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Test results of a catalytic combustor for a gas turbine

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Abstract

A catalytically assisted low NO_x combustor has been developed which has the advantage of catalyst durability. Combustion characteristics of catalysts at high pressure were investigated using a bench scale reactor and an improved catalyst was selected. A combustor for multi-can type gas turbine of 10 MW class was designed and tested at high-pressure conditions using liquefied natural gas (LNG) fuel. This combustor is composed of a burner system and a premixed combustion zone in a ceramic type liner. The burner system consists of catalytic combustor segments and premixing nozzles. Catalyst bed temperature is controlled under 1000°C, premixed gas is injected from the premixing nozzles to catalytic combustion gas and lean premixed combustion is carried out in the premixed combustion zone. As a result of the combustion tests, NO_x emission was lower than 5 ppm converted at 16% O_2 at a combustor outlet temperature of 1350°C and a combustor inlet pressure of 1.33 MPa.

Keywords: Catalytic combustor; Gas turbine; Nitrogen oxides; Palladium

1. Introduction

Recently, the use of gas turbine systems such as combined cycle and co-generation systems has gradually increased in the world. But even when a clean fuel such as LNG (liquefied natural gas) is used, thermal NO_x is generated in the high temperature gas turbine combustion process. If catalytic combustion can be applied to the combustor of the gas turbine, it is expected to lower NO_x emission more economically. Under such high temperature and high pressure conditions as in the gas turbine, however, the durability of the catalyst is still insufficient.

With the aim of overcoming this problem, joint R&D on low NO_x combustor applied catalytic combustion was started by CRIEPI (Central Research Institute of Electric Power Industry) and KEPCO (The Kansai Electric Power Co., Inc.) in 1988 [1]. A concept of the catalytic combustor combined with premixed combustion was designed. The role of catalytic combustion is only to assist lean premixed combustion, so the catalyst temperature can be reduced to a temperature under 1000°C. As a result, it is expected to avoid catalytic deactivation at high temperatures and thermal and mechanical shock fracture of the honeycomb monolith.

Incidentally, in the case of methane combustion by Pd catalyst, self-oscillation phenomena were observed and they impeded fuel increase to the catalyst. In order to reduce the self-oscillation phenomena and to maintain the catalyst temperature under 1000°C, the combustion characteristics of catalysts at high pressure were investigated using a bench scale reactor.

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Table 1
Targets for combustor performance

Combustor exit gas temperature (T_g)	>1300°C
NO_x emission	<5 ppm (16% O_2)
Combustion efficiency (η)	>99.9%
Total pressure loss (ΔP)	<5%
Pattern factor (PF)	<15%

Aiming at achieving the combustion performance indicated in Table 1, a combustor for 10 MW class multi-can type gas turbine was designed, the improved catalyst was applied and evaluated in a test under high-pressure conditions using LNG fuel.

2. Combustor concept

The combustor concept is shown in Fig. 1 [1]. This combustor is composed of a burner system and a premixed combustion zone. The burner system consists of catalytic combustor segments and premixing nozzles, which are arranged in parallel. Catalytic combustion temperature is controlled under 1000°C, premixed gas is injected from the premixing nozzles to catalytic combustion gas and lean premixed combustion is carried out in the premixed combustion zone after the burner system. The benefits of this system are as follows:

1. Low NO_x emission.
2. Prevention of the thermal degradation of the catalyst.
3. Prevention of the thermal shock fracture of the ceramic monolith of the catalyst.
4. Less necessity of finely uniform pre-mixture for the catalyst.

3. Catalyst improvement

In the case of this combustor, NO_x emission is mainly caused by the premixed gas from the premixing nozzles, which has a higher fuel concentration than that for the catalytic combustor segments. For this reason, it is necessary to make the fuel concentration for the catalytic combustor segments as high as possible to reduce NO_x emission while keeping the catalyst temperature under 1000°C. In order to increase fuel concentration, it is necessary to keep the reaction rate suitably low in the catalyst bed. But using Pd catalyst, which has high activity in methane combustion, self-oscillation phenomena occur and the peak temperature exceed the limitation point. From these standpoints, catalyst improvement was studied.

Table 2 shows the properties of a base catalyst of Pd/Pt and an improved catalyst of Pd/Pt/Rh. Inui and Iwana [2] have suggested that the addition of Rh had a great effect in reducing self-oscillation in city gas combustion using the Cu catalyst.

At first, the ignition temperature was examined under the conditions in Table 3. The catalyst bed temperature was measured with sheath thermocouples

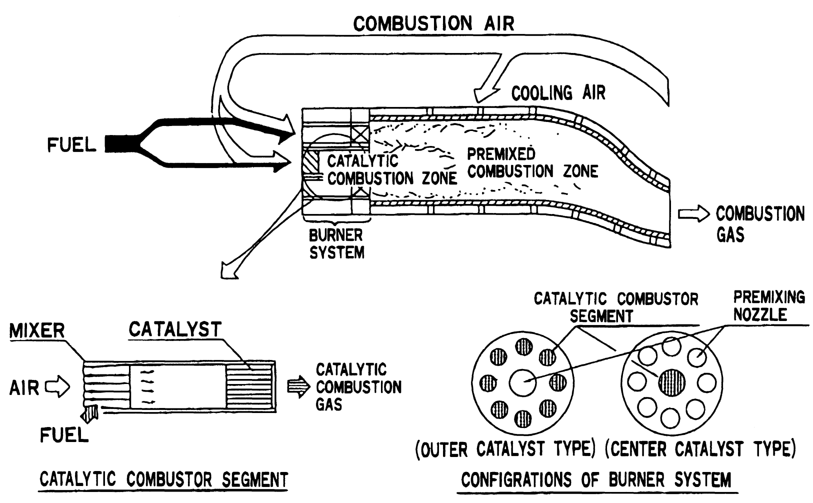

Fig. 1. Combustor concept.

Table 2
Catalyst properties

	Pd/Pt	Pd/Pt/Rh
Substrate	Cordierite honeycomb monolith ϕ 25 mm×L25 mm×200 cpi (cells/in.^{2})	
Washcoat	Stabilized $Al_2O_3$80 g/l+$ZrO_2$20 g/l	
Catalyst	Pd20 g/l+Pt5 g/l	Pd20 g/l+Pt5 g/l+Rh2 g/l

Table 3
Test conditions

Pressure (P)	0.89 MPa
Space velocity (SV)	7.8×10^6 h^{-1}
Fuel concentration	3.5 vol%
Fuel	Natural gas (CH_4=99.2 vol%, CO_2=0.7 vol%, N_2=0.1 vol%)

cemented in honeycomb cells. The rising rate of the catalyst inlet gas temperature (T_{ci}) was kept at 2°C/min. The ignition temperature was defined as T_{ci} at the point of the rapid increase in the outlet gas temperature of the catalyst. Next, keeping T_{ci} at 400°C and the other conditions constant, the reaction temperature was observed for 7 h.

Ignition temperature of both catalysts was about 310°C and the ignition activity of Pd/Pt/Rh was similar to Pd/Pt.

The reaction test results are shown in Fig. 2. The upper limit of oscillating temperature of Pd/Pt/Rh (Tu(Pd/Pt/Rh)) was lower than that of Pd/Pt (Tu(Pd/Pt)) and the lower limit of that of Pd/Pt/Rh (Tl(Pd/Pt/Rh)) was higher than that of Pd/Pt (Tl(Pd/Pt)). The oscillation period of Pd/Pt/Rh was similar to Pd/Pt and was approximately 40 s. The amplitude of oscillating temperature of Pd/Pt/Rh was about 30% smaller than that of Pd/Pt. Next, the same test was conducted on the catalysts aged in an electric furnace for 1000 h and the degradation of Pd/Pt/Rh was lower than that of Pd/Pt.

4. Combustor design and testing

In this combustor concept, air is distributed to catalysts, premixing nozzles and liner cooling, and fuel is distributed to preburner, catalyst and premixing nozzles. Fuel and air distribution is one of the most important considerations in designing this combustor. Fuel distribution to the preburner was determined by the catalyst inlet temperature of 400°C which is sufficiently high to stabilize Pd/Pt/Rh catalyst. In order to stabilize the premixed combustion with low temperature gas under 800°C from the catalyst bed, air and fuel distribution to the catalyst was increased as much as possible, and fuel concentration was limited

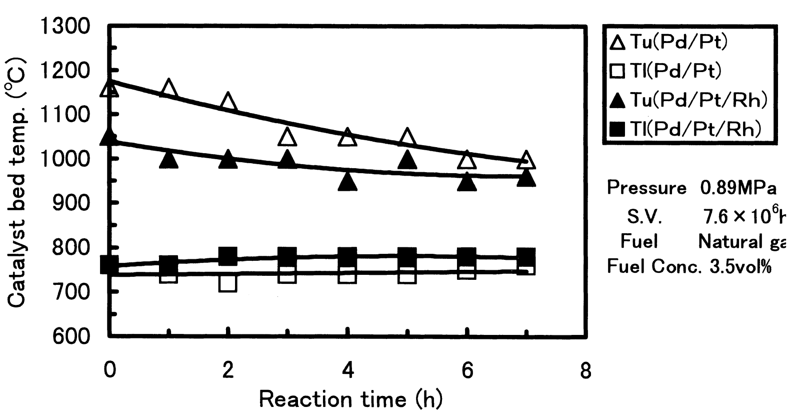

Fig. 2. Catalyst bed temperature.

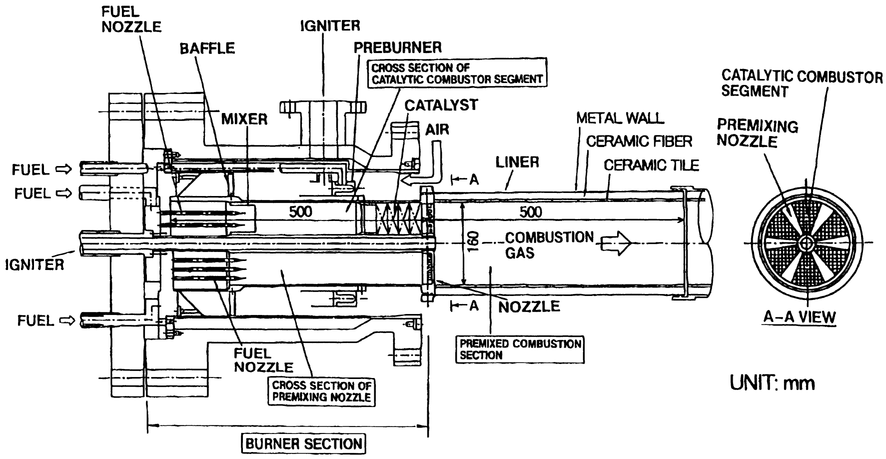

Fig. 3. Schematic of tested combustor.

to 1000°C of the peak temperature of the catalyst bed. Fuel and air distribution to the premixing nozzle was determined from the standpoint of combustion stability and targeted NO_x limitation of 5 ppm (at 16% O_2). The liner cooling air was minimized by use of a ceramic liner [3] to lower the NO_x emission. In order to avoid backfire into the premixing nozzle, gas velocity in the nozzle was maximized within the pressure loss limitation.

The designed combustor is shown in Fig. 3. The scale is equivalent to one combustor of a multi-can type, 10 MW class gas turbine. The burner section shown in Fig. 3 consists of an annular preburner, six catalytic combustor segments and six premixing nozzles. The catalyst segments and premixing nozzles are arranged alternately to form a circle. The premixed combustion section consists of a ceramic liner and a transition piece. The ceramic liner consists of an outer metal wall, ceramic fiber layer and inner ceramic tiles. The ceramic tiles hold the ceramic fiber layer to the metal wall.

Air is heated to 400°C by the preburner and is distributed to the catalyst and premixing nozzles. The peak temperature of the catalyst bed is kept below 1000°C and premixed gas from the premixing nozzles is injected into the catalytic combustion gas at right angles, then recirculating flow occurs after the end face of the premixing nozzles. As a result, stabilized by both the catalytic combustion gas and the recirculating flow, lean premixed combustion over 1300°C is carried out. Table 4 shows the LNG fuel properties, which were sampled from the fuel line and analyzed by TCD gas chromatography. Fig. 4 shows the shape of the tested catalyst of Pd/Pt/Rh, which is segmented in small pieces to avoid thermal shock. The cell pitch

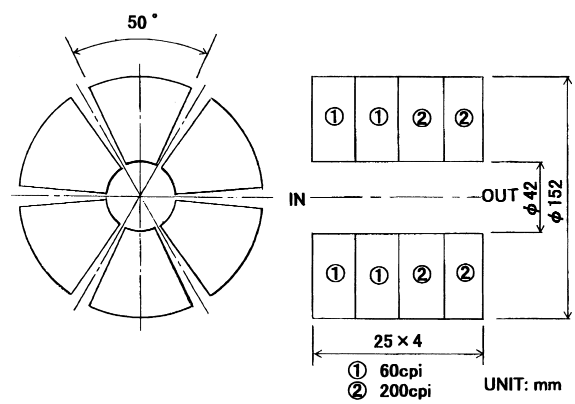

Fig. 4. Shape of catalyst bed.

Table 4
Fuel compositions

Component	CH_4	C_2H_6	C_3H_8	i-C_4H_{10}	n-C_4H_{10}	i-C_5H_{12}	n-C_5H_{12}	N_2
Concentration (vol%)	80.38	9.60	6.62	1.46	1.90	0.00	0.00	0.04

Table 5
Base load conditions

Inlet air pressure (P_a)	1.33 MPa
Air flow rate (V_a)	7250 m_N^3/h
Fuel flow rate (V_f)	270 m_N^3/h
Combustor inlet air temperature (T_{bi})	370°C
Catalyst inlet gas temperature (T_{ci})	400°C
Catalyst bed temperature (T_c)	<1000°C
Adiabatic flame temperature (T_{th})	1350°C

and the length of the catalyst bed were determined by the gas temperature to stabilize premixed combustion. The catalyst bed temperatures are measured with thermocouples that are inserted and cemented in the catalyst cells.

Table 5 shows the test conditions at a base load. Catalytic combustion and premixed combustion were initiated under the conditions of 0.35 MPa, then air and fuel is increased in proportion to the increasing pressure, assuming an air bypass valve [4] is applied to this combustor.

Fig. 5 shows the adiabatic flame temperature (T_{th}) and the mean temperatures at each section of the combustor, combustor inlet air (T_{bi}), catalyst inlet gas (T_{ci}), catalyst bed (T_c) and combustor exit gas (T_g). The pressure was increased while keeping the range of excess air ratio (λ) of 2.0–2.3. The mean temperature and the peak temperature of catalyst bed measured with 18 thermocouples located 5 mm inside from the bed outlet were from 750°C to 800°C and about 1000°C, respectively. Fig. 6 shows the emissions and the combustion efficiency. Combustion efficiency (η) was over 99.99% and stable combustion was kept between 0.34 and 1.33 MPa. NO_x emission

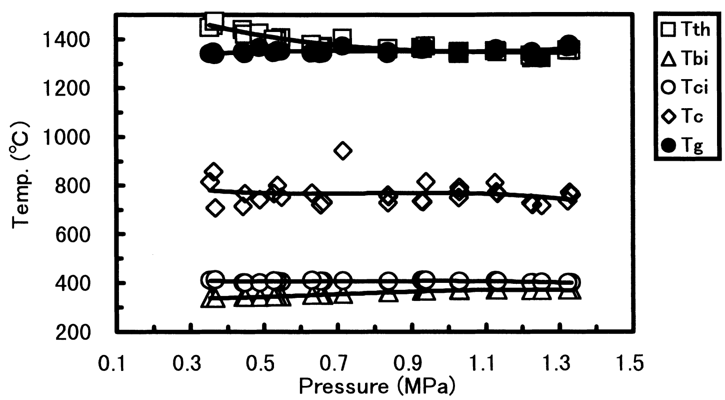

Fig. 5. Mean temperature at each section of combustor.

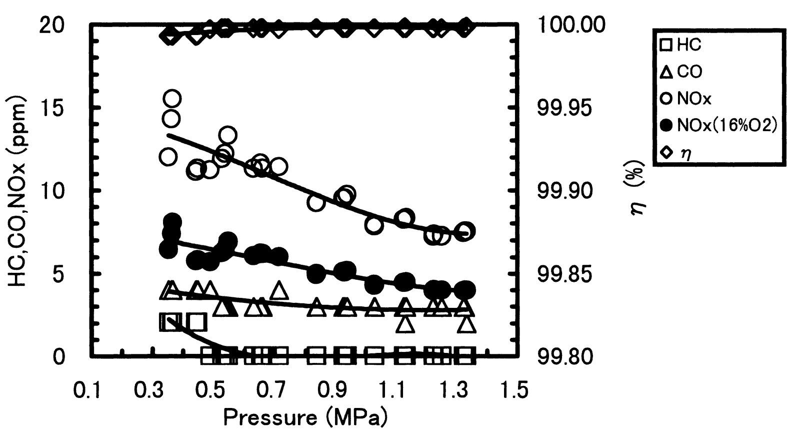

Fig. 6. Emission and combustion efficiency.

decreased with increasing pressure, 5 ppm NO_x converted at 16% O_2 was achieved over 0.93 MPa and at the base load condition, it was 4 ppm. T_{bi} rose from 330°C at 0.34 MPa to 370°C at 1.33 MPa. Then the load of preburner was reduced with increasing pressure to keep T_{ci} at 400°C. The tendency of the total NO_x emissions was affected by the preburner, which was the main source of NO_x emissions.

Pattern factor (PF) was measured with 24 thermocouples at the combustor exit. It is defined as follows:

$$PF = \frac{T(\text{maximum}) - T(\text{mean})}{T(\text{mean}) - T(\text{inlet})} \times 100.$$

It was an extremely low level around 3.5% between 0.34 and 1.33 MPa. Combustor pressure loss (ΔP) decreased with increasing pressure, 5% was achieved over 0.44 MPa and at the base load condition, it was 3.9%. It is defined as follows:

$$\Delta P = \frac{P(\text{inlet}) - P(\text{exit})}{P(\text{inlet})} \times 100.$$

The combustion test was conducted twice using the same catalyst and similar performance of the combustor and the catalyst was obtained through the test.

5. Conclusion

A catalytically assisted low NO_x combustor was designed. The catalyst was improved and the combustor for a 10 MW-class gas turbine was tested with using the improved catalyst at high pressures. As a result, stable low NO_x combustion below 5 ppm was demonstrated at a combustor exit gas temperature of 1350°C.

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