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Development of a low NO_x catalytic combustor for a gas turbine

Yasushi Ozawa [a,*], Tomoharu Fujii [a], Shunji Kikumoto [a], Mikio Sato [a], Hisashi Fukuzawa [a], Mikindo Saiga [b], Shinji Watanabe [b]

[a] *Central Research Institute of Electric Power Industry, 2-6-1 Nagasaka, Yokosuka, Kanagawa 240-01, Japan*

[b] *Kansai Electric Power Co., Inc., 3-11-20 Nakoji, Amagasaki, Hyogo 661, Japan*

Abstract

Catalytic combustion is an advanced combustion technology and is effective as a NO_x control for a 1300°C class gas turbine for power generation, but the catalyst reliability at high temperatures is still insufficient. To overcome this difficulty, catalytic combustors combined with premixed combustion were designed. In this concept, it is possible to obtain combustion gas at a temperature of 1300°C while keeping the catalyst bed temperature below 1000°C. Catalyst segments are arranged alternately with premixing nozzles for the mixing of catalytic combustion gas and fresh premixture. An air bypass valve was fitted to this combustor for extending the range of stable combustion. As a result of the atmospheric combustion tests, NO_x emission was lower than 5 ppm, combustion efficiency was almost 100%, and high combustion efficiency was obtained in the range of 900–1300°C of the combustor exit gas temperature. A full-pressure combustion test is planned to prove the combustor performance.

Keywords: Combustion; Gas turbines; Nitrogen oxides

1. Introduction

Gas turbines have been used widely in recent years. However, nitrogen oxides (NO_x) are also generated in a high-temperature gas turbine combustor. In order to reduce NO_x emissions from thermal power plants using gas turbines, water/steam injection or selective catalytic reduction (SCR) is incorporated. These processes raise the cost of power generation. In the 1970's, development of catalytic combustors was initiated as an alternative NO_x control technology [1–3], but catalytic combustors have not been commercialized. With the aim of achieving the combustion performance indicated in Table 1, joint R&D on a low NO_x catalytic combustor for a gas turbine

Table 1
Target of designed catalytic combustor performance

Combustor exit gas temperature (Tg)	1300°C
NO_x emission	< 10 ppm
Combustion efficiency (η)	> 99.9%
Total pressure loss (ΔP)	< 5%
Pattern factor (P.F.)	< 15%

Table 2
Schedule of catalytic combustor development program

	'88	'89	'90	'91	'92	'93	'94
Feasibility study	×	×					
Preliminary test (LPG)		×	×	×			
Type A combustor test (NG)				×	×		
Type b combustor test (NG)							
Atmospheric pressure test					×	×	×
High-pressure test							×

* Corresponding author.

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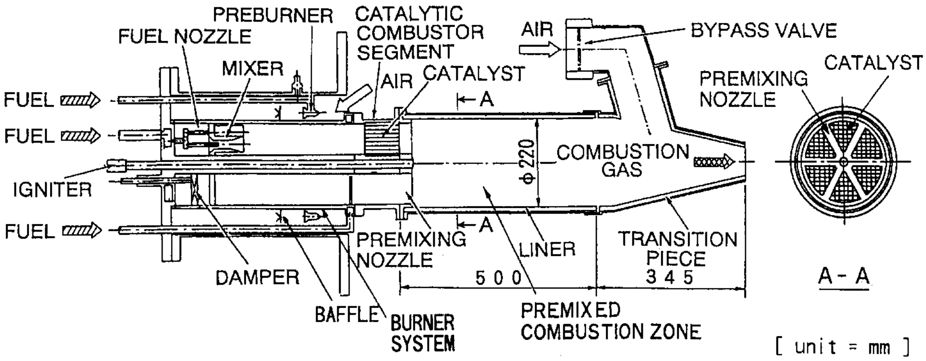

Fig. 1. Schematic of catalytic combustor.

was started by CRIEPI (Central Research Institute of Electric Power Industry) and KEPCO (Kansai Electric Power Co., Inc.) in 1988. Table 2 shows the joint work program.

2. Design of combustor

The following issues remain still to be proved for practical use of the catalytic combustor:

- Thermal degradation of catalyst
- Thermal shock fracture of ceramic monolith
- Necessity of uniform fuel/air mixture.

As the catalysts become larger and larger, their mechanical and thermal reliability is reduced. Therefore, if the assembly of small catalyst segments is able to be applied to the combustor, the structural reliability of catalyst will be maintained.

When the catalytic combustion method is independently applied to higher temperature gas turbines, the catalyst temperature rises over its thermal degradation limit. In this case, a uniform fuel/air mixture is required to avoid thermal degradation at the local hot spots in the catalyst. If lean premixed combustion, which emits relatively small amounts of NO_x, is combined with catalytic combustion, it is possible not only to prevent the deterioration of catalysts caused by heat but also to control NO_x. Moreover, by keeping the catalyst temperature low, a certain degree of lack of uniformity in the fuel/air mixture is permitted. Furthermore, since the combustion load is shared with the premixed combustion zone, it will be possible to reduce the load on the catalysts, the pressure losses and the volume of catalysts. Based on these concepts, an advanced catalytic combustor shown in Fig. 1 was designed.

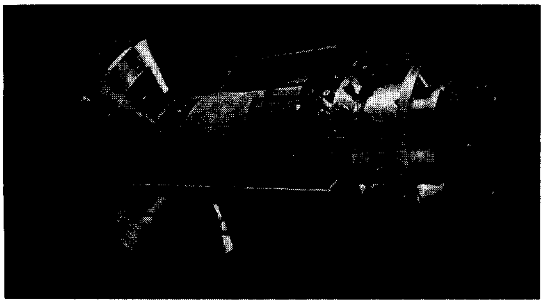

Fig. 2. Burner system of catalytic combustor.

Fig. 2 shows the arrangement of the burner system. The scale is equivalent to one combustor of 20 MW class multi-can type gas turbine. The combustor is composed of a burner system and a premixed combustion section. The burner system consists of an annular preburner, 6 catalytic combustor segments and 6 premixing nozzles. The premixed combustion section consists of a ceramic fiber type liner [4] and a transition piece installed with an air bypass valve. The catalyst segments and premixing nozzles are arranged alternately to form a circle. Air is heated to 400°C by the preburner and is distributed to the catalyst segments and premixing nozzles. Catalytic combustion is conducted below 1000°C. Premixed gas from the premixing nozzles is injected to the catalytic combustion gas, and lean premixed combustion at 1300°C is carried out. The air bypass valve is effective in low load operation of gas turbines [5].

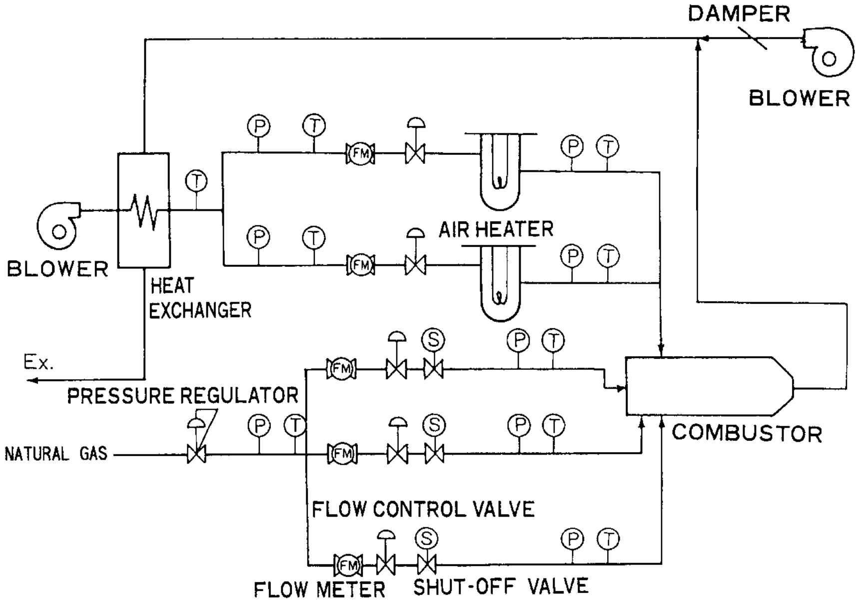

Fig. 3. Schematic diagram of test facility.

Table 3
Standard conditions

Pressure	Atmospheric pressure
Inlet air temp.	350°C (by electric heater and heat exchanger)
Premixed gas temp. of cat. bed inlet	400°C (by preburner)
Gas temp. of cat. bed outlet	< 1000°C
Combustor exit gas temp. (*Tg*)	1300°C
Combustion loading rate	$2.3 \cdot 10^7$ kcal/(m^3 h atm)
Total air flow rate	1017 m^3_N/h
Fuel	Natural gas (CH_4 = 99.2%, CO_2 = 0.7%, N_2 = 0.1%)

The catalyst is 25 mm in length and 3.3 mm in cell pitch, and is mounted in a single stage. The major active component of the catalyst is palladium, which is supported on stabilized alumina wash-coated on cordierite monolith.

3. Combustion test conditions

Fig. 3 shows the piping diagram for this combustor and the standard conditions used for the tests are shown in Table 3. Combustion air is preheated by a heat exchanger and electric heaters to 350°C, and supplied to the combustor. Fuel is fed to the combustor from 3 lines used for the preburner, the catalyst and the premixing nozzle, respectively. Natural gas is used as a fuel, of which the composition is 99.2% CH_4, 0.7% CO_2, and 0.1% N_2. The combustion test is carried out under atmospheric pressure. Fig. 4 also shows the location of major instrumentation and Table 4 shows the measurement methods. The outlet temperature

Table 4
Measurement instruments

Items	Measurement instruments
Temperature	Type-K or type-R thermo-couples (JIS)
Pressure	Solid state pressure sensor
Flow rate	Orifice flow meters
Emission	Gas Analyzer
NO_x, NO	Chemi-luminescence
CO	Non-dispersive infrared
CO_2	Non-dispersive infrared
O_2	Paramagnetic
UHC	Flame ionization

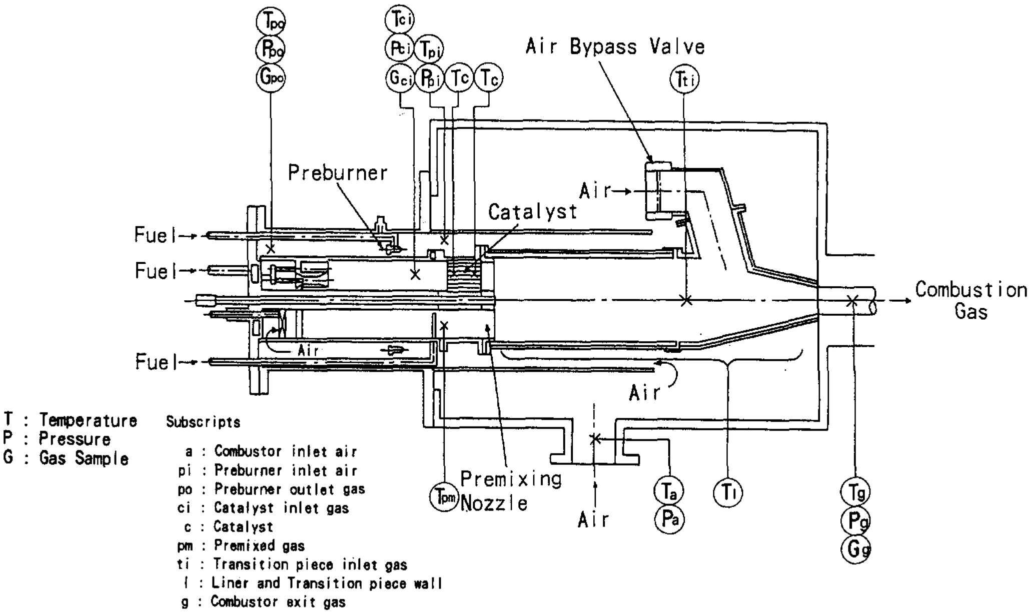

Fig. 4. Location of major instrumentation.

of the catalyst bed is measured with 24 sheathed thermocouples inserted in the cells near the exit end of the bed. The temperature at the transition piece inlet is measured at 5 points by sheathed thermocouples. The combustor exit gas temperature is measured with a traversing array of 5 thermocouple rakes installed at the transition piece exit. Gas samples are taken continuously through a water-cooled stainless steel probe with 5 suction holes installed at the transition piece exit.

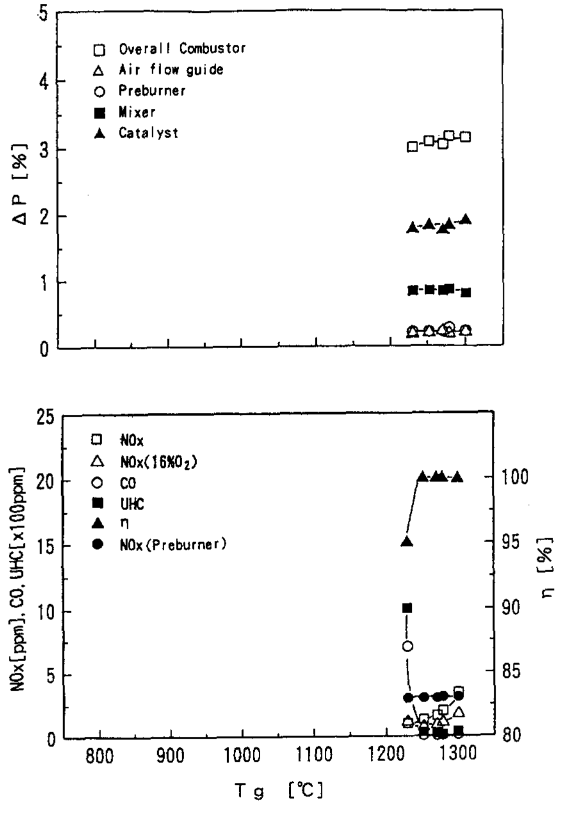

Fig. 5. Combustor performance (1) without bypass air.

4. Results and discussion

Fig. 5 shows the performance of the combustor without bypass air. Stable combustion was main-

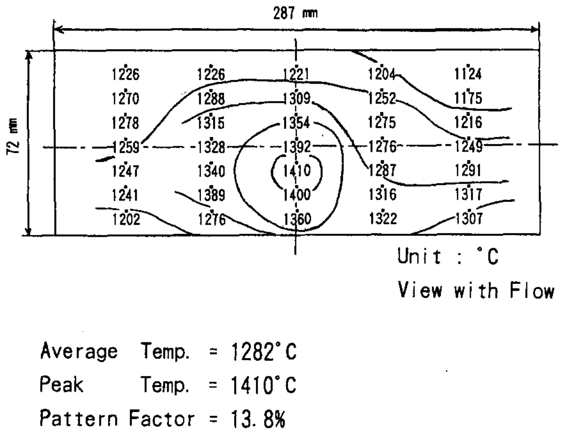

Fig. 6. Temperature distribution of combustor exit gas without bypass air.

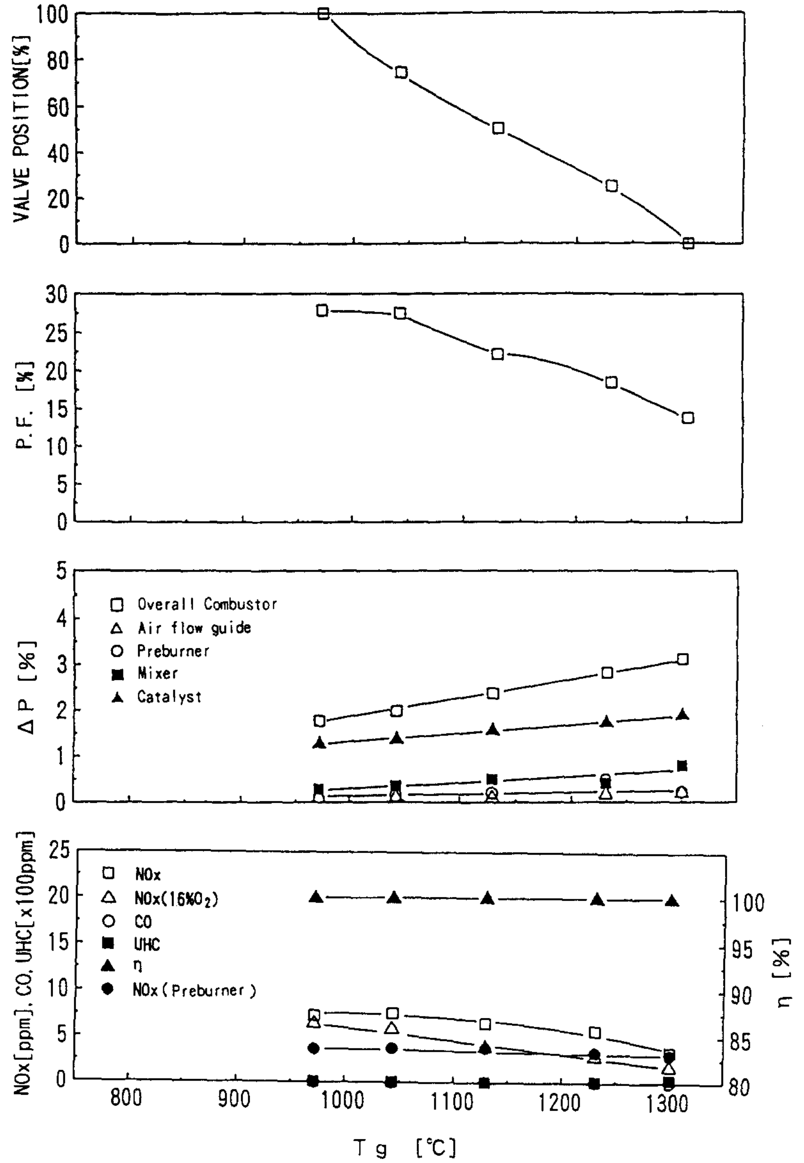

Fig. 7. Combustor performance (2) with controlled air bypass valve.

tained at combustor exit gas temperature (Tg) in excess of 1250°C. NO_x emission was below 4 ppm (2 ppm at 16% O_2), combustion efficiency (η) was almost 100% and total pressure loss (ΔP) was about 3% at 1300°C (2.16 of total excess air ratio, λt). ΔP was calculated by the following equation:

$\Delta P(\%)$ = pressure loss · 100/Pa

Pa (atm) = combustor inlet pressure and pressure loss is measured in atmosphere. ΔP was mainly caused by the catalyst bed.

Fig. 6 shows the temperature distribution at the combustor exit. Pattern factor (P.F.) was about 14% at the standard condition. P.F. was calculated by the following equation;

P.F. (%) = (Tg peak − Tg) · 100/(Tg − Ta)

Ta (°C) = mean temperature of combustor inlet air; Tg (°C) = mean temperature of combustor exit gas; Tg peak (°C) = peak temperature of combustor exit gas.

Fig. 7 shows the performance of combustor using the air bypass control valve. Tg was varied

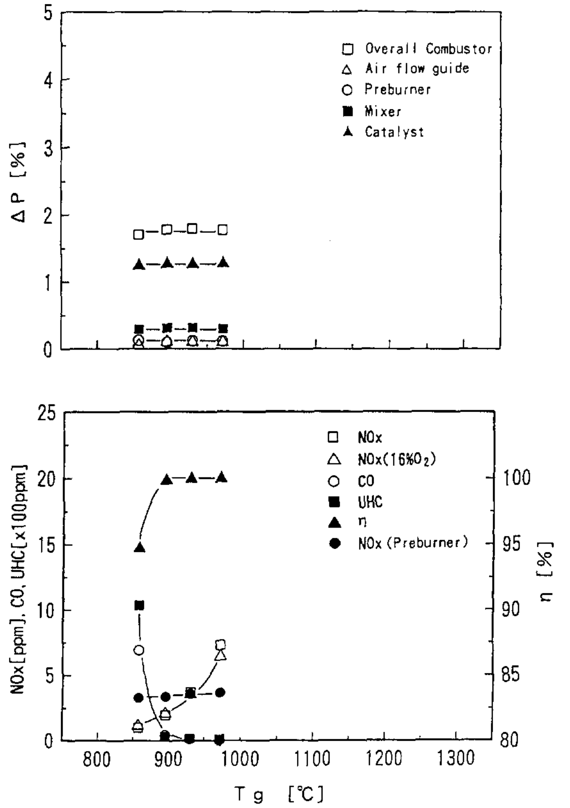

Fig. 8. Combustor performance (3) with full opened air bypass valve.

by controlling the air bypass valve and the fuel rate simultaneously to maintain the catalyst bed temperature and the inlet gas temperature of the transition piece constant. NO_x emission was below 8 ppm (7 ppm at 16% O_2), η was almost 100% and ΔP was below 3% at 970–1300°C ($\lambda t = 3.73$–2.16). NO_x emission from the preburner was about 3 ppm, which was main source of total NO_x emission. Because of the air flow from the air bypass valve, when valve position increased, P.F. was increased.

Fig. 8 shows the performance of combustor with the full opened air bypass valve. Stable combustion was maintained at 900–970°C ($\lambda t = 4.34$–3.73). NO_x emission was below 8 ppm (7 ppm at 16% O_2), η was over 99.9% and ΔP was below 2%. The premixed combustion became unstable below 900°C ($\lambda t > 4.34$).

These results under atmospheric pressure indicate that it was possible to achieve below 8 ppm of NO_x emission and over 99.9% of η at 900–1300°C by controlling the fuel and the bypass air flow. Also no abnormality of the catalyst was observed after about 50 hours combustion test.

Before this study, another combustor was studied, which had a burner system composed of a catalytic combustor arranged at the center and premixing nozzles arranged along its periphery [6]. The test result revealed the following problem:

- If there was not a ceramic baffle plate as a mixing device after the catalyst, the combustion was unstable and oscillatory.
- Owing to this baffle plate, ΔP grew larger.

By changing the design of burner system for the advanced catalytic combustor, these problems were solved. As the catalyst segments and premixing nozzles were arranged alternately to form a circle, mixing in the premixed combustion zone was promoted and stable combustion with low NO_x and low ΔP was achieved without a baffle.

In the case of this combustor system, control of combustion efficiency in the catalyst bed is important to reduce NO_x emissions. The catalyst temperature is limited up to 1000°C. The catalyst temperature depends on fuel concentration and the combustion efficiency in the catalyst bed. When the combustion efficiency of the catalyst is properly controlled and large amounts of fuel are fed to the catalyst, fuel for the premixing nozzles can be reduced to keep 1300°C of combustor exit gas temperature. Because thermal NO_x is formed in high-temperature zones after the premixing nozzles, total NO_x emissions of the combustor decrease with decreasing fuel concentration in the premixing nozzles. As a result, by controlling the combustion efficiency of the catalyst NO_x emissions can be reduced. This was the basis for the catalyst design. However, the catalyst system may need to be modified for operation at high pressure.

The air bypass valve has been very effective in extending the operating range of catalytic and premixed combined combustion. Though the temperature uniformity at combustor outlet was dropping with increasing bypass air flow, the design of the air bypass valve may need to be modified.

In future, the following studies will be needed:

- proving the combustor performance at high pressure,
- assessing the catalyst durability (long-term deactivation, cracking and flaking),
- defining control techniques for incorporating this type of combustor into a gas turbine engine control system.

5. Conclusion

A catalytic combustor, combined with premixed combustion was designed and tested under atmospheric pressure using natural gas. NO_x emission was under 4 ppm at 1300°C, which is within the target level, and it was possible to achieve stable combustion over 900°C by controlling with an air bypass valve. For example the combustor exit gas temperature of 930°C is approximately equivalent to the temperature at the half-load operation of a 20 MW gas turbine. It is considered that this combustor design system is effective for NO_x control in gas turbines for power generation.

As the next stage of this joint R&D, the high pressure tests of catalyst and combustor will be conducted.

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