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DEVELOPMENT OF HYDROGEN AND NATURAL GAS CO-FIRING GAS TURBINE

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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.

The Mitsubishi Heavy Industries Ltd. (MHI) Group is promoting research and development of a large gas turbine with hydrogen and natural gas co-firing capabilities. This effort is supported by the New Energy and Industrial Technology Development Organization (NEDO).

With a newly developed combustor, a 30vol% of hydrogen co-firing test has been successfully completed. This co-firing capability results in a reduction in carbon dioxide (CO2) emissions of 10% when compared to conventional natural gas thermal power plant.

NOMENCLATURE

BFG	Blast Furnace Gas
CCS	Carbon dioxide Capture and Storage
CO2	Carbon Dioxide
COG	Coke Oven Gas
DLN	Dry Low NOx
GTCC	Gas Turbine Combined Cycle
IGCC	Integrated coal Gasification Combined Cycle
LNG	Liquefied Natural Gas
NOx	Nitrogen Oxides

INTRODUCTION

An aggressive implementation of renewable energy is ongoing as a response to global warming. The effective utilization of fossil fuels for low environmental pollution is being targeted as part of the solution. In addition to electricity and heat energy, hydrogen is expected to play an important energetic role in the near future. The MHI Group is developing technology to utilize hydrogen as such an energy source.

The use of wind power generation worldwide is a good example of the accelerated introduction of renewable energy. Since 2011, the wind generation annual increase has been in the order of 40.5 GW and is predicted to further expand to a maximum of about 2,110 GW and supply up to 20% of total electricity by 2030 [1]. With increasing renewable energy power generation facilities, there is excess electric power capacity. The excess power is considered to be an issue because of the typical large output fluctuations associated to renewable energy.

Energy storage technology is necessary to effectively utilize the abovementioned excess electric power to store the energy in batteries or using other existing or developing technologies. In particular, when the fluctuation cycle is long and a significant amount of energy capacity is required, it is effective to apply this excess energy to produce and store hydrogen. This stored fuel can be used as an energy source when renewable energy doesn’t supply enough energy to meet demand.

Combustion of hydrogen does not generate CO2, therefore, high efficiency gas turbines represent a promising power generation technology to effectively utilize hydrogen. The amount of CO2 generated by gas turbines can be reduced by replacing natural gas with hydrogen as fuel.

Figure 1 shows MHPS hydrogen rich fuel operating experiences. The company has been active developing rich fuel firing for large scale gas turbine use in thermal power plants. For many years, refinery by-product gas (called off-gas) and others has been used to generate power in Japan and other countries. The experience accumulated while burning these gases with various hydrogen content ratios in MHPS gas turbines has worked as the technical foundation for the current hydrogen combustion R&D activities. However, most of those plants applied diffusion type combustors, and often had additional water or steam injection; known as “wet” control approach. This reduces emissions at the expense of reduced efficiency. In order to realize high efficiency, MHPS focused on further development for its existing natural gas fired combustor technology of Dry Low NOx (DLN) to be able to accommodate co-firing hydrogen and natural gas.

This paper presents the outline of this effort and future prospects of technological development enabling hydrogen co-firing.

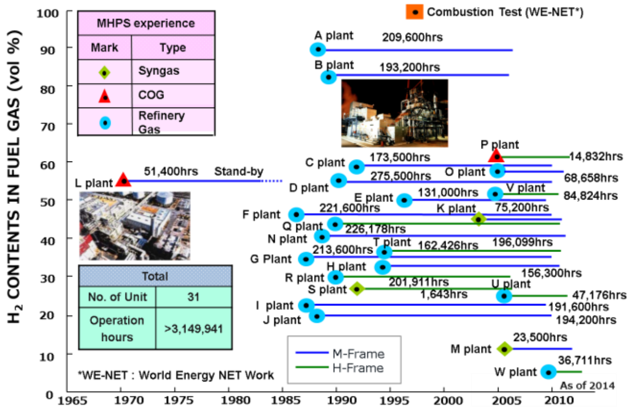

Fig. 1 Hydrogen rich fuel operating experiences

CHARACTERISTICS 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 oxides, a known cause of acid rain). Figure 2 compares the premixed combustion and the diffusion combustion characteristics. Since the premixed combustion can reduce the flame temperature compared with the diffusion combustion, NOx can be reduced without steam/water injection. The premixed combustion is a technology currently widely applied to low NOx combustor. On the other hand, the stable combustion range for the premixed combustion is narrower than that of the diffusion combustor, and also there is higher tendency of the flashback phenomenon to occur. Figure 3 provides sketches of the flashback phenomenon. 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 flame 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 out the upstream non-cooled combustor part. Therefore, it is important to prevent the flashback to occur.

When natural gas and hydrogen are mixed, the flame characteristics 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 flame speed. It has been confirmed that hydrogen has a higher flame speed calculated by GRI3.0 [2] in comparison with natural gas as shown in figure 4. For this reason, when hydrogen is mixed to natural gas fuel, 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.

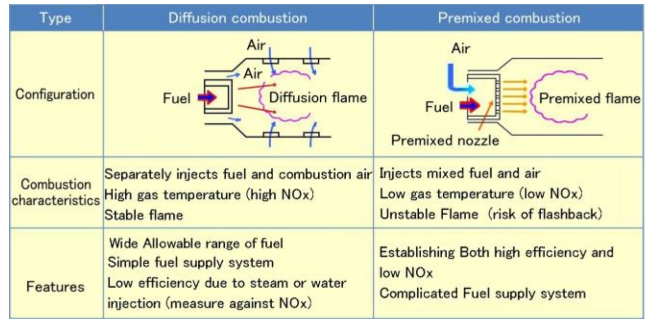

Fig. 2 Comparison of Diffusion and Premixed combustion

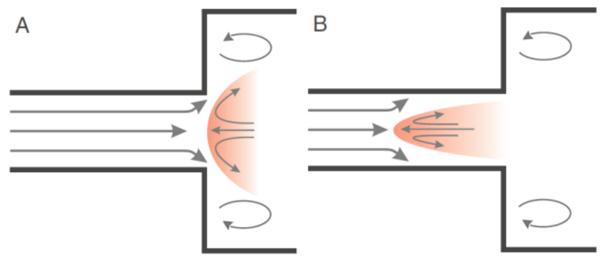

Fig. 3 Sketches of a stable flame(A) and a flame with flashback(B)

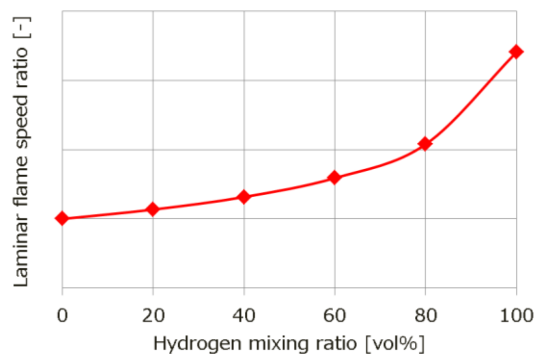

Fig. 4 Laminar flame speed with natural gas and hydrogen

OUTLINE OF FLASHBACK PREVENTION TECHNOLOGY

Concept of new combustor

Figure 5 shows schematic of MHPS gas turbine DLN combustor. The DLN combustion system consists of one pilot nozzle at the center of the fuel nozzle and several main swirler nozzles for premixed flame. The swirling flow is formed to promote the mixing of fuel and air. Several articles[3],[4],[5] 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 flame speed.

Figure 6 illustrates the outline of a conventional combustor and a new combustor developed with the purpose of preventing an increase in 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 a small hole 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 vortex core of the swirling flow (hereinafter referred to as vortex core). It is considered that the flashback phenomenon in the swirling flow is caused by the flame moving upstream in the vortex core where the flow velocity is slow. In the new combustor, the air is injected from the tip of the nozzle in order to increase the flow velocity at the vortex core. The injected air extinguishes the low flow velocity region of the vortex core and prevents flashback.

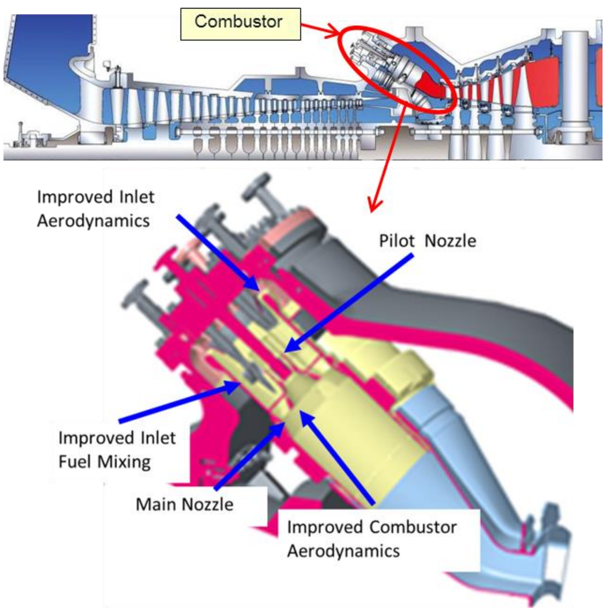

Fig. 5 Schematic of MHPS gas turbine DLN combustor

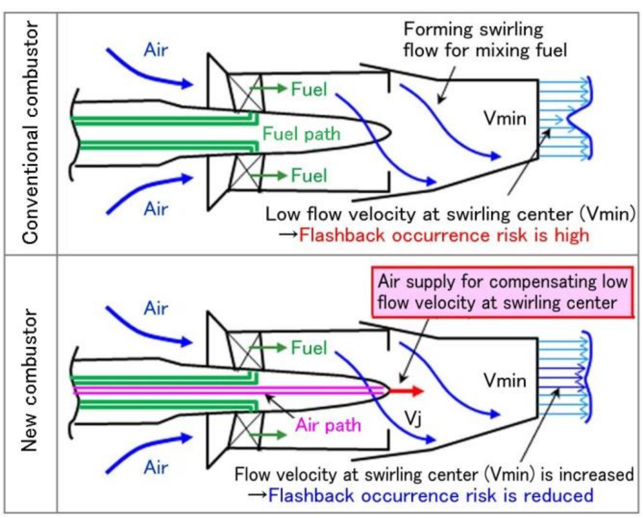

Fig. 6 Outline of conventional combustor and new combustor

Verification by flow test

In order to verify the new combustor, flow velocity distribution was measured with an air flow test. Figure 7 is a photograph of the equipment used for the flow test. The vortex core 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 vortex core 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 achieving high time resolution, it is possible to evaluate the instantaneous minimum flow velocity at the measurement position.

Figure 8 compares the flow velocity distributions of the conventional combustor and the new combustor in the swirling region. Paying attention to the minimum flow velocity, which is considered to determine the occurrence of the flashback phenomenon, it was confirmed that flow velocity of the new combustor is much higher than that of the conventional combustor in the swirling center. 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. Therefore the flow velocity distribution of those regions is the same as that of the conventional combustor.

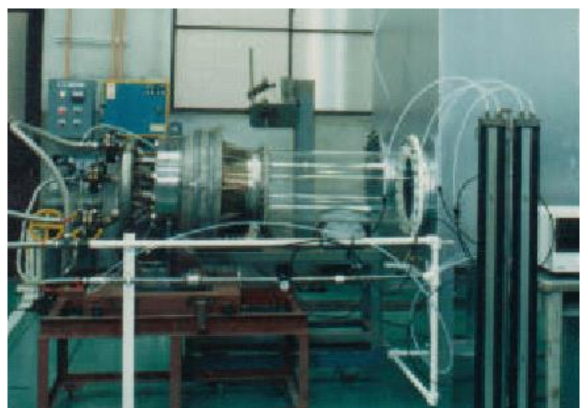

Fig. 7 Photograph of flow test equipment

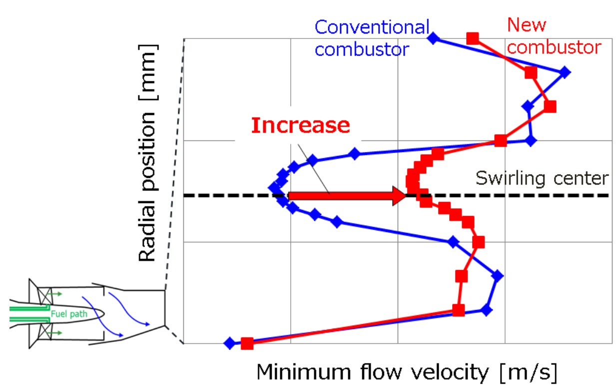

Fig. 8 Comparison of flow velocity distributions in swirling region

Verification by actual pressure combustion rig test

In order to investigate the combustion characteristics of the new combustor with hydrogen co-firing, actual pressure combustion rig tests were conducted. Important combustion characteristics of a gas turbine combustor include NOx and combustion dynamics. NOx is regulated on the amount of emissions in terms of the environmental aspect. On the other hand, 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 pressure conditions corresponding to gas turbine pressure is necessary. Therefore, through the actual gas turbine pressure combustion rig test (hereinafter referred to as the combustion rig test) using a full-scale combustor (in the gas turbine 16 to 20 combustors are used), the combustion characteristics of hydrogen co-firing were confirmed. For the combustion rig test, an actual pressure combustion test facility at Mitsubishi Hitachi Power Systems Takasago was used as shown in Figure 9. The high pressure and high temperature air used in the combustion rig test is 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 mixing fuel of the actual plant, hydrogen is added in the natural gas supply line and supplied to combustor. Since hydrogen is added sufficiently upstream of the test facility, it is evenly mixed with natural gas before reaching the combustor.

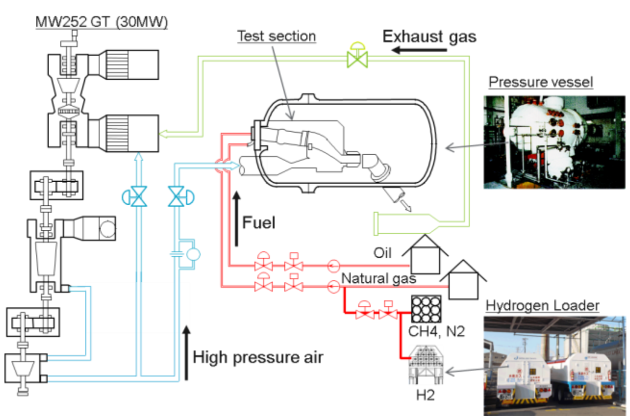

Fig. 9 Configuration of actual pressure combustion test equipment

It is successfully performed that combustion test where a 30vol% hydrogen-natural gas mix was applied. This achieved a reduction in carbon dioxide (CO2) emissions of 10% compared to natural-gas-fired power plant. The test was performed at a firing condition of a turbine inlet temperature of 1600 degC using J-Series gas turbine. Figure 10 describes NOx with respect to the hydrogen mixing ratio under that firing condition. It was confirmed that as the hydrogen mixing ratio increased, NOx tended to increase slightly. It is considered that the flame position in the combustor moved upstream because the flame speed increased due to the mixing of hydrogen in the fuel. However, it was confirmed that even under the conditions with the hydrogen mixing ratio of 30vol%, NOx was within the operable range. Figure 11 describes combustion dynamics with respect to the hydrogen mixing ratio under the same conditions. It was confirmed that combustion dynamics level was not significantly affected by 30vol% 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 combustion dynamics is made possible by applying the new combustor. [6]

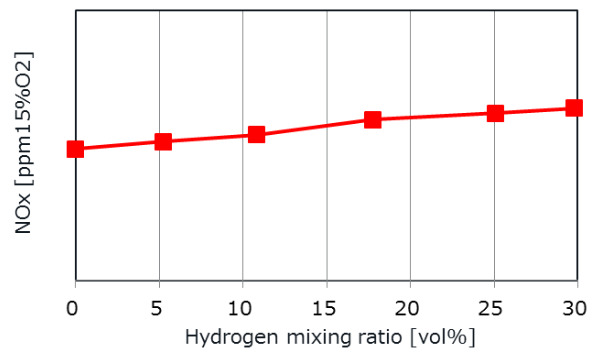

Fig. 10 NOx with respect to hydrogen mixing ratio

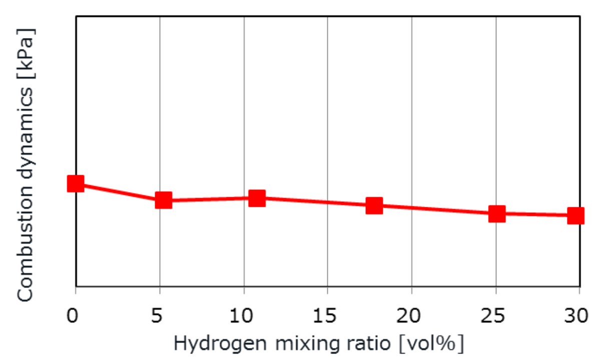

Fig. 11 Combustion dynamics with respect to hydrogen mixing ratio

NEXT STAGE

Having tested 30vol% hydrogen co-firing, the next stage is to continue up to 100vol% hydrogen. This will probably involve more development of the cluster combustor. Based on the multi-cluster combustor developed for CCS-IGCC (Carbon dioxide Capture and Storage- Integrated coal Gasification Combined Cycle), improved design for higher temperature of 1600 degC or higer is under investigation. Figure 12 shows comparison between combustor types including the cluster combustor.

MHPS will participate in a hydrogen conversion project in the Netherlands. This project will convert one of the three 440 MW gas turbines at Nuon's Magnum power plant at Groningen in the Netherlands. MHPS supplied the original three gas turbines at the plant. The project aims to complete the conversion of the gas turbine by 2023. This will be the first commercial hydrogen-fired GTCC.

The project also includes the involvement of Nuon/Vattenfall, Statoil, and Gasunie. Statoil will focus on producing hydrogen by converting natural gas into hydrogen and carbon dioxide. The carbon dioxide will be stored in underground facilities off the Norwegian coast, allowing for carbon-neutral energy production. Gasunie is carrying out research into how the hydrogen can be transported to and stored at the Magnum power station. Figure 13 shows a photograph of Nuon's Magnum power plant. [7]

	Diffusion Combustor	Premixed Combustor	Cluster Combustor
Combustor Type			
Low NOx technology	N2 Dilution, Water and Steam injection	Dry	Dry
GT experience	Middle and Small size GT, IGCC	Large size GT	Under investigation
Usable fuel	H2Rich, IGCC, BFG, LNG, Oil etc.	LNG, Oil, H2mixing etc.	H2Rich, IGCC, LNG, Oil etc.
H2 density restriction	None	~30vol% NEDO project	~100vol% NEDO project

Fig. 12 Comparison between combustor types

Fig. 13 Nuon's Magnum power plant in Groningen, the Netherlands

CONCLUSIONS

MHI Group is working on the development of a hydrogen and natural gas co-fired gas turbine to target reduced CO2 emissions. This effort is supported by the New Energy and Industrial Technology Development Organization (NEDO).

A new combustor that suppresses the generation of the low flow velocity in the swirling center region was developed in order to minimize the occurrence of flashback typically induced during hydrogen co-firing.

The prospect for gas turbine operation up to 30 vol% hydrogen co-firing conditions was developed and tested. Development of plant operation technology for hydrogen co-firing is ongoing with a final target focusing on 100vol% hydrogen firing in pursue of a hydrogen based society.

ACKNOWLEDGEMENTS

These developments of hydrogen and natural gas co-firing and 100vol% hydrogen firing are supported by the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

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