficult to cope with the remarkably high propagation speed of hydrogen flame, and the flashback countermeasure was not sufficient. Then, in order to reach higher than 30% hydrogen combustion, modification of a different combustor developed for IGCC, called multi-cluster has been adapted to large frame gas turbines.

In this section, the basic concept and verification results of hydrogen firing combustor are presented.

Basic concept of hydrogen combustor

By utilizing high flame holding properties of hydrogen, a premixing system capable of suppressing NOx without depending on flame holding by strong swirling flow was examined. Thus, multi cluster combustor, a shape in which hydrogen fuel and air are premixed in each pipe by arranging many fine tubular channels, was considered.

Cluster burner is roughly divided into two types**.** One is co-axial jet type, which is applied to combustors for Integrated coal Gasification Combined Cycle (IGCC) plants with high hydrogen fuel (Asai et al., 2016) as shown Figure 15. The other is jet-in-crossflow type as shown Figure 16 (Ichikawa et al., 2019) In each type, it is important to control the hydrogen fuel concentration distribution within a range that does not cause flashback and can suppress NOx. The design parameters include fuel injection hole diameter, and premixing distance, etc.

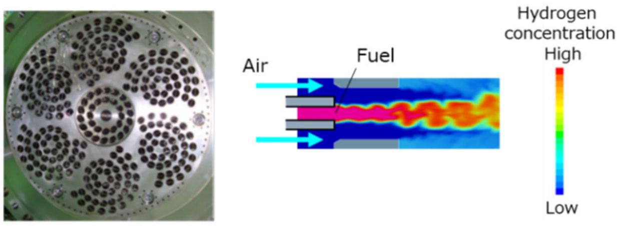

Fig. 15 Coaxial jet nozzle type
(Left：Combustor image,　Right：Part size CFD result)

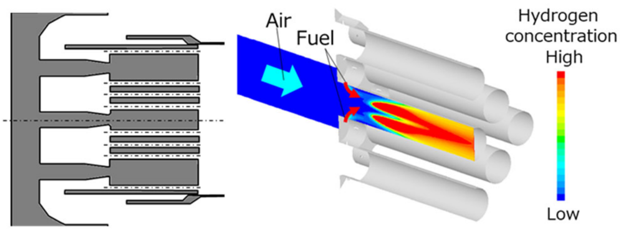

Fig. 16 Jet in crossflow nozzle type
(Left：Combustor image,　Right：Part size CFD result)

Verification by high pressure combustion rig test

Combustion tests were conducted with an elemental burner developed for hydrogen combustion at elevated pressures. Figure 17 shows the elemental burner combustion test facilities. The maximum working pressure and maximum working temperature of the combustion testing shell were 2.5 MPa and 500°C, respectively.

Figure 18 shows the NOx trends with respect to adiabatic flame temperature. The grey dotted line shows the NOx target value. This test result shows that NOx increased with adiabatic flame temperature. Based on the test results, it was estimated that NOx would fall below the target value under gas turbine operating condition.

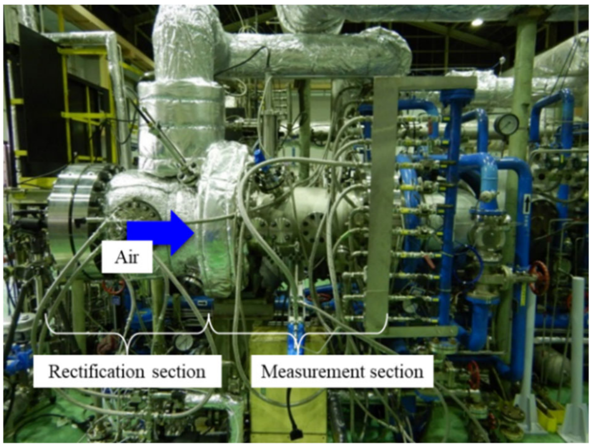

Fig. 17 Elemental burner combustion test facilities


Fig. 19 Saltend power plant in the UK (Humber)

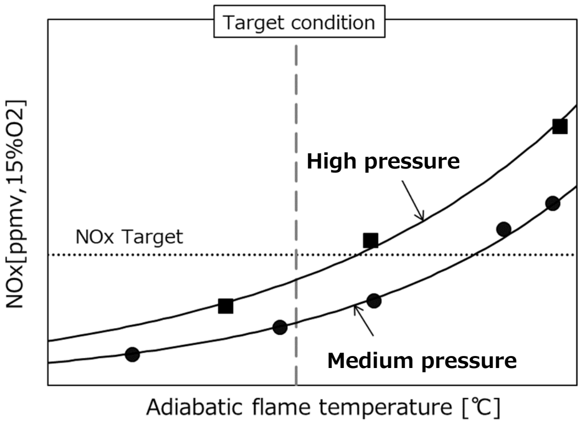

Fig. 18 NOx with respect to adiabatic flame temperature

Future prospects

MPW has been participating Zero Carbon Humber Partnership in the UK to create the world's first net zero industrial cluster by 2040 (MPW, 2020). The anchor project in this partnership is the Hydrogen to Humber (H2H) Saltend project which will establish the world's largest hydrogen production plant with carbon capture in Saltend Chemicals Park. In the first phase, this could reduce emissions by circa 900,000 tonnes per year as industrial customers switch fuel to low-carbon hydrogen and Triton Power's gas power plant blends hydrogen into the fuel supply via its upgraded MPW turbines.

MHI Group will continue to lead the development of hydrogen gas turbine technologies, and to contribute advanced projects globally to realize the sustainable development of economic activity while helping prevent global warming.

CONCLUSIONS

Aiming to realize a sustainable society, the MHI Group is promoting research and development of hydrogen gas turbine technologies with the support of NEDO.

As the first step to accelerate the hydrogen use by thermal power plants, a hydrogen co-firing combustor has been developed which can enable the use of existing facilities without large-scale modification. With a recently modified combustor, a 30 vol.% of hydrogen co-firing test has been successfully completed. This co-firing capability results in a reduction in carbon dioxide (CO_2) emissions by 10% when compared to conventional natural gas thermal power plant.

Next, for 100% hydrogen firing, modifications of a different combustor developed for IGCC are in progress. The elemental burner combustion tests at elevated pressures demonstrated that the modified concept burner achieved stable combustion and showed the possibility of suppressing NOx emissions.

ACKNOWLEDGEMENTS

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