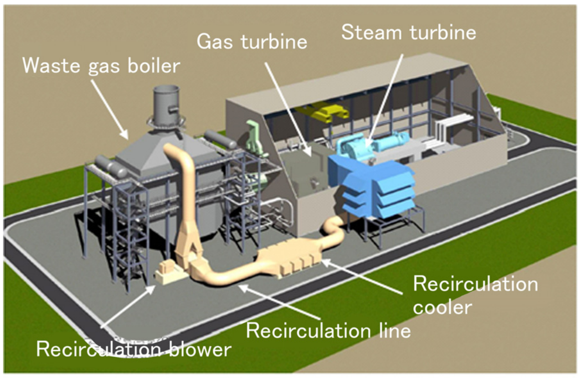
Development of Low NOx Combustion System with EGR for 1700°C-class Gas Turbine



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Gas-turbine combined-cycle power generation is expected to lead to a long-term extension of power-generation markets all over the world by providing clean and economic thermal power plants. Mitsubishi Heavy Industries (MHI) is developing technologies that will be applied to a 1700°C-class gas turbine as part of a national project in order to pursue much higher efficiency, and has been promoting the development of a combustor with an exhaust gas recirculation (EGR) system for achievement of low NOx combustion systems for ultrahigh-temperature gas turbines. In 2011, the last year of development research of technologies for practical application, MHI constructed a high-pressure combustion test device simulating exhaust gas recirculation, and obtained test results that attained the development target of NOx concentration of 50 ppm or less with exhaust gas recirculation. This document describes a high-pressure combustion test that simulates exhaust gas recirculation.

1. Introduction

Gas-turbine combined-cycle (GTCC) power generation is a clean and efficient power generating system, and will be increasingly in demand in the future from economic and social perspectives for the reasons noted below:

(1) The long-term global market for GTCC power generation is expected to grow.
(2) Significant demand exists for GTCC power generation for infrastructure improvement in developing countries because GTCC systems can be constructed quickly and provide a stable source of electricity.
(3) The need exists in developed countries for highly efficient power generation for further enhancement of economic efficiency and environmental adaptability.
(4) The superior load-absorbing capability of GTCC power generation can be further expected when considering the growth of renewable energy and its optimal combination with nuclear-energy power generation.

The thermal efficiency of GTCC power generation increases along with the temperature increase at the inlet of the turbine (outlet of combustor) as shown in **Figure 1**. MHI has been engaged in developing a 1700°C-class gas turbine[1-3] as part of a national project to improve energy efficiency since 2004, and has been working on technology development for factors such as the combustor, compressor, turbine, cooling, heat shield coating, etc., with a target combined-cycle efficiency of 62 to 65% (LHV).

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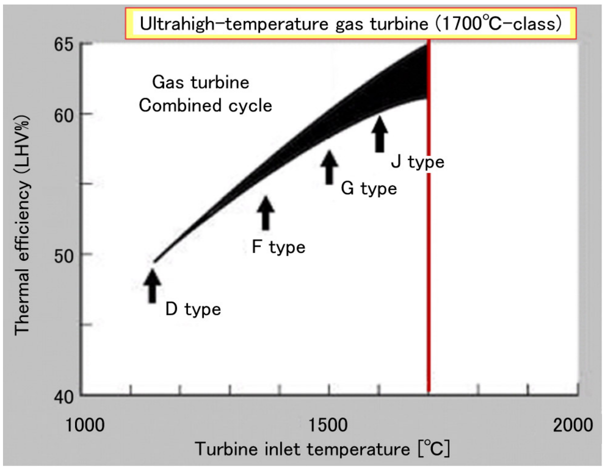

Figure 1 Trend of combined-cycle efficiency
The 1700°C-class gas turbine is the highest-temperature and highest-efficiency gas turbine in comparison to MHI's production gas turbines, and can attain a thermal efficiency of 62 to 65%. CO_2 emission intensity can be reduced to approximately half of a conventional pulverized coal fired thermal power plant.

Figure 2 shows MHI's history of low NOx combustor development.[4-6] MHI has continuously worked on increasing the temperature at the inlet of the turbine in terms of thermal efficiency, and has introduced combustion technology for the suppression of pollutants such as the nitrogen oxide (NOx) generated in the combustion of fossil fuels. The formation of NOx increases exponentially as the combustion temperature increases. For 1700°C-class combustors, NOx formation increases so significantly by almost an order of magnitude in comparison to 1500°C-class combustors, even with the use of conventional lean premix combustion systems.[7] Because the cost of dealing with such high levels of NOx with denitration devices is unrealistically high, the new development of a low NOx combustion system suitable for 1700°C-class gas turbines is required. For this project, MHI employs an exhaust gas recirculation (EGR) system, which is the first to be used with a low NOx combustion system for a gas turbine anywhere in the world, and is developing a combustor suitable for the system. In terms of the development of a combustor with exhaust gas recirculation systems, MHI has already verified the NOx reduction effect of an exhaust gas recirculation system through a medium pressure combustion test using a full-scale combustor.[8-10] This document describes a high pressure combustion test conducted at a pressure equivalent to that of actual use.

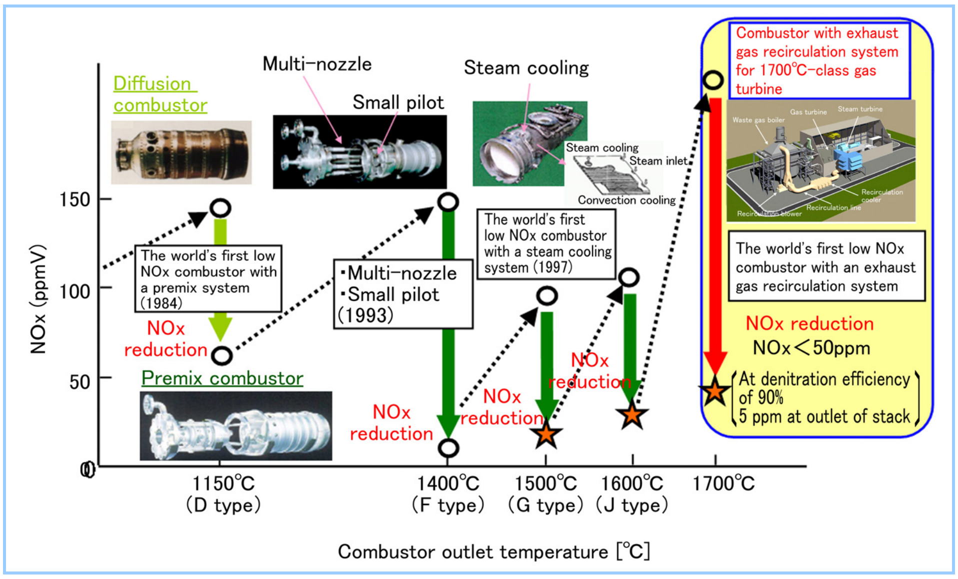

Figure 2 History of MHI's low NOx combustor development
MHI has been aiming at the enhancement of combustor outlet gas temperature for higher efficiency combined with NOx reduction, and is working on the use of exhaust gas recirculation systems for 1700°C-class ultrahigh-temperature combustors to promote NOx reduction.

2. Overview of exhaust gas recirculation system

Figure 3 illustrates a schematic diagram of an exhaust gas recirculation system for a 1700°C-class gas turbine. The exhaust gas recirculation method used here is a semi-closed method that mixes some of the exhaust gas with air and reduces the O_2 concentration in the combustion air. The exhaust gas is divided downstream of the heat recovery steam generator (HRSG) and is mixed with ambient air through the cooler, and then introduced into the compressor.

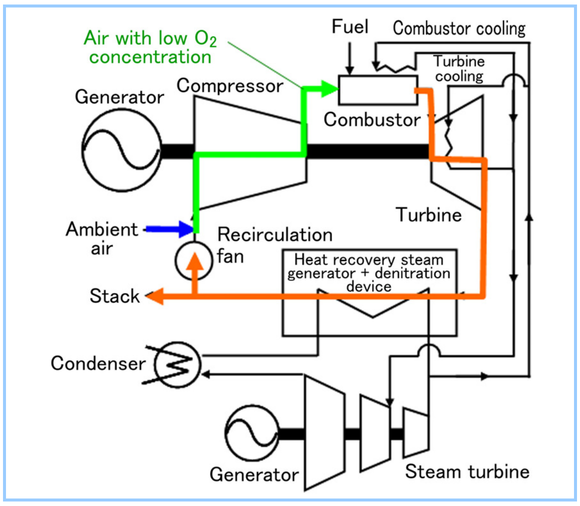

Figure 3 Schematic diagram of exhaust gas recirculation (EGR) system
Exhaust gas generated in the combustor passes through the heat recovery steam generator, mixes with ambient air, and then enters into the compressor, resulting in air with a low O_2 concentration being supplied to the combustor.

Table 1 shows the development targets of a 1700°C-class combustor with an exhaust recirculation system. The combustor employs a lean premix combustion method for the reduction of NOx emissions, and aims at a NOx emission concentration of 50 ppm (converted to 15% O_2) or less. The cooling method used for the combustor is a recovery steam cooling system, which has been verified through previous use with MHI G-type combustors.

Table 1 Specifications and development targets of exhaust gas recirculation combustor

Specifications and development targets of exhaust gas combustor	
Gas temperature at combustor outlet	1700°C
Combustion method	Premix combustion
Cooling method of combustor	Steam cooling
NOx	50 ppm (converted to 15% O_2) or less
CO	10 ppm (converted to 15% O_2) or less

3. NOx emission characteristics with exhaust gas recirculation

To study NOx reduction due to exhaust gas recirculation under conditions equivalent to those of actual use, an analysis of one-dimensional laminar flow premixed combustion was conducted. GRI Mechanism Ver. 3.0[11] (53 chemical species and 325 elementary reactions) was used for the detailed kinetic reaction mechanism model. To clarify the correlation between NOx formation and the amount of exhaust gas recirculation, calculation was performed using the O_2 concentration at the inlet of the combustor as the parameter (**Table 2**).

Table 2 Calculation conditions

	Calculation conditions (rated conditions at 1700°C)	
	Inlet O_2 concentration	EGR rate
1	21.0 vol%	0.0%
2	19.6 vol%	10.0%
3	17.0 vol%	26.6%

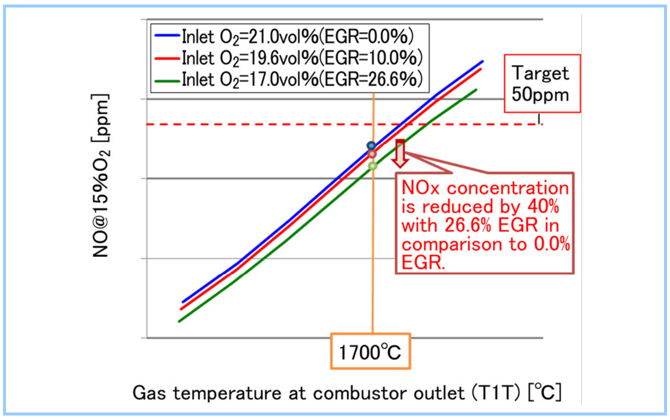

Figure 4 Correlation between combustor outlet temperature and NOx concentration (calculation results)
The effect of EGR variation on the formation of NOx under conditions of high pressure equivalent to those of actual use was evaluated. The calculation results verify that NOx concentration was reduced by approximately 40% with 17.0% O_2 concentration (26.6% EGR rate) at a temperature of 1700°C in comparison to standard air.

Figure 4 shows the correlation between NOx concentration (converted to 15% O_2) and combustor outlet temperature (T1T) for each O_2 concentration at the inlet. These results were obtained by constant premixed combustion calculation using the O_2 concentration at the inlet (EGR rate) as the parameter. NOx concentration has a tendency to decrease along with the lowering of the inlet O_2 concentration (increase of EGR rate). The calculation results verify that the NOx concentration is reduced by approximately 40% with a 26.6% EGR rate at a combustor outlet temperature of 1700°C (1973 K) in comparison to a 0.0% EGR rate.

4. High-pressure combustion test with actual combustor

4.1 Simulation of exhaust gas recirculation

In the combustion test, both a combustor for generating exhaust gas (preburner) and a water spray duct were used to simulate an exhaust gas recirculation system. **Figure 5** illustrates the equipment structure schematically. The air supplied to the main combustor was adjusted to a certain O_2 concentration and a certain gas temperature by installing the preburner upstream of the main combustor and the water spray duct downstream of the preburner.

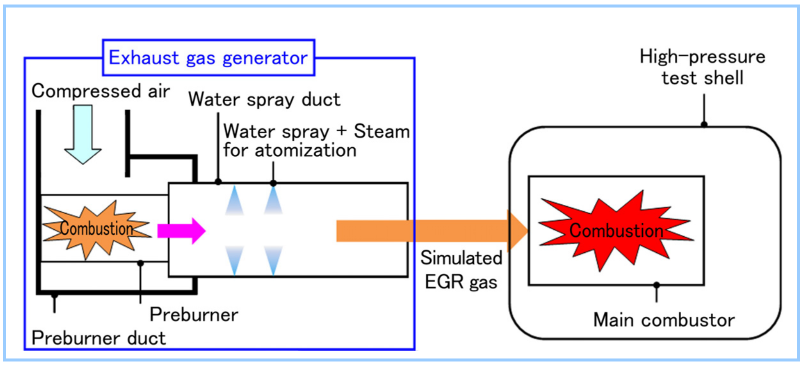

Figure 5 Simulation of an exhaust gas recirculation (EGR) system
For simulating EGR in the high-pressure combustion test, a preburner was installed upstream of the main combustor as an exhaust gas generator that controlled the concentration of O_2 supplied to the main combustor, and the combustion gas temperature was controlled by a water spray duct.

4.2 High-pressure combustion test device

Figure 6 illustrates the structure of the equipment in the high-pressure test shell. The simulated EGR gas generated in the exhaust gas generator passes through the diffuser and the sector, which is installed in the test shell and simulates the shape of a combustor casing, and is then supplied to the main combustor. Exhaust gas is sampled at the measuring duct downstream of the combustor outlet for the measurement of NOx, CO, etc. The design specifications of the test shell include a maximum operating pressure of 31 ata (3.04 MPa) and a maximum operating temperature of 550°C (823 K).

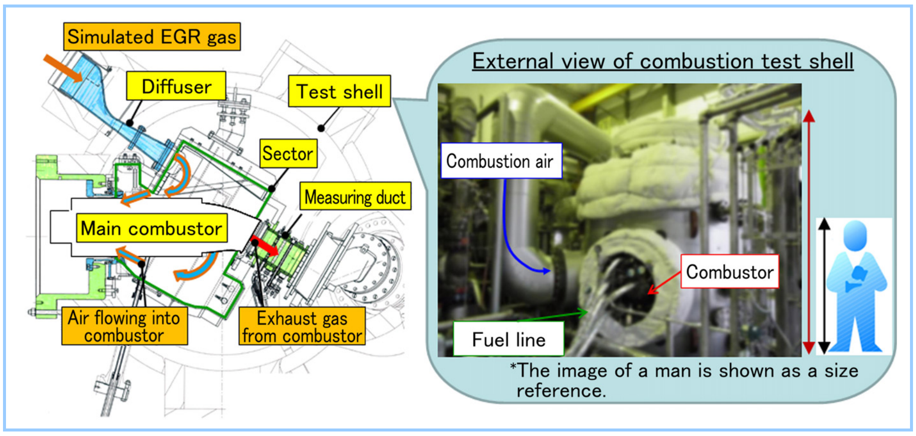

Figure 6 Structure of equipment in the high-pressure test shell
Simulated EGR gas passes through the diffuser in the test shell and the sector, which simulates a combustor casing, and is then supplied to the combustor. Exhaust gas is sampled at the measuring duct for measurement of NOx, CO, etc.

In the case of this test, unlike an ordinary combustion test using ambient air, NOx was also generated in the exhaust gas generator upstream of the combustor. Therefore gas composition measurement was also performed for the combustion air upstream of the main combustor, and the

NOx generated in the main combustor was calculated using the difference between NOx concentrations at the inlet and the outlet of the main combustor. The effect of the NOx concentration contained in the air at the inlet on NOx formation during combustion was studied through an analysis of the one-dimensional laminar flow premixed combustion, and it was found that the NOx concentration contained in the air at the inlet had no effect on NOx formation during combustion under the test conditions where the equivalent ratio was 0.7 to 0.9. If an exhaust gas recirculation system in actual use has a denitration device installed outside of the recirculation system, it is necessary to add the NOx concentration contained in the air at the inlet of the combustor to the evaluated NOx concentration at the combustor outlet. This document assumes that the denitration device is installed within the recirculation system as shown in Figure 3.

Among the test conditions, the combustor pressure, the inlet air temperature, and the flow rate were equivalent to those of actual use. And to study the effect of EGR rate on NOx formation, a combustion test was conducted under conditions of a high inlet O_2 concentration (19.6 vol%) for a low EGR rate (10%) and a low inlet O_2 concentration (17.0 vol%) for a high EGR rate (26.6%).

4.3 Test results

Figure 7 shows the test results. This figure represents the correlation between NOx concentration and combustor outlet temperature (T1T). The NOx formation under the low O_2 condition was reduced significantly to approximately a quarter (23%) of the NOx formation under the high O_2 condition at a combustor outlet temperature of 1700°C (1973 K), and attained the development target of 50 ppm. The much higher NOx reduction in this case compared with the aforementioned NOx reduction (approximately 60%) studied with one-dimensional laminar flow premixed combustion analysis seems to be for the reasons noted below: (1) the flame temperature suppression effect of EGR occurred greatly because the premixed air/fuel concentration was uneven under conditions equivalent to those of actual use and therefore there existed a local high flame temperature generated by a rich fuel zone and (2) the lower O_2 concentration led to a lower combustion speed, and therefore the flame position moved downward, resulting in enhancement of the evenness of the air/fuel mixture concentration during combustion and a reduction of residence time.

Figure 8 shows the CO concentration at the combustor outlet. Although there was concern over an increase in the CO contained in the exhaust gas because of lowering the O_2 concentration and chemical reactions with the use of EGR, the CO concentration reached the development target of 10 ppm under both the low and high O_2 conditions. As indicated by the fact that the CO concentration did not change significantly, the combustion efficiency at the combustor outlet did not worsen significantly.

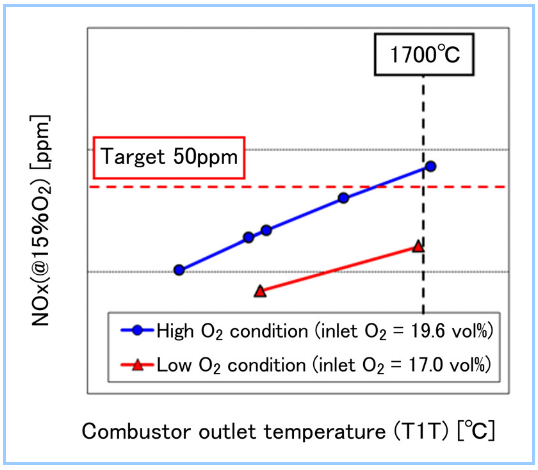

Figure 7 NOx emission characteristics (results of high-pressure combustion test)
The NOx formation under the low O_2 condition was reduced significantly in comparison to that under the high O_2 condition at a combustor outlet temperature of 1700°C, and attained the development target of 50 ppm.

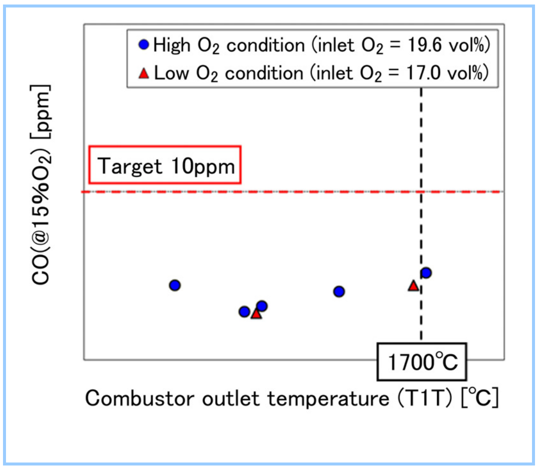

Figure 8 CO emission characteristics (results of high-pressure combustion test)
Although there was concern over an increase in CO because of worsened combustion efficiency with the use of EGR, the CO concentration decreased below the target of 10 ppm under both the low and high O_2 conditions.

Figure 9 shows the combustion vibration measurement results. The internal pressure fluctuation did not exceed the limited value under either the high O_2 or low O_2 conditions. Although there was concern about worsening of the flame holding behavior under the low O_2 condition with EGR added, there was no unstable combustion that induced combustion vibrations.

These test results verify that the 1700°C-class combustor can attain NOx and CO emission targets, and stable combustion is maintained under conditions equivalent to those of actual use with EGR added.

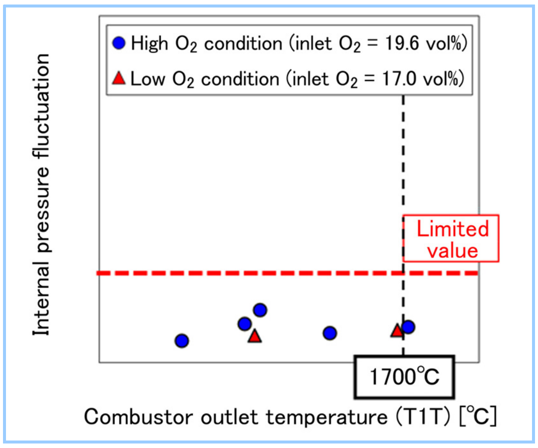

Figure 9 Combustion vibration characteristics (results of high-pressure combustion test)
The internal pressure fluctuation did not exceed the limited value under either the high O_2 or low O_2 conditions. These results verify that flame holding behavior does not worsen and stable combustion is maintained even with EGR added.

5. Conclusion

MHI has been developing technologies that will be applied to a 1700°C-class gas turbine, which has the world's highest combustor outlet temperature, as part of a national project. This research uses high-pressure combustion tests with a full-scale combustor simulating exhaust gas recirculation to verify that a NOx concentration of 50 ppm or lower and CO concentration of 10 ppm or lower can be attained at a combustor outlet temperature of 1700°C (1973 K), and that stable combustion without combustion vibrations can be made even under low O_2 conditions where there is concern over worsening of flame holding behavior. These results verify the effectiveness of an EGR system for low NOx behavior and flame stability of 1700°C-class gas turbines.

The latest numerical simulation technologies and measuring methods obtained in previous technological development of 1700°C-class gas turbines have been evolved into the development of MHI's 1600°C-class gas turbines (J-type), and have contributed to their immediate commercialization. MHI is willing to further improve NOx reduction and promote the enhancement of combustor performance.

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