Chapter 1

Development of a State-of-the-Art Dry Low NOx Gas Turbine Combustor for IGCC with CCS

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Additional information is available at the end of the chapter

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Abstract

The successful development of the coal-based integrated gasification combined cycle (IGCC) with carbon capture and storage (CCS) requires gas turbines capable of achieving dry low nitrogen oxide (NOx) combustion of hydrogen-rich syngas fuels for low emissions and high plant efficiency. This chapter describes the development of a "multi-cluster combustor" as a state-of-the-art dry low NOx combustor for hydrogen-rich syngas fuels. The combustor consists of multiple clusters of pairs of one fuel nozzle and one air hole that are installed coaxially. The essence of the design concept is the integration of two key technologies: rapid mixing of fuel and air for low NOx and flame lifting for flashback-resistant combustion. The combustor has been developed in three steps: burner development, combustor development, and feasibility demonstration for practical plants. The combustor was tested with a practical syngas fuel in a multi-can combustor configuration in an IGCC pilot plant in the final step. The combustor achieved the dry low NOx combustion of the syngas fuel in the pilot plant and the test results demonstrated the feasibility for achieving dry low NOx combustion of the syngas fuel in practical plants.

Keywords: integrated gasification combined cycle (IGCC), carbon capture and storage (CCS), gas turbine, dry low NOx combustor (DLNC), multi-cluster combustor, hydrogen-rich syngas fuels

1. Introduction

Coal is a vital energy source for power generation with over 40% of the electricity produced worldwide stemming from coal [1]. Coal is able to ensure energy supply stability and security due to its low cost, abundant reserves, and worldwide availability. However, conventional pulverized coal–fired power plants are the most carbon dioxide (CO_2)-intensive source of power generation. An effective method for cutting CO_2 emissions from coal-fired power plants is to employ a coal-based integrated gasification combined cycle (IGCC). IGCC plants release less CO_2 than conventional pulverized coal–fired power plants because of their higher plant efficiency. IGCC also possesses the capability to capture and store CO_2 before combustion [precombustion carbon capture and storage (CCS)]. CCS technology suppresses the release of CO_2 into the atmosphere by capturing and storing CO_2 emissions from thermal power plants. A report by the Intergovernmental Panel on Climate Change (IPCC) estimates that an IGCC plant with CCS might cut CO_2 emissions by about 80–90% compared with an IGCC plant without CCS [2]. However, the major technical hurdle with CCS is that CCS decreases plant efficiency because of the additional energy for capture and storage. The report by the IPCC estimates that a CCS-equipped IGCC plant might need 14–25% more energy than an IGCC plant of equivalent output without CCS [2]. Improving the efficiency of CCS-equipped IGCC plants is a key to the successful combination of the two technologies. In order to achieve high plant efficiency and low emissions, a gas turbine in IGCC plants requires a diluent-free ("dry"), low NOx combustor. This chapter describes the development of a state-of-the-art dry low NOx combustor intended for CCS-equipped IGCC plants.

2. CCS-equipped oxygen-blown IGCC technology and technical hurdles with gas turbines

2.1. Overview

Coal-based IGCC technology with CCS converts coal to syngas, removes CO_2 from the syngas, and generates electric power in the combined cycle by utilizing the produced hydrogen-rich syngas as gas turbine fuel. An oxygen-blown IGCC plant with a precombustion CCS system is composed of five key components: an air separation unit (ASU), a gasifier, a syngas cleanup unit, a CCS system, and a combined cycle unit. A schematic diagram of the plant is shown in **Figure 1**.

The plant generates electric power through the process as follows. The ASU separates air into oxygen (O_2) and nitrogen (N_2). The gasifier converts coal to raw syngas by reacting it with oxidant (oxygen). The gasifier employs oxygen as the oxidant, and this type of gasification is referred to as "oxygen-blown." This chapter addresses oxygen-blown IGCC technology. The syngas cleanup unit removes impurities, such as particulate matter, sulfur, and ammonia from the raw syngas, producing a clean syngas consisting mainly of carbon monoxide (CO) and hydrogen (H_2). A shift reactor of the CCS system converts CO in the clean syngas to H_2 and CO_2 by a water-gas shift reaction, producing a shifted syngas. A CO_2 capture unit removes CO_2 from the shifted syngas, thus producing a hydrogen-rich syngas. The hydrogen-rich syngas is supplied to a gas turbine as fuel. A gas turbine combustor burns the syngas, and the combustion gas operates a turbine, which, in turn, generates electric power. A heat recovery steam generator (HRSG) produces steam using the waste heat of exhaust gas from the gas turbine, and sends the steam to the gasifier in order to produce the raw syngas and to a steam turbine in order to generate additional power. The gas turbine combustors are required to operate on oil fuel as the startup fuel at ignition and during part load in order to provide the HRSG with the waste heat until the syngas fuel is supplied to the gas turbine [3].

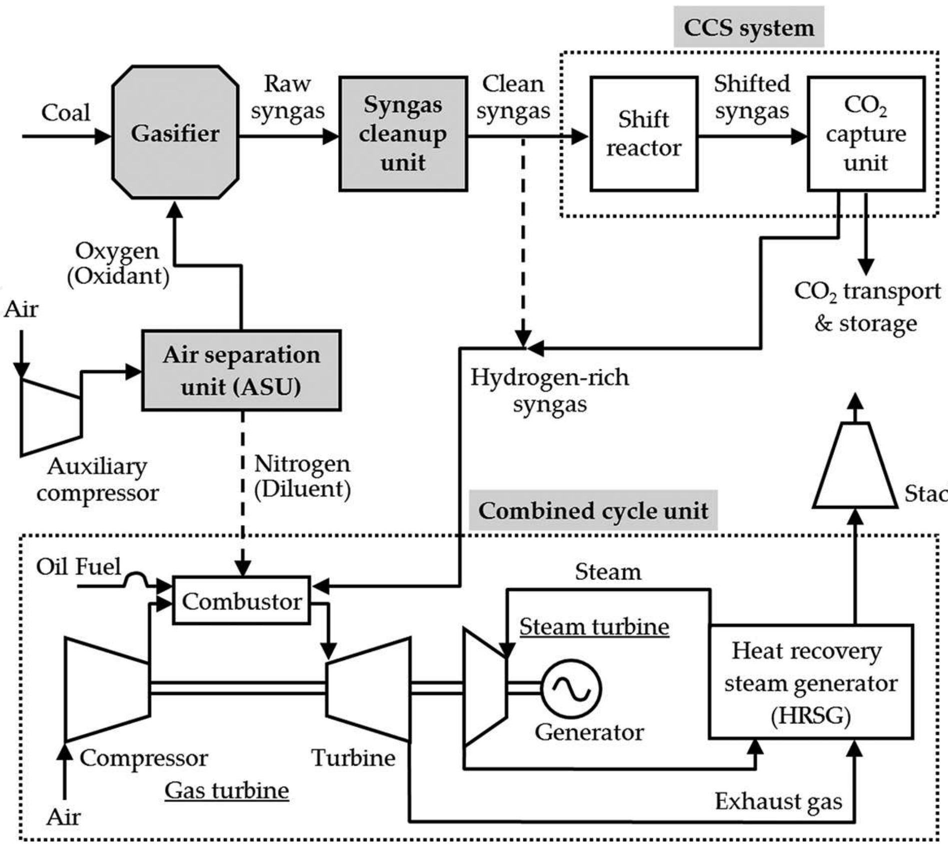


Figure 1. Schematic diagram of oxygen-blown IGCC plant with precombustion CCS system.

2.2. Technical hurdles with gas turbines

The implementation of IGCC technology with CCS poses significant challenges to gas turbine combustors owing to properties of hydrogen-rich syngas fuels. **Figure 2** shows the variation in fuel compositions against the carbon capture rate for typical syngas fuels [4]. The fuel compositions vary widely depending on the carbon capture rate. As the carbon capture rate increases from 0 to 90%, as a result of the conversion of CO to H_2 and CO_2 in the shift reactor, H_2 concentration increases widely from approximately 25 to over 80 vol%. Some properties of hydrogen, specifically its higher flame speed, lower ignition energy, and broader flammability limits compared with conventional gas turbine fuels (e.g., natural gas), increase the risk of flashback and autoignition [5].

The challenges posed by these properties of hydrogen require advanced combustion technologies for hydrogen-rich syngas fuels. Conventional gas turbine combustors are incapable of achieving low NOx emissions and high plant efficiency for hydrogen-rich syngas fuels. **Figure 3** summarizes technical hurdles with their use. The combustors are broadly classified into two types: premixed combustors and diffusion-flame combustors. Conventional premixed combustors are capable of achieving low NOx by supplying premixed fuel-air mixtures because they maintain low local flame temperatures. However, premixed combustors burning hydrogen-rich fuels are prone to flashback into their large premixing section because they are highly tuned to operate on low-flame-speed fuels like natural gas. This flashback tendency characteristic hinders the application of premixed combustion technology to

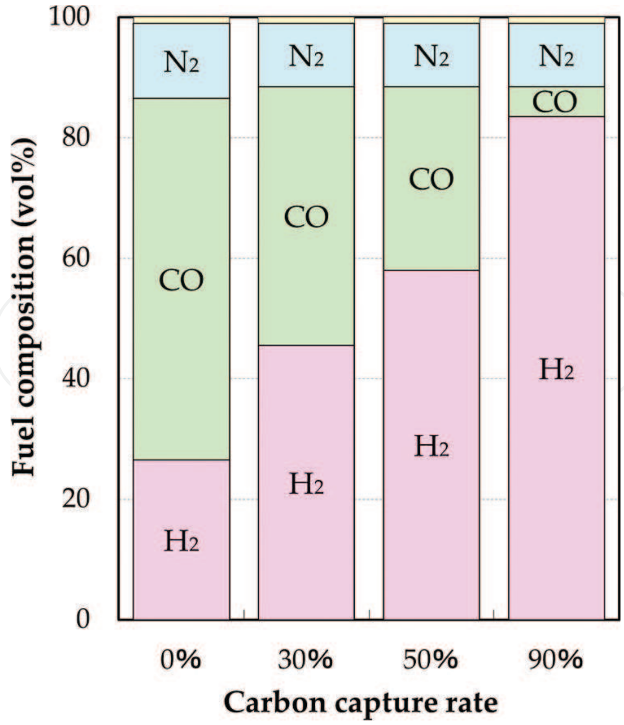


Figure 2. Fuel compositions of typical syngas fuels in oxygen-blown IGCC with CCS.

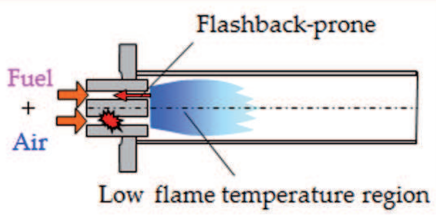
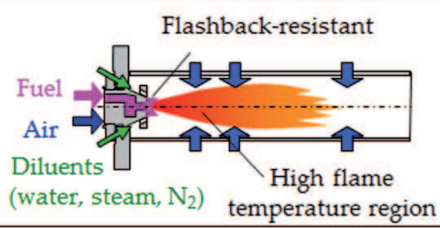
	Premixed combustor	Diffusion-flame combustor
Combustor type		
Merit	Low NOx	Flashback-resistant
Demerit	Flashback-prone	Plant efficiency decrease (due to injection of diluents for NOx decrease)
Employed for IGCC	No	Yes

Figure 3. Technical hurdles with conventional combustors.

hydrogen-rich syngas fuels in IGCC. In contrast, conventional diffusion-flame combustors are capable of achieving flashback-resistant combustion of hydrogen-rich fuels by supplying fuel and air separately into their combustion chamber. However, diffusion-flame combustors are incapable of achieving high plant efficiency because they require additional energy to inject a diluent, such as water, steam, or nitrogen, into the combustion zone in order to suppress the increased NOx emissions due to high local flame temperatures. IGCC plants have thus far employed diffusion-flame combustors at the expense of decreased plant efficiency in order to achieve flashback-resistant combustion of hydrogen-rich fuels.

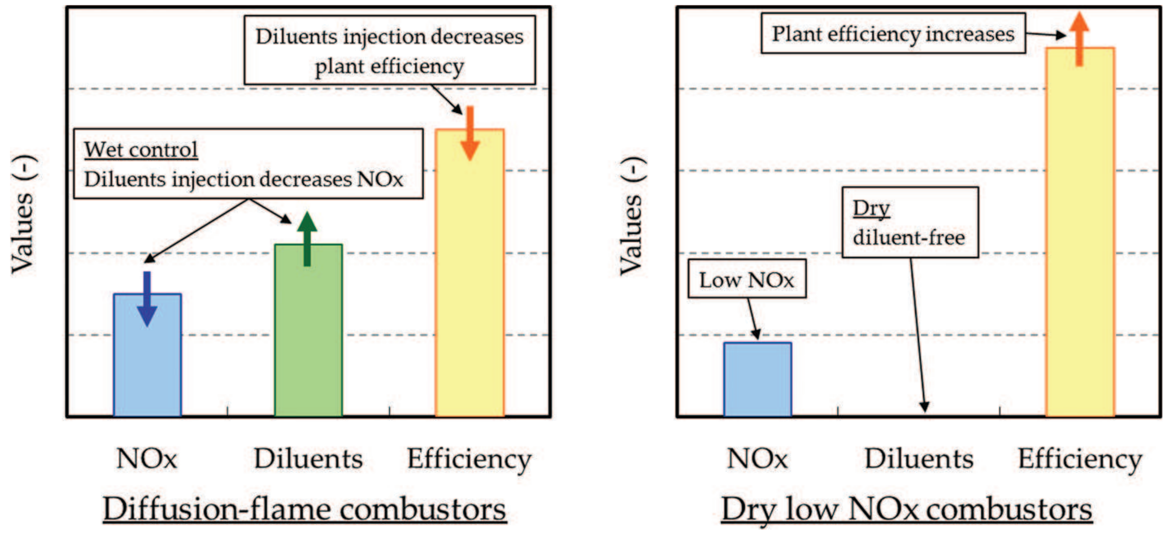


Figure 4. Advantages of dry low NOx combustor.

A solution to these hurdles is to develop state-of-the-art technologies for diluent-free (dry), low NOx combustion of hydrogen-rich fuels. **Figure 4** compares the advantages of dry low NOx combustors (DLNC) with those of diffusion-flame combustors. Diffusion-flame combustors decrease NOx by injecting diluents. This method is referred to as "wet control." However, injection of diluents decreases plant efficiency. In contrast, dry low NOx combustors achieve low NOx diluent-free (dry) combustion, thereby increasing plant efficiency. The successful implementation of IGCC technology with CCS requires state-of-the-art technologies for the dry low NOx combustion of hydrogen-rich syngas fuels that can achieve both lower NOx emissions and higher plant efficiency.

Many research groups and gas turbine manufacturers have been developing dry low NOx combustion technologies for hydrogen-rich fuels [6–18]. Technologies described in the literature include a multi-tube mixer fuel nozzle [7], a triple-fuel syngas burner [8], a MBtu EV burner [9], a low-swirl injector [10], a flameless-oxidation burner [11], a micro-mixing lean-premix injector [12], a DLN micromix burner [13, 14], a DLE combustor with supplemental burners [15], a lean premixed swirl-stabilized hydrogen burner with axial air injection [16], a rich catalytic hydrogen injector [17], and a rich/lean staged burner [18]. This chapter describes the development of a state-of-the-art dry low NOx combustor for hydrogen-rich syngas fuels in CCS-equipped oxygen-blown IGCC plants.

3. A state-of-the-art dry low NOx combustor

3.1. Combustor configuration

Figure 5 shows the configuration of the state-of-the-art dry low NOx combustor [19]. The combustor consists of multiple fuel nozzles and multiple air holes. The key elements of the combustor each consist of one fuel nozzle and one air hole that are installed coaxially. A cluster of key elements constitutes one burner, which forms one flame. The air holes are embedded in one plate. Multiple burners constitute a can combustor, and several can combustors are installed on a gas turbine. The combustor is classified as a multi-can type [20]. Hereafter, this burner is referred to as a "cluster burner," and this combustor is referred to as a "multi-cluster combustor."

An individual multi-cluster combustor consists of multiple cluster burners, a cylindrical liner, a cylindrical casing, and an end cover. **Figure 6** illustrates a cross-sectional diagram of an individual multi-cluster combustor. The cluster burners are installed on the end cover equipped with fuel supplying systems. The liner is mounted concentrically inside the casing. **Figure 7** illustrates a detailed diagram of the cluster burners. The burners consist of one pilot burner at the center and several identical main burners surrounding the pilot burner. The combustor forms seven individual flames, each of which is anchored to the corresponding burner. The combustor assigns the function of maintaining operational stability to the pilot burner and the function of maintaining low NOx operation to the main burners.

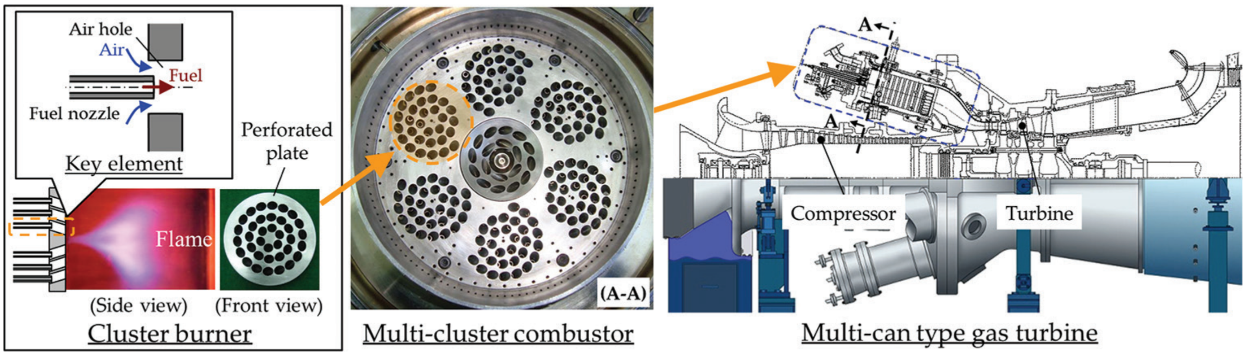


Figure 5. Configuration of the state-of-the-art dry low NOx combustor for hydrogen-rich syngas fuels.

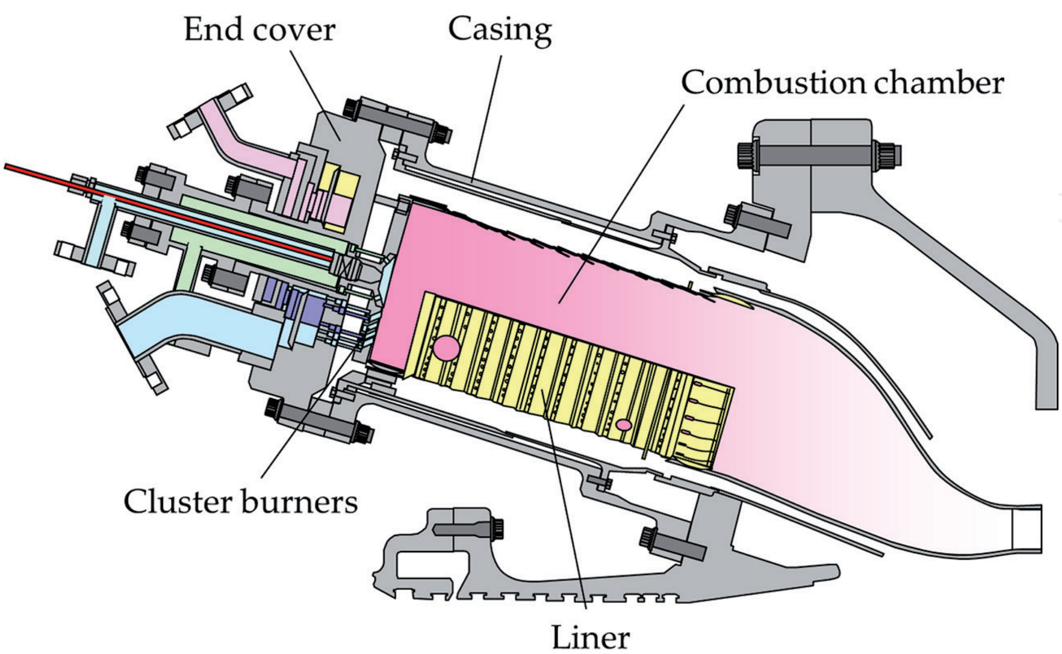


Figure 6. Cross-sectional schematic diagram of individual multi-cluster combustor.

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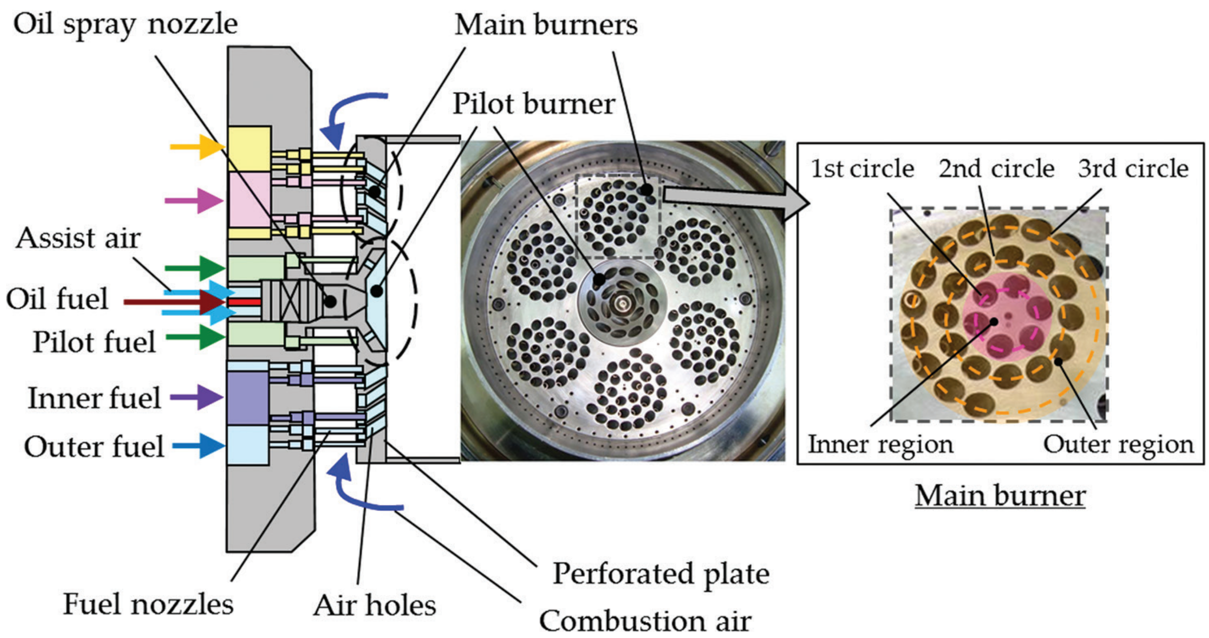

Figure 7. Detailed diagram of cluster burners.

The pilot burner can ensure combustion stability over the operating range by forming a well-stabilized flame in the center. The pilot burner is equipped with an air-assisted oil spray nozzle at the center. The oil spray nozzle operates on oil fuel at ignition and during part load before syngas fuel is supplied to the gas turbine in IGCC plants [19].

The main burners can achieve homogeneous fuel-air mixing for low NOx combustion by dispersing fuel to multiple injection points. The injection points are arranged in three circles on each main burner: six points on the first circle with the smallest diameter, 12 points on the second circle with the intermediate diameter, and 12 points on the third circle with the largest diameter. Here, the region within each first circle on the perforated plate is referred to as the “inner region,” and the region outside each first circle is referred to as the “outer region.” The gaseous fuel injected from six fuel nozzles on each first circle is referred to as “inner fuel,” and the gaseous fuel injected from 24 fuel nozzles on each of the second and third circles is referred to as “outer fuel.” The main burners characterize the low NOx performance of the combustor [19].

3.2. Burner concept

The next subsections describe the concept of the cluster burner for hydrogen-rich fuels. The essence of this burner concept is the integration of two key technologies: rapid mixing of fuel and air for low NOx combustion and flame lifting for flashback-resistant combustion. The cluster burner provides both the advantage of the premixed combustor of low NOx combustion and the advantage of the diffusion-flame combustor of flashback-resistant combustion.

3.2.1. Rapid mixing for low NOx *combustion*

Rapid mixing achieves low NOx combustion. Thermal NOx from atmospheric air is formed extensively at high temperatures [6, 21]. As a result, NOx emissions are decreased to low levels by eliminating high-temperature regions. Such high-temperature and NOx-generating regions are removed by the formation of homogeneous fuel-air mixtures before combustion, because of the rapid mixing of fuel and air within a short distance. Here, rapid mixing achieves low NOx combustion.

The cluster burner mixes fuel and air rapidly by producing multiple coaxial fuel-air jets, each of which consists of a central fuel jet surrounded by an annular air jet. The burner is equipped with multiple injection points. The burner installs the fuel nozzles in separate air holes coaxially at each injection point, thereby producing multiple coaxial fuel-air jets [19].

The coaxial jets mix fuel and air rapidly within a short distance by enhancing turbulence through contracting and expanding air passages. **Figure 8** shows the fuel concentration distribution in the mixing process of a coaxial jet analyzed by large eddy simulation (LES). The simulation results show that turbulence increases the amplitude of a wavelike disturbance at the boundary between fuel and air jets downstream of the air hole exit, thus mixing fuel and air rapidly. The burner disperses fuel by multiplying the coaxial jet, thereby enhancing mixing of fuel and air [19].

Conventional premixed combustors can mix fuel and air almost completely. However, premixed combustors burning hydrogen-rich fuels are prone to flashback into their large premixing section because of their higher flame speeds. Thus, this flashback characteristic hinders the application of premixed combustion technology to hydrogen-rich fuel combustion.

3.2.2. Flame lifting for flashback-resistant combustion

Flame lifting achieves flashback-resistant combustion. Flame lifting means that a flame is stably held at a point away from the burner. As a result, flame lifting suppresses the occurrence of flashback into the burner.

The burner can lift a flame by generating converging and diverging swirl flows downstream from itself. **Figure 9** illustrates a cross-sectional diagram of the main burner to describe the operating principle of this flame-lifting technology. The air holes cause the combustion air passing through them to swirl because the central axis of each air hole is inclined in the direction of a tangent to each circle. The swirling flow issuing from the air holes first converges toward and then diverges from an axial position (flame-anchoring point) located away from the burner. As shown in the figure, the converging-diverging swirl flows induce a pressure profile in the

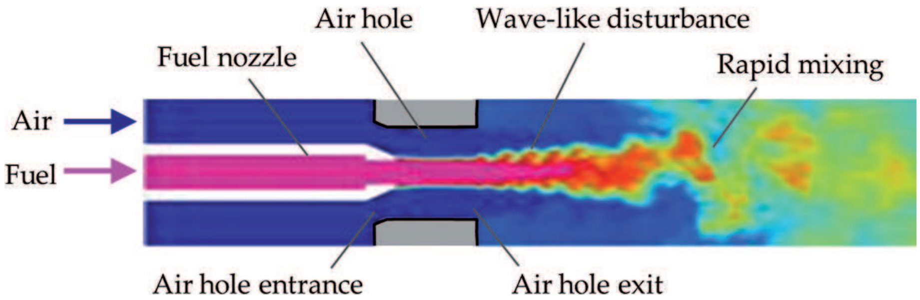

Figure 8. Mixing process of a coaxial jet.

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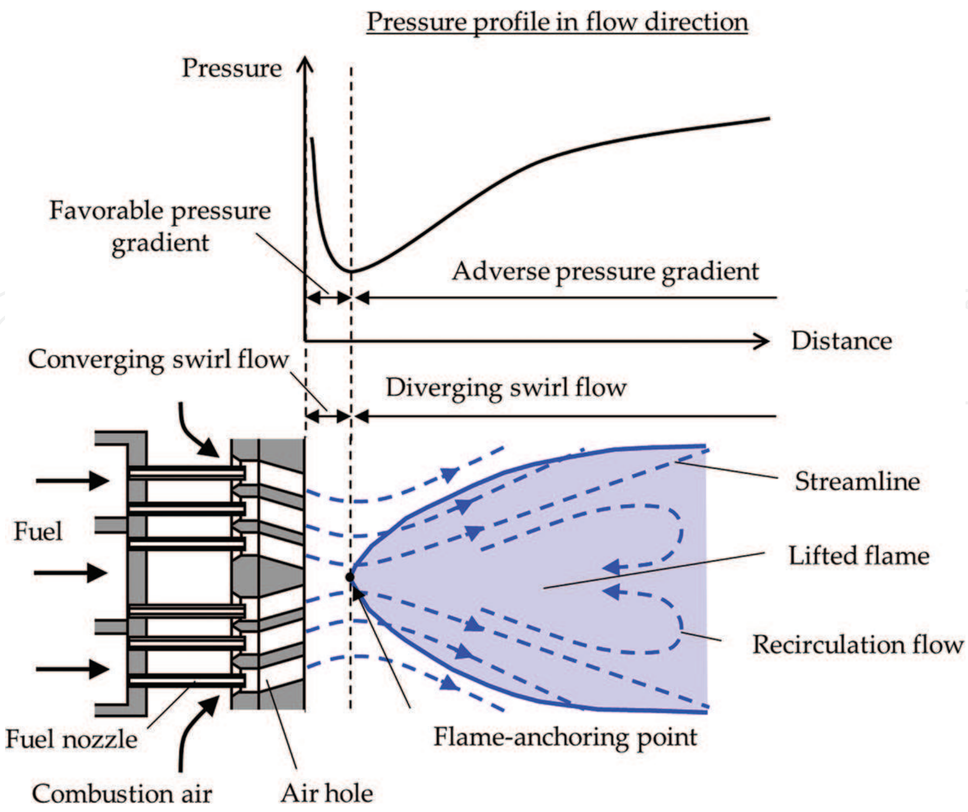

Figure 9. Operating principle of flame-lifting technology for the main burner.

flow direction. The converging flow induces a favorable pressure gradient due to the decrease in pressure downstream with increasing swirl velocity, whereas the diverging flow induces an adverse pressure gradient due to the increase in pressure downstream with decreasing swirl velocity. The adverse pressure gradient causes a vortex breakdown at the boundary between the converging and diverging swirl flows, thereby generating a recirculation flow. The recirculation flow stabilizes the flame by providing a stable heat source of combustion gas for the continuous ignition of fresh reactants. The reverse flow of the combustion gas from the boundary can be suppressed by the favorable pressure gradient in the converging flow. As a result, the flame is stabilized at the flame-anchoring point on the boundary. According to this operating principle, the flame is lifted from the burner and thus can suppress the flashback into the burner [19].

3.3. Combustor operability

The combustors are required to operate stably from ignition through part load to base load in practical IGCC plants. The next subsections describe the fuel supply system and fuel staging.

3.3.1. Fuel supplying system

The fuel supply system supplies syngas and oil fuels to the multi-cluster combustor. **Figure 10** shows the fuel supplying system for the combustor [19]. The six main burners are divided into two groups (F2 and F3) consisting of three burners each, and arranged alternately around the pilot burner (F1). The syngas fuel is distributed into five fuel circuits: F1 fuel to the F1 pilot

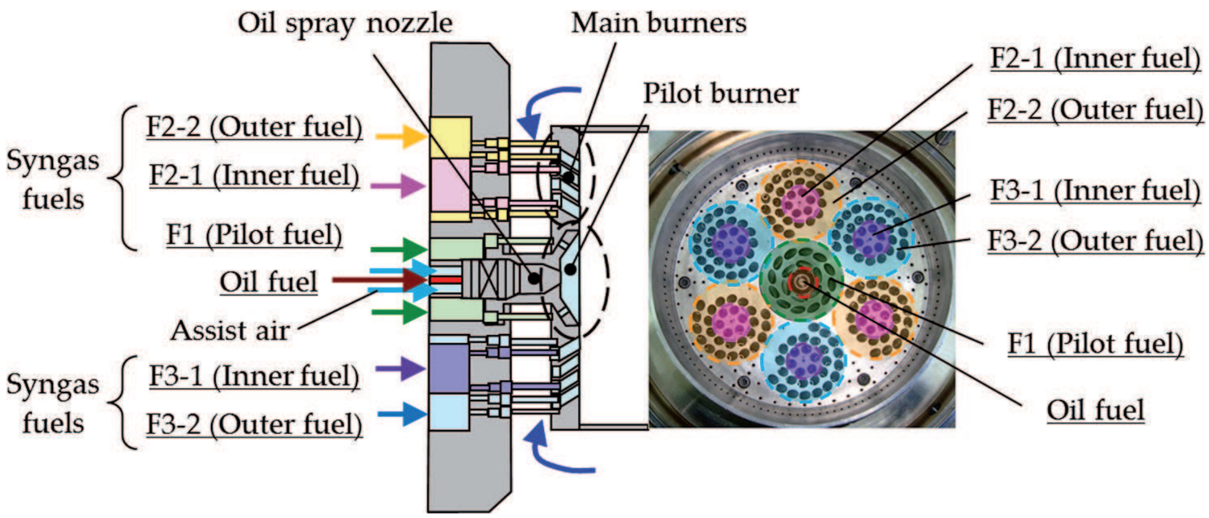

Figure 10. Fuel supplying system.

burner, F2-1 fuel to the inner region of the F2 main burners, F2-2 fuel to the outer region of the F2 main burners, F3-1 fuel to the inner region of the F3 main burners, and F3-2 fuel to the outer region of the F3 main burners. The oil fuel is supplied to the oil spray nozzle.

The fuel distribution ratios (F1 ratio and outer-fuel ratio) are important test parameters influencing combustion performance. The F1 ratio is defined as the ratio of the mass flow rates of F1 fuel to all fuel. The F1 ratio is expressed as follows:

$$\text{F1 ratio (\%)} = \frac{Gf_{F1}}{Gf_{all}} = \frac{Gf_{F1}}{Gf_{F1} + Gf_{F2-1} + Gf_{F2-2} + Gf_{F3-1} + Gf_{F3-2}} \tag{1}$$

where *Gf* denotes the mass flow rate, and subscripts "all," "F1," "F2-1," "F2-2," "F3-1," and "F3-2" denote all the fuel, F1 fuel, F2-1 fuel, F2-2 fuel, F3-1 fuel, and F3-2 fuel, respectively. The outer-fuel ratio is defined as the ratio of the mass flow rates of the outer fuel to all fuel supplied to the main burners. The outer-fuel ratio is expressed by Eq. (2).

$$\text{Outer} - \text{fuel ratio (\%)} = \frac{Gf_{F2-2} + Gf_{F3-2}}{Gf_{F2-1} + Gf_{F2-2} + Gf_{F3-1} + Gf_{F3-2}} \tag{2}$$

3.3.2. Fuel staging

The multi-cluster combustor can achieve low emissions and high operability over the entire operating range by switching combustion modes according to operating conditions. The combustor switches the modes by manipulating the combination of operating burners for which the fuel circuit is fueled. The fuel staging with combustion modes and switching loads hinges on such factors as operating conditions, operational requirement, and environmental regulation for each practical plant. This chapter shows an instance of the fuel staging sequences and combustion modes. **Figure 11** shows the fuel staging [22]. In this figure, colored regions shown on the burner pictures indicate operating burners. This fuel staging consists of three distinct combustion modes: oil mode, partial mode, and final mode. The combustor operates on oil fuel in the oil mode and on syngas fuel in the partial and the final

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Operating range	Turbine speed (%)	Low ← Gas turbine load (%)	→ High
Fuel	Oil	Syngas	
Mode	Oil mode	Partial mode	Final mode
Operating burners	Oil spray nozzle	F1 + F2-1 + F2-2 + F3-1	F1 + F2-1 + F2-2 + F3-1 + F3-2
			

Figure 11. Fuel staging.

modes. The combustor switches from the oil mode, through the partial mode, to the final mode between ignition and base load.

In the oil mode, the combustor operates on oil fuel with the oil spray nozzle. The oil mode is used to ignite, accelerate, and operate the combustor over low loads. The oil fuel operation requires injection of diluent into the combustion zone to lower NOx emissions to the level required by environmental regulations, because NOx from oil fueled combustion increase owing to the local high-temperature regions compared with syngas fueled combustion. The combustor injects diluent nitrogen from the fuel nozzles in the outer regions of the main burners. The diluent nitrogen is separated from air by the ASU in IGCC plants. In the partial mode, the combustor operates on syngas fuel with the pilot burner (F1), inner regions of the F2 and F3 main burners (F2-1 and F3-1), and outer regions of the F2 main burners (F2-2). The partial mode is employed during part load from a low load to a middle load. At a low part load, the combustor switches from oil to syngas fuels. The combustor achieves stable combustion over low to middle loads by combusting the pilot fuel and inner fuel of the main burners associated with flame stabilization. In the final mode, the combustor operates on syngas fuel with the pilot burner and all the main burners. The final mode is used from a middle part load to base load. The combustor achieves low NOx combustion by distributing syngas fuel to all the burners [22].

4. Combustor development

4.1. Development approach

This section describes the development work for the multi-cluster combustors intended for hydrogen-rich syngas fuels in CCS-equipped oxygen-blown IGCC plants. **Figure 12** shows the development approach for the multi-cluster combustors. The development approach consists of three steps: burner development; combustor development; and feasibility demonstration for practical plants.

	Step 1 Burner Development	*Step 2* Combustor Development	*Step 3* Feasibility demonstration for practical plants
Purpose	Optimization of burner configurations	Optimization of combustor configurations	Demonstration of combustor performance in practical plants
Configuration	- Pair of a fuel nozzle and an air hole - Single burner	Single-can combustor	Multi-can combustors
Test	- Single-nozzle mixing test - Single-burner combustion test	Single-can combustor test	Real gas turbine test in multi-can combustor configuration
Pressure	Atmospheric pressure	Medium and high pressures	Practical pressure
Fuel	Test fuels (mixtures of H_2, CH_4, & N_2)	Test fuels (mixtures of H_2, CH_4, & N_2)	Practical syngas fuels
Evaluation	- Emissions (NOx, CO, UHC) - Stability (Pressure fluctuations)	- Emissions (NOx, CO, UHC) - Stability (Pressure fluctuations) - Reliability (Metal temperatures)	- Emissions (NOx, CO, UHC) - Stability (Pressure fluctuations) - Reliability (Metal temperatures) - Operability (Dynamic characteristics)

Figure 12. Development approach for multi-cluster combustors.

In Step 1, the purpose is to optimize configurations of single burners with pairs of a fuel nozzle and an air hole by performing single-nozzle mixing test and single-burner combustion test at atmospheric pressure with test fuels comprised of H_2, methane (CH_4), and N_2. Step 1 evaluates performance of single burners in terms of emissions of NOx, CO, and unburned hydrocarbons (UHC), and stability, which is related to pressure fluctuations due to combustion oscillation. The single-burner combustion test showed that the operating range of stable low NOx combustion was restricted by the occurrence of combustion oscillation, and it was probably triggered by the attachment of the flame to the perforated plate due to the ignition of flammable mixtures in the wake behind the plate [3]. In order to suppress the combustion oscillation, a convex burner was suggested. The convex burner was equipped with a convex perforated plate, of which the center projected into the combustion chamber and the surface was inclined. The combustion test showed that the convex burner was effective in suppressing the combustion oscillation and it expanded the operating range of stable low NOx combustion [23].

In Step 2, the purpose is to optimize configurations of single-can combustors by performing the single-can combustor test at medium and high pressures with test fuels that were mixtures of H_2, CH_4, and N_2 on the basis of the burner configurations optimized in Step 1. Step 2 evaluates performance of single-can combustors in terms of emissions, stability, and reliability. The performance for the reliability is related to metal temperatures of burners and liners. On the basis of the findings from the single-burner combustion tests, multi-cluster combustors equipped with the flat burner and the convex burner were developed.

In Step 3, the purpose is to demonstrate combustor performance in practical plants by real gas turbine test in a multi-can combustor configuration at practical pressure with practical syngas fuel. Step 3 evaluates performance of multi-can combustors in terms of emissions, stability, reliability, and operability. The performance for the operability is related to dynamic characteristics of the combustors during their operation.

The next subsections describe the development work in Step 2 and Step 3.

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4.2. Single-can combustor test

Step 1 evaluated performance of the flat burner and the convex burner by performing the single-burner combustion test in order to optimize the burner configuration. This subsection describes the development of multi-cluster combustors equipped with the flat burner and the convex burner [24, 25].

Figure 13 shows the configurations of two types of prototype multi-cluster combustors: a flat multi-cluster combustor and a convex multi-cluster combustor. The two combustors differed in terms of the main burner configurations. The flat combustor was equipped with one concave pilot burner at the center and six flat main burners surrounding the pilot burner. The convex combustor was equipped with one concave pilot burner at the center and six convex main burners surrounding the pilot burner. The combustors were tested at a medium pressure under the base load condition.

Figure 14 shows a schematic diagram of the single-can combustor test facility. A single-can combustor was assembled into the test stand. An air compressor supplied combustion air to the combustor through a preheater, and the pressure in the combustion chamber was adjusted with a back pressure valve downstream. The test fuels were mixtures of H_2, CH_4, and N_2. The fuel supplying system independently supplied the following gases to a gas mixer: H_2 from H_2-cylinder-loaded trailers; CH_4 from CH_4-cylinder-loaded trailers; and N_2 from a liquefied nitrogen tank. The gas mixer produced a gas mixture with certain volume percentages (vol%) of the three gases as a test fuel. The compositions of the gas mixture were varied by changing the flow rates of the constituents independently. The gas mixture was separated into five fuel circuits. The measuring equipment consisted of a gas analyzer and a fluctuating-pressure-measuring system. The gas analyzer measured gas concentrations in the exhaust gas at a measuring duct downstream in the test stand. The fluctuating-pressure-measuring system measured pressure fluctuations inside the combustion chamber.

Combustor		Flat multi-cluster combustor	Convex multi-cluster combustor
Surface shape	Pilot burner	Concave	Concave
	Main burners	Flat	Convex
Photo			

Figure 13. Configurations of prototype multi-cluster combustors.

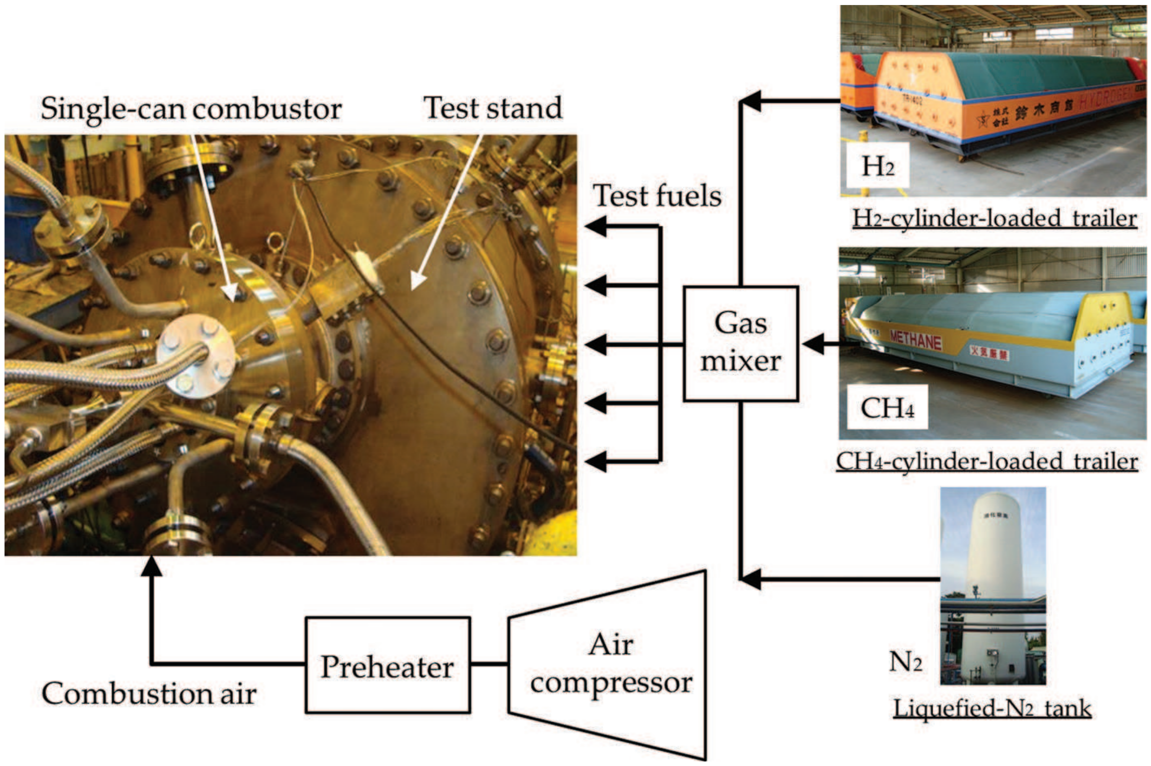

Figure 14. Single-can combustor test facility.

The practical syngas fuels used in IGCC plants include a large amount of CO. However, the road traffic law in Japan prohibits the transport of a large amount of CO required for combustor tests mainly for safety reasons. This practical restriction requires use of CO-free test fuels for the combustor tests. **Table 1** lists properties of three mixtures of test fuels used. The test fuels contained 40, 55, and 65 vol% H_2, simulating the practical hydrogen-rich syngas fuels at carbon capture rates of 0, 30, and 50% for CCS-equipped oxygen-blown IGCC, respectively. Hereafter, the test fuels are referred to as "CCS-0% fuel," "CCS-30% fuel," and "CCS-50% fuel."

Minimization of NOx requires homogeneous lean combustion. Homogeneous lean combustion was achieved by supplying syngas fuel to each fuel nozzle of the main burners at the

Test fuels		**CCS-0% fuel**	**CCS-30% fuel**	**CCS-50% fuel**
Constituents:				
H_2	vol%	40.0	55.0	65.0
CH_4	vol%	18.0	15.7	6.3
N_2	vol%	42.0	29.3	28.7
Density	kg/m^{3*}	0.640	0.490	0.429
Lower heating value	MJ/m^{3*}	10.0	10.8	8.6
	MJ/kg	15.7	22.0	20.1

*At 273.15 K, and 0.1013 MPa.

Table 1. Properties of test fuels.

same flow rate. This uniform fuel supply yielded an outer-fuel ratio of 80%. This ratio equaled the proportion of the number of fuel nozzles in the outer region (24 nozzles) to the total number of fuel nozzles (30 nozzles) of each main burner. This study set the target outer-fuel ratio at 80% for minimum NOx. This study defines a certain value of the maximum design amplitude of pressure fluctuations for safely operating the combustors. The combustors are required to be developed so that they can maintain the pressure fluctuation amplitudes below the maximum design value. The maximum design value is referred to as the criterion of combustion oscillation here. The combustion oscillation with an amplitude above the criterion may increase the risk of damage to the combustors.

Figures 15 and **16** show variations in pressure fluctuation amplitude and NOx emissions, respectively, for the flat combustor as a function of the outer-fuel ratio. In **Figure 15**, the amplitude of pressure fluctuation was normalized by the maximum design value. For CCS-0% fuel, the flat multi-cluster combustor could increase the outer-fuel ratio to the target ratio with the pressure fluctuation amplitude below the criterion, and thus achieved the minimum NOx at the target ratio. For CCS-30% and CCS-50% fuels, however, the flat combustor could not increase the outer-fuel ratio to the target ratio because the pressure fluctuation amplitudes increased abruptly above the criterion before the outer-fuel ratio reached the target ratio. Consequently, the NOx minimization was restricted by the abrupt increase in pressure fluctuation amplitude above the criterion.

In contrast, **Figure 17** shows that the convex multi-cluster combustor could increase the outer-fuel ratio to the target ratio with the pressure fluctuation amplitude below the criterion for CCS-0%, CCS-30%, and CCS-50% fuels. **Figure 18** shows that the convex combustor achieved the minimum NOx at the target ratio for all the test fuels. The test results demonstrated that the convex combustor was effective in suppressing the occurrence of combustion oscillation for hydrogen-rich fuels.

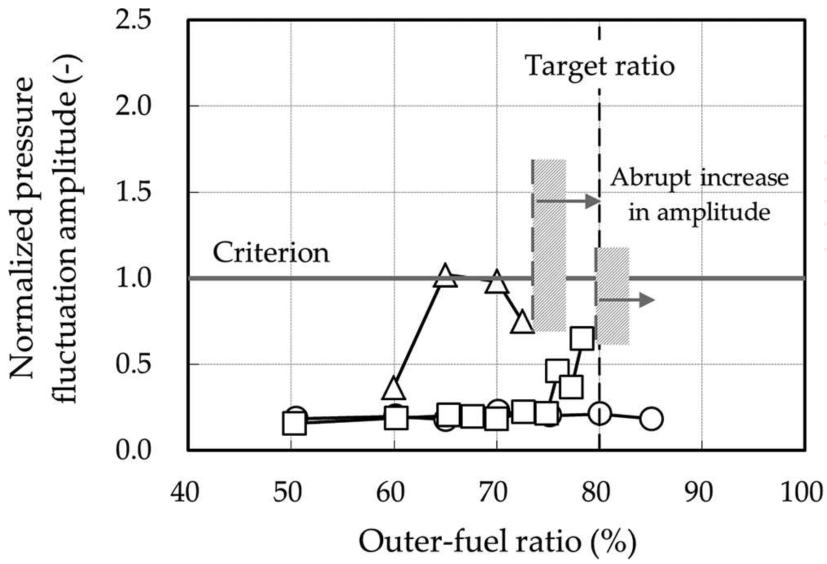

Figure 15. Pressure fluctuation amplitude in single-can combustor test for flat multi-cluster combustor. Symbols: circles, CCS-0% (H_2 = 40 vol%); squares, CCS-30% (H_2 = 55 vol%); triangles, CCS-50% (H_2 = 65 vol%).

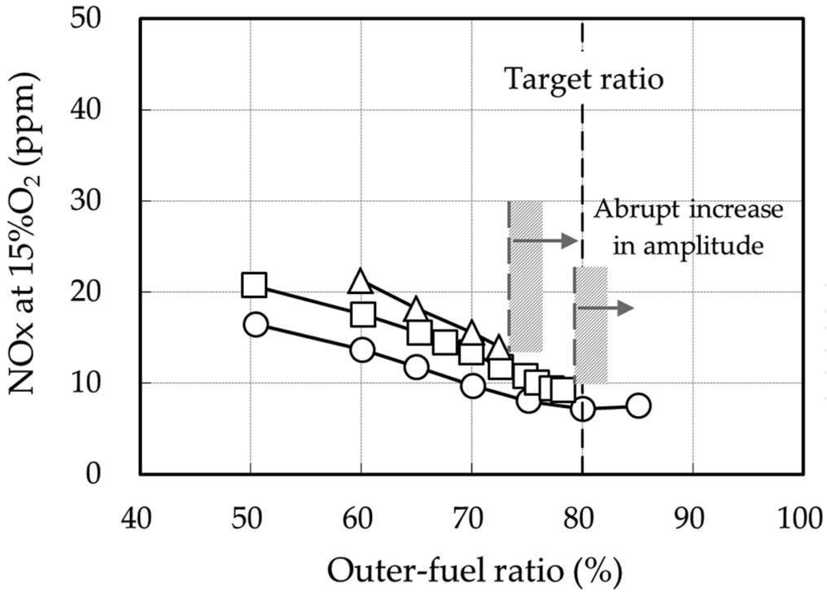

Figure 16. NOx emissions in single-can combustor test for flat multi-cluster combustor. Symbols: circles, CCS-0% (H_2 = 40 vol%); squares, CCS-30% (H_2 = 55 vol%); triangles, CCS-50% (H_2 = 65 vol%).

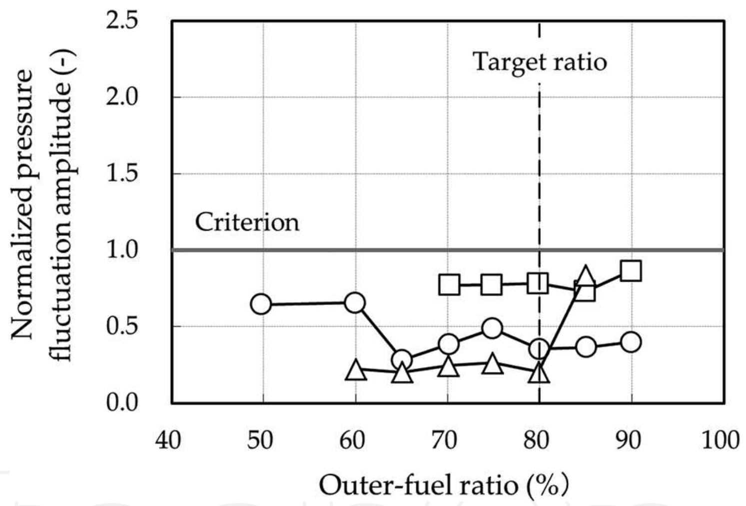

Figure 17. Pressure fluctuation amplitude in single-can combustor test for convex multi-cluster combustor. Symbols: circles, CCS-0% (H_2 = 40 vol%); squares, CCS-30% (H_2 = 55 vol%); triangles, CCS-50% (H_2 = 65 vol%).

Both multi-cluster combustors achieved flashback-free combustion throughout the tests. The test results demonstrated that the multi-cluster combustors could feasibly achieve the dry low NOx combustion of hydrogen-rich surrogate fuels with hydrogen content to 65 vol%.

4.3. Pilot plant test

In order to demonstrate the feasibility for practical IGCC plants, the multi-cluster combustor was tested on a real gas turbine in a multi-can combustor configuration in an IGCC pilot plant at practical pressure with practical syngas fuel [19, 22, 26, 27].

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4.3.1. Pilot plant EAGLE and test conditions

The pilot plant was an oxygen-blown integrated coal gasification power generation pilot plant "EAGLE" ("coal Energy Application for Gas, Liquid and Electricity") at the Wakamatsu Research Institute of the Electric Power Development Co., Ltd. (J-POWER) (Japan). This pilot plant (**Figure 19**) was a test facility for developing coal gasification technologies with innovative

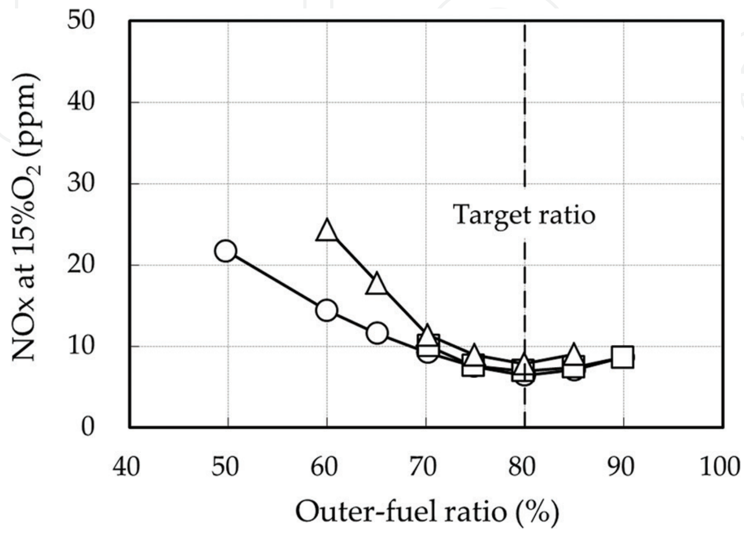

Figure 18. NOx emissions in single-can combustor test for convex multi-cluster combustor. Symbols: circles, CCS-0% (H_2 = 40 vol%); squares, CCS-30% (H_2 = 55 vol%); triangles, CCS-50% (H_2 = 65 vol%).

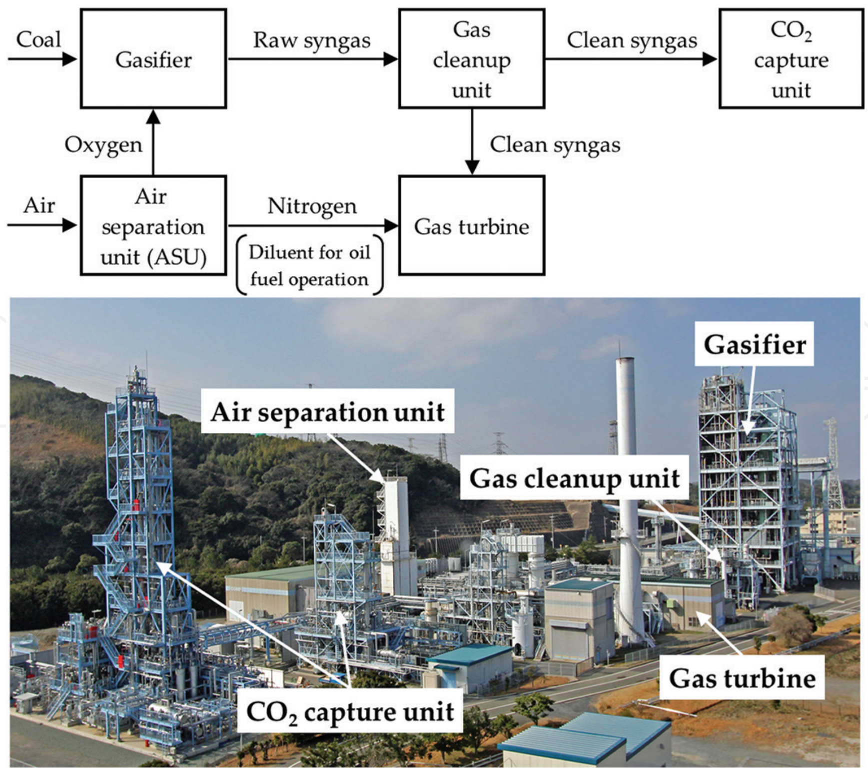

Figure 19. EAGLE pilot plant (photo courtesy of J-POWER).

CO_2 capture [28–32]. The five main components of the EAGLE plant were an ASU, a gasifier, a gas cleanup unit, a gas turbine, and a CO_2 capture unit. The ASU separated air into oxygen and nitrogen. Oxygen was supplied to the gasifier as an oxidant for the gasification process. Nitrogen was supplied to the gas turbine as a diluent for oil fuel operation. The gasifier converted coal to raw syngas by reacting it with oxygen. The gasifier employed an oxygen-blown, single-chamber, two-stage, swirling flow entrained bed gasification method. The gas cleanup unit removed impurities from the raw syngas, thus producing a clean syngas consisting mainly of CO, H_2, and N_2. The clean syngas was supplied separately to the gas turbine and the CO_2 capture unit. This separate syngas supply was employed because of the plant's operational circumstance that the test of the gas turbine combustor proceeded with the test of the CO_2 capture individually in the test series [32].

The gas turbine was an open simple-cycle/single-shaft type. It was originally equipped with a conventional diffusion-flame combustor with one oil fuel supplying system and one syngas fuel supplying system. The diffusion-flame combustor needed to inject diluent nitrogen into the combustion chamber to decrease NOx emissions. The diffusion-flame combustor on the gas turbine was replaced by the multi-cluster combustor with four additional syngas fuel supplying systems for the present tests. The multi-cluster combustor for the IGCC was developed for middle and small capacity gas turbines. The flat multi-cluster combustor was employed for the test because it was applicable to hydrogen-rich syngas fuels with intermediate hydrogen contents and its structural reliability was ensured by the simple structure of the flat perforated plate.

The syngas fuel burned in the tests was comprised mainly of CO, H_2, and N_2. The syngas fuel contained approximately 50 vol% CO, 20 vol% H_2, and 20 vol% N_2. Distillate oil was also burned for oil fuel operation. The EAGLE pilot plant test was conducted from startup on distillate oil to the maximum load (corresponding to 80% of the gas turbine load) on syngas produced in the test series.

The measuring systems consisted mainly of a gas analyzer, fluctuating-pressure-measuring system, and metal-temperature-measuring system. The gas analyzer measured the concentrations of NOx, CO, O_2, and CO_2 contained in the exhaust gas. The exhaust gas was sampled at multiple points in a cross section located in the exhaust duct downstream from the turbine. The fluctuating-pressure-measuring system measured pressure fluctuations at a point inside the combustion chamber on each can combustor. The metal-temperature-measuring system was equipped with thermocouples to measure metal temperatures of the liner and burner perforated plate [27].

4.3.2. Combustor performance at maximum load

This subsection evaluates combustor performance at a maximum gas turbine load of 80% [19]. The combustor operated with all the syngas-fueled burners in the final mode at the maximum load.

Figure 20 shows the maximum amplitudes of pressure fluctuations in all the cans at the maximum load versus the outer-fuel ratio. The amplitudes were maintained at low values well below the criterion over the whole test range. This result demonstrated that the multi-cluster combustor achieved stable operation with low levels of pressure fluctuation amplitudes. The stable combustion performance was probably due to the stable lifted flames formed by the cluster burners.

Figure 21 shows the NOx emissions at the maximum load as a function of the outer-fuel ratio. The NOx decreased with increasing outer-fuel ratio until reaching the target ratio (80%); it yielded the minimum value at the target ratio, and then increased again with increasing outer-fuel ratio above the target ratio. The minimum NOx value was 10.9 ppm at the target ratio. The minimum NOx value at the target ratio was achieved by homogeneous lean combustion with a uniform equivalence ratio over the region in the main burners. The higher NOx values at outer-fuel ratios below and above the target ratio were due to the formation of high-temperature flames with a higher equivalence ratio in the inner region and the outer region, respectively.

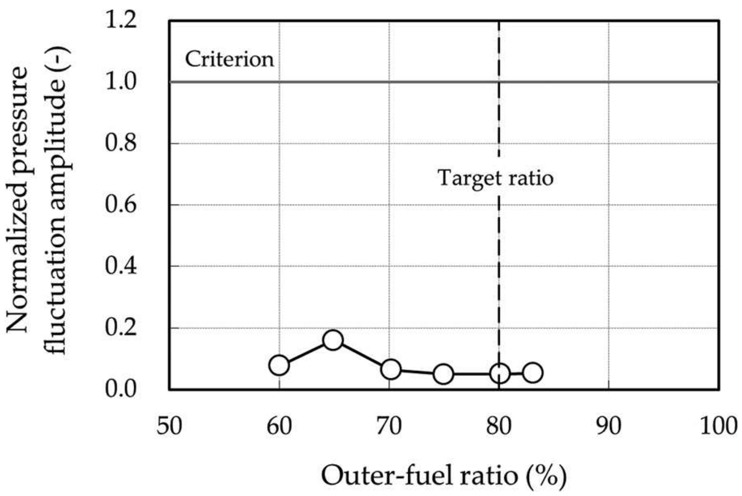

Figure 20. Pressure fluctuation amplitude at maximum gas turbine load of 80%.

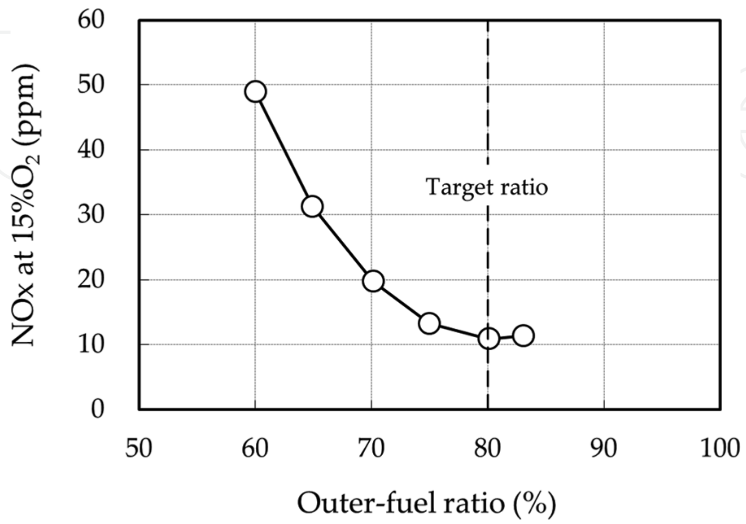

Figure 21. NOx emissions at maximum gas turbine load of 80%.

The multi-cluster combustor features diluent-free (dry), low NOx combustion. In order to demonstrate this feature, the dry low NOx performance of the multi-cluster combustor was compared with the diluent-controlled low NOx performance of the diffusion-flame combustor. **Figure 22** compares the NOx emissions for the multi-cluster combustor and the diffusion-flame combustor at the maximum load plotted against the normalized mass-flow-rate ratio of diluent nitrogen to syngas fuel [19]. The data for the multi-cluster combustor yielded the minimum NOx value of 10.9 ppm as attained at the target ratio. The data for the diffusion-flame combustor were obtained in tests of the combustor in the same plant. This figure plots the data in the operating range. The prediction curve represents predicted NOx values for the diffusion-flame combustor. This curve was predicted on a correlation between NOx and the stoichiometric flame temperature of a fuel/air/diluent mixture, which is representative of the actual flame temperature closely associated with the NOx formation rate in diffusion flames [33, 34]. This figure shows that the multi-cluster combustor achieved low NOx below around 10 ppm at a N_2/fuel ratio of zero (diluent-free (dry)). In contrast, the diffusion-flame combustor yielded much higher NOx around 200 ppm at a N_2/fuel ratio of zero, and needed diluent nitrogen to decrease NOx to the same level as that achieved by the multi-cluster combustor as a diluent-free condition. This comparison demonstrated that the multi-cluster combustor could feasibly achieve dry low NOx combustion of the syngas fuel in the IGCC pilot plant.

4.3.3. Combustor performance at part load

The combustor is required to operate stably from ignition through part load to the maximum load in practical IGCC plants. This subsection evaluates the performance of the combustor at part load in the plant [22].

Figure 23 shows the variations in NOx emissions as a function of the gas turbine load. From 0% load (full speed no load) to 30% load, the combustor operated on distillate oil with diluent

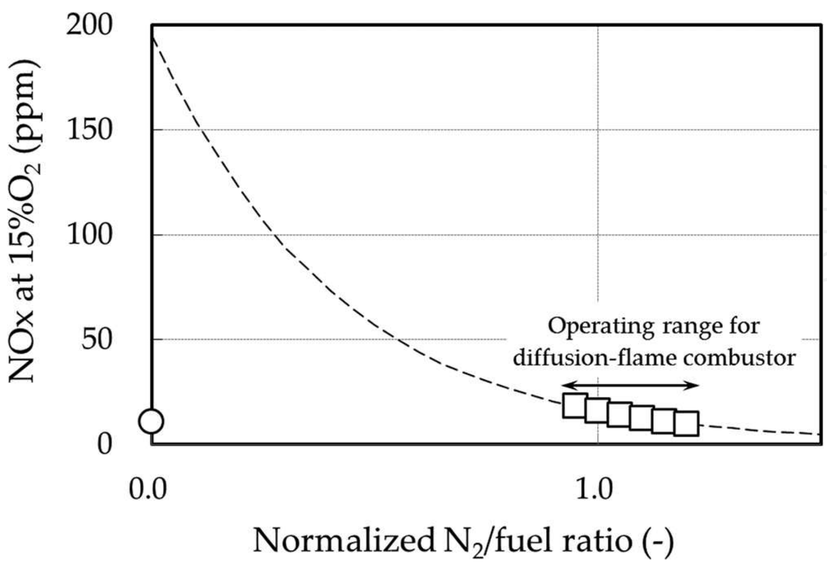

Figure 22. NOx comparison between multi-cluster combustor and diffusion-flame combustor at maximum gas turbine load. Symbols: circles, multi-cluster combustor; squares, diffusion-flame combustor; dotted line, prediction curve for diffusion-flame combustor.

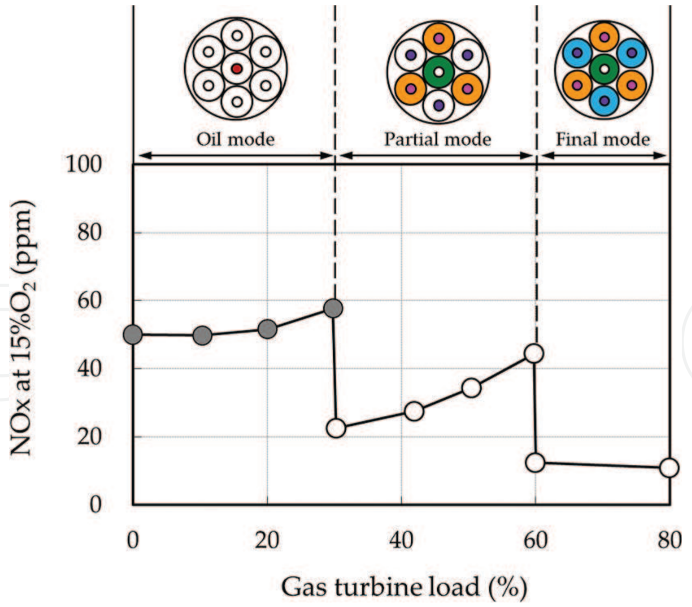

Figure 23. Variations in NOx emissions with gas turbine load.

nitrogen injection to control NOx in the oil mode. NOx increased with the load during oil operation between 0 and 30% load. At 30% load, the combustor switched from distillate oil to syngas. During this switching, the combustor disconnected the supply of diluent nitrogen for NOx control. NOx decreased from 58 to 23 ppm when the combustor switched the diluent-controlled oil operation to diluent-free syngas operation. From 30 to 60% load, the combustor operated on syngas in the partial mode. NOx increased with the load between 30 and 60% load. At 60% load, the combustor switched from the partial mode to the final mode, where the pilot burner and all the main burners were operating. NOx decreased from 44 to 12 ppm at this mode-switching load. This NOx decrease was due to the dispersion of fuel to all the burners. Finally from 60 to 80% load, the combustor operated on syngas in the final mode. NOx abruptly decreased at 60% load, and then gradually decreased with the load between 60 and 80% load. These results demonstrated that the multi-cluster combustor achieved dry low NOx of less than 12 ppm in the final mode above 60% load.

High values of combustion efficiency close to 100% indicate complete combustion, whereas low values of combustion efficiency indicate incomplete combustion, as manifested mainly in the form of CO emissions in the exhaust gas. Combustion efficiency is defined as the ratio of actual heat energy released in combustion to the theoretical heat energy available in fuel. In this study, the actual heat energy was calculated by subtracting the waste heat due to CO emissions in the exhaust gas from the theoretical heat energy. The theoretical heat energy was calculated as the heat liberated when fuel was completely burned [26].

Figure 24 shows combustion efficiency as plotted against the gas turbine load. The combustion efficiency periodically increased and decreased with the load. The combustion efficiency increased with the load in each mode, and decreased at each mode-switching load. The combustion efficiency decreased from 99.8 to 98.7% when switching from the oil mode to the partial mode at 30% load, and decreased from 99.9 to 99.5% when switching from the partial mode to the final mode at 60% load. In summary, the multi-cluster combustor attained combustion efficiencies over 99.1% on oil operation between 0 and 30% load, and attained combustion efficiencies over 98.7% on syngas operation between 30 and 80% load. This result demonstrated that the combustor attained high values of combustion efficiency during oil and syngas operation at part load.

Figure 25 shows the maximum pressure fluctuation amplitudes in all the cans as a function of the gas turbine load. The combustor maintained the amplitudes at values below the criterion

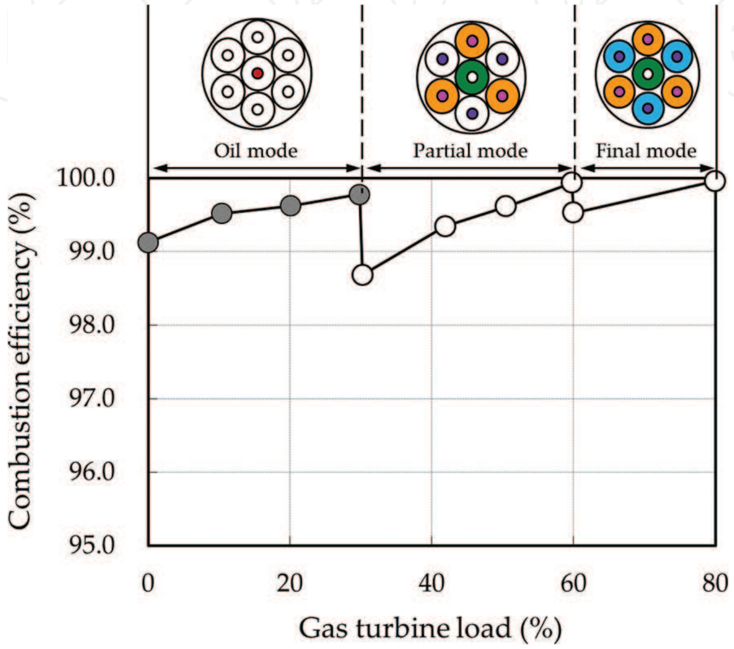

Figure 24. Variations in combustion efficiency with gas turbine load.

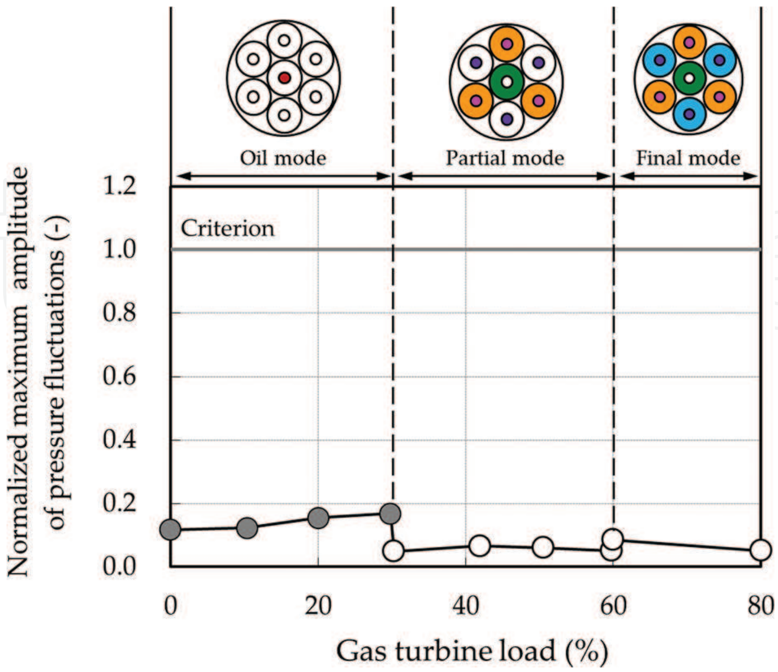

Figure 25. Variations in maximum amplitude of pressure fluctuations with gas turbine load.

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over the entire load range. The result demonstrated that the combustor achieved stable operation with low pressure fluctuation amplitudes at part load.

Figure 26 shows the maximum values of all liner metal temperatures in all the cans as a function of the gas turbine load. The combustor maintained the liner metal temperatures at values below the criterion over the load range. The liner metal temperatures yielded the maximum values around the liner end tip.

The multi-cluster combustor achieved flashback-free combustion throughout part load. The test results demonstrated the feasibility of dry low NOx combustion of the practical syngas fuel in the IGCC pilot plant.

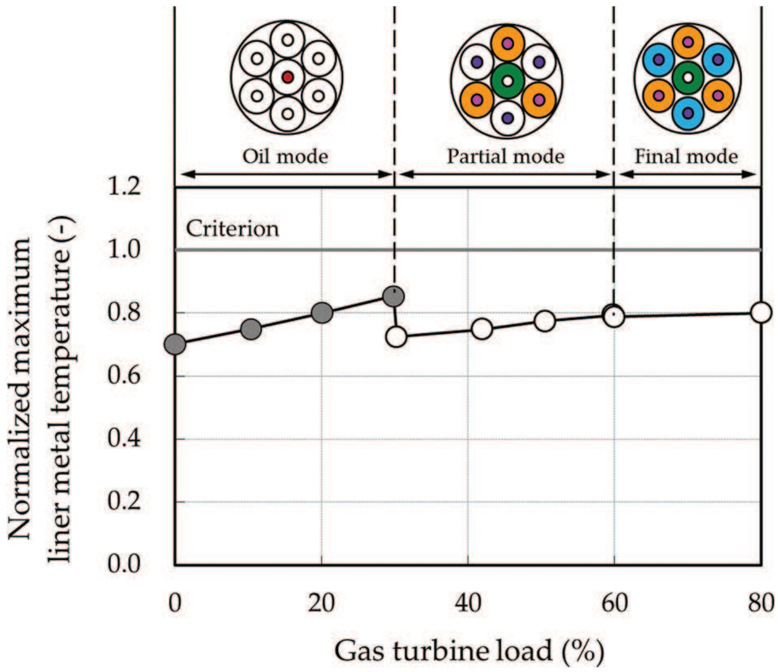

Figure 26. Variations in maximum liner metal temperature with gas turbine load.

5. Conclusions

This chapter described the development of the multi-cluster combustor as a state-of-the-art dry low NOx combustor for hydrogen-rich syngas fuels that can achieve both low NOx and high plant efficiency. The development approach consisted of three steps: burner development; combustor development; and feasibility demonstration for practical plants. This chapter focused mainly on the second and third steps. The main findings from these steps are summarized as follows.

- The single-can combustor test results showed that the convex combustor was effective in suppressing the occurrence of combustion oscillation.
- The test results in the IGCC pilot plant demonstrated the feasibility of the multi-cluster combustor for achieving dry low NOx combustion of the hydrogen-rich syngas fuel in the plant.

6. Next steps

6.1. IGCC demonstration test

On the basis of the experiences in the IGCC pilot plant test, a multi-cluster combustor was developed and installed on a middle capacity gas turbine in an oxygen-blown IGCC demonstration plant of the Osaki CoolGen Corporation, Japan [35–37]. The Osaki CoolGen project has been implemented as an "integrated coal gasification fuel cell combined cycle (IGFC) demonstration project" [37, 38]. This demonstration project is aiming at innovative low-carbon coal-fired thermal power generation by combining IGFC technology with innovative CO_2 capture technologies, thereby dramatically cutting CO_2 emissions from coal-fired thermal power plants. IGFC technology is expected to be an extremely efficient coal-fired thermal power generation technology. This demonstration project consists of three stages. The first stage is an oxygen-blown IGCC demonstration test. The project for the first stage is subsidized by the Ministry of Economy, Trade and Industry (METI) of Japan. The second stage is an oxygen-blown IGCC with CO_2 capture demonstration test. The final stage is a CO_2-capturing IGFC demonstration test. The project for the second and final stages is subsidized by the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

6.2. Applications of multi-cluster combustors

The single-can combustor test results described in Section 4.2 showed that the multi-cluster combustors are capable of achieving dry low NOx combustion of hydrogen-rich fuels with hydrogen content to 65 vol%. Thus, the multi-cluster combustor is also applicable for by-product gases with the same range of hydrogen contents. **Figure 27** shows suitable hydrogen-rich fuels including O_2-blown IGCC/CCS syngas and by-product gases based on the hydrogen content and the volumetric lower heating value. By-product gases include coke oven gas (COG) from ironworks and off-gas from oil refineries. Use of by-product gases as a gas turbine fuel can offer low-cost power generation because it provides fuel cost economy.

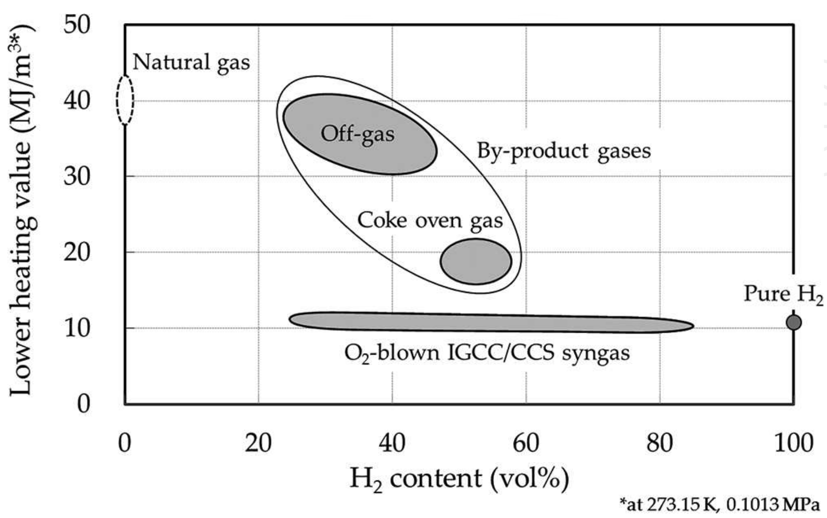

Figure 27. Suitable hydrogen-rich fuels.

The development of the multi-cluster combustors is expected to progress to application to by-product gases and further higher hydrogen content fuels (ultimately pure hydrogen) in order to expand the applicable hydrogen content range.

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