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Experimental Evaluation of a Low NOx LBG Combustor Using Bypass Air

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ABSTRACT

A 150-MW, 1300°C (1573 K) class gas turbine combustor firing coal-gasified fuel has been designed. Main purpose of the present paper is first to estimate CO and NOx emissions, and second to discuss the low NOx combusion technology burning such a low-BTU gas. The full-scale, atmospheric-pressure combustion tests were conducted over a wide range of conditions using bypass air.

The results are summarized as follows:

(1) A designed combustor has an excellent combustion efficiency of 99.6 percent even when the calorific value of fuel drops to 650 kcal/m^{3}N.
(2) CO and NOx emissions can be estimated by the air ratio in primary combustion zone.
(3) The role of air bypass valve is important for low NOx combustion, and to give stable combustion at lower load conditions.
(4) Ammonia conversion to NOx is minimized with a optimum air ratio in primary combustion zone.

NOMENCLATURE

C.R.	= Ammonia conversion to NOx	
Gac/Gat	= (Air flow rate in a combustor) /(Total air flow rate)	
HHV	= Higher heating value of fuel	kcal/m^{3}N
LHV	= Lower heating value of fuel	kcal/m^{3}N
Δp	= Combustor pressure drop	%
ta	= Preheated air temperature	°C
tf	= Preheated fuel temperature	°C
tg	= Outlet gas temperature	°C
λ	= Air ratio [(f/a)stoich/(f/a)actual]	
λp	= Air ratio in primary combustion zone	
η	= Combustion efficiency	
θ	= Air bypass valve angle	degree

INTRODUCTION

In response to the energy situation and environmental issues of recent years, considerable attention has been focused on a system of combined cycle power generation which, as a technology for using fossil fuels, is more efficient than other power generation systems, yet also highly effective in protecting the environment. In cooperation with the Japanese Government and Japan's electric power companies, the Central Research Institute of Electric Power Industry (CRIEPI) is developing a system of coal-gasification, combined-cycle power generation using gasified coal as fuel. In this connection, CRIEPI is at present engaged in the research and development of a series of technologies, including gasifier, hot gas clean-up and gas turbines.

Among other things, coal-gasified fuel characteristically has a lower heating value than conventional fuels, such as LNG (Liquefied natural gas), and contains ammonia, which serves as a source of fuel-NOx formation. But, if we can achieve the goal of higher exit gas temperature and lower NOx for a gas turbine combustor, it will then be possible to increase dramatically the thermal efficiency and environmental adaptability of a combined cycle power generation plant.

Takano et al. (1987) [1] designed a 145-MW, 1150°C(1423 K) class combustor firing blast furnace gas, which contained no ammonia in the fuel. There are few research reports and many obscure points on the formation of fuel NOx.

With the principal aim of improving the combustion stability and the NOx emissions of coal gasified fuel within a wide load range, we designed and manufactured a gas turbine combustor using a bypass air that permits adjustment of the air ratio in a combustor to its most suitable level. Since the present report concerns the results of combustion tests conducted under atmospheric pressure of a gas turbine combustor of the 150-MW and 1300°C (1573 K) class, our comment will focus mainly on the proposed combustor's combustion and NOx emission characteristics. The design point conditions of the combustor for the proposed 150-MW power plant are shown in Table 1.

Table 1 Design point conditions

Turbine inlet gas temperature	1300 °C
Turbine inlet gas flow rate	20.82 kg/s
Compressor outlet pressure	14.4 ata
Compressor outlet temperature	370 °C
Coal gas fuel temperature	357 °C
Combustor air flow rate	13.68 kg/s
Coal gas fuel flow rate	7.14 kg/s
Fuel-air ratio	0.522 kg/kg
Air ratio	2.26
LHV of coal gas fuel	928 kcal/m^{3}N

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CHARACTERISTICS OF COAL-GASIFIED FUEL

An example of coal-gasified fuel composition is illustrated in Table 2. The main combustible component is CO. Even if H_2 and small amount of CH_4 is included, the remaining 70 percent or so will be inert components. As a result, the higher calorific value is only about 1000 kcal/m^3N. Furthermore, a small amount of NH_3, which serves as the source of NOx formation, is also included. Figure 1 compares the adiabatic flame temperature of coal-gasified fuel and that of LNG. At 1660°C(1933 K), the maximum flame temperature of coal-gasified fuel (LBG) is lower than that of LNG, which is 2100°C(2373 K).

Table 2 Standard properties of test fuel

Composition	CO	18.3 Vol %
	H_2	6.9 Vol %
	CH_4	2.5 Vol %
	CO_2	12.9 Vol %
	H_2O	3.0 Vol %
	N_2	56.3 Vol %
	NH_3	1000 ppm V
HHV		1000 kcal/m^3N (4187 kJ/m^3N)
LHV		944 kcal/m^3N (3953 kJ/m^3N)
tf		360 °C

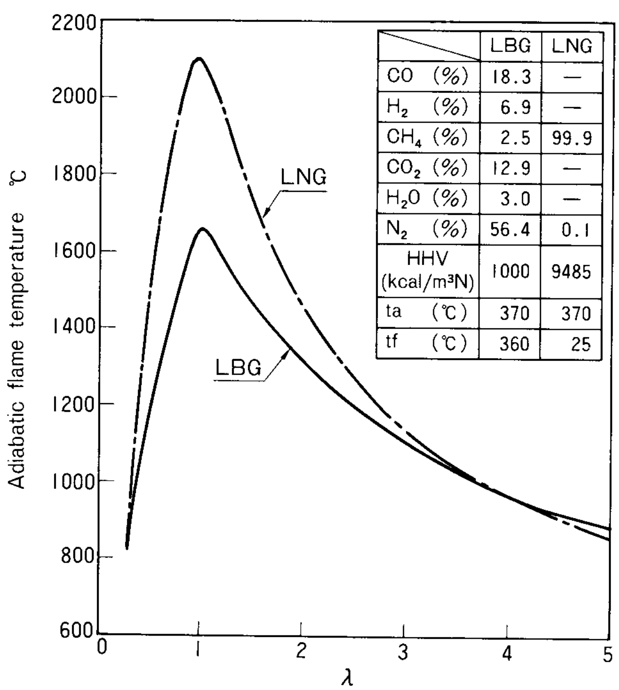

Fig. 1 Theoretical adiabatic flame temperature

PROBLEMS AND COUNTERMEASURES

We indicate below the problems involved in developing a gas turbine combustor for use in coal gasification system.

Stable combustion technology

Coal-gasified fuel does not burn as efficiently as LNG and other fuels. Hence, a suitable set of combustion conditions will be established by maintaining, within the wide load range of a gas turbine, a fixed level of air ratio in a combustor by adopting a bypass air valve.

High temperature technology

Since the calorific value of coal-gasified fuel is low, the amount of fuel flow for supplying a fixed level of heat flow will necessarily increase. Furthermore, since the air ratio of a combustor will be set at a low level along with the rise in the gas temperature at the turbine inlet, the absolute amount of air used for cooling the combustor wall will be reduced substantially. To cope with such a condition, a plate fin[2], with two layer composite structure capable of effectively cooling the liner wall with a small amount of cooling air, will be adopted.

Low NOx combustion technology

Since the flame temperature of coal-gasified fuel is low, only a small amount of thermal NOx is formed, but fuel NOx is formed from NH_3. In order to restrain the formation of fuel NOx, a rich-lean combustion method[3] will be adopted. This will make the primary combustion zone of a combustor excessively rich. An air bypass valve is also set for the purpose of adjusting the air ratio in a combustor within a wide load range and wide fuel properties.

EXPERIMENTAL EQUIPMENT AND METHOD

The distribution diagram of the testing facility is shown in Figure 2. The fuel gas is adjusted so that it will have the same composition as coal-gasified fuel. This is accomplished by making C_3H_8·CO_2· steam react in a reformer for improving quality, diluting the resultant CO, H_2 and the like with N_2, and adding NH_3. A centrifugal compressor will be used to supply the air.

The cross section of the atmospheric combustion testing rig is shown in Figure 3. Total air flow rate is 2900 m^3N/h and the outlet gas temperature is 1300°C at the design point. Combustion tests are conducted under atmospheric conditions. The outstanding feature of this equipment is that the amount of air that flows into a combustor can be adjusting by using a bypass air valve. Figure 4 indicates the flow and pressure drop characteristics measured when the bypass valve is open and when it is shut. Thus, for example, if the valve is opened at 90 degrees, 51 percent of the air flow will flow into the combustor while 49 percent is bypassed. The principal items measured include (a) the compostion of fuel gas (gas chromatography), (b) the temperature of the surface of the combustor wall (K-type thermocouples): (c) the gas temperature at the exit (R-type thermocouple); and the composition of combustion gas (O_2, CO, CO_2, NO, NO_2, THC).

An outline of designed combustors are shown in Figure 5. The diameter inside the combustor is about 300 mm, the length 810 mm. The combustor is equivalent to a 1300°C, 150 MW class combustor. The calorific capacity of combustion chamber under the rated load condition is 3×10^7 kcal/(m^3·h·atm). Two layer composite structure was adopt-

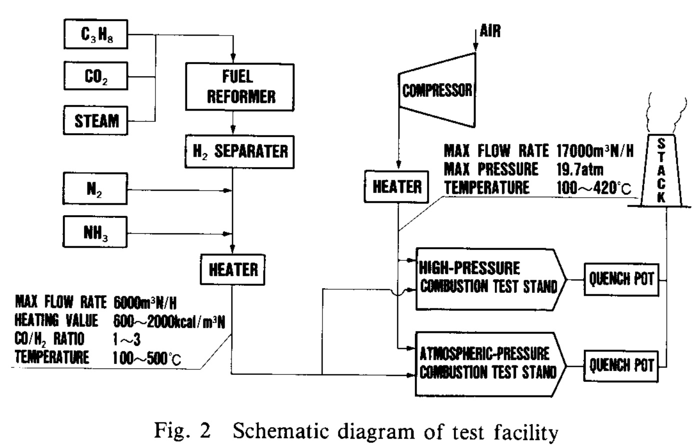

Fig. 2 Schematic diagram of test facility

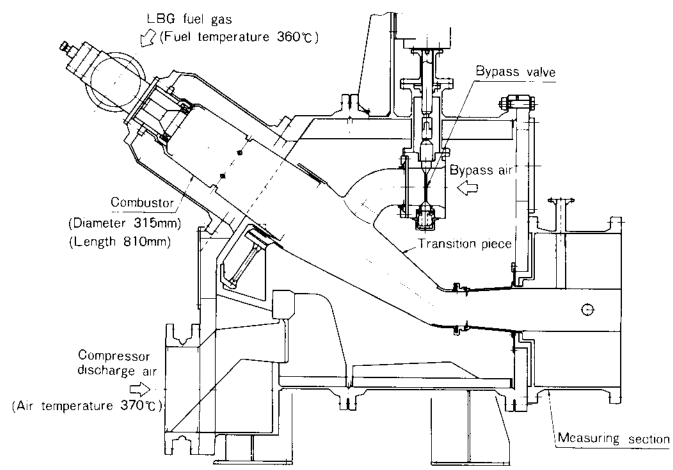

Fig. 3 Atmospheric pressure full-scale combustor testing section

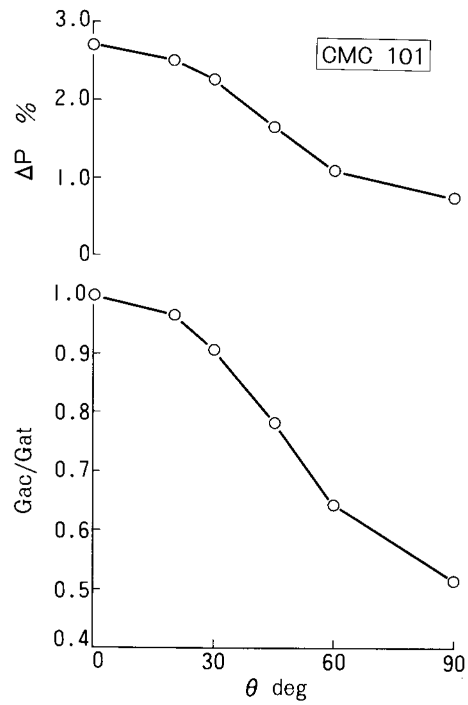

Fig. 4 Flow rate property of air bypass valve

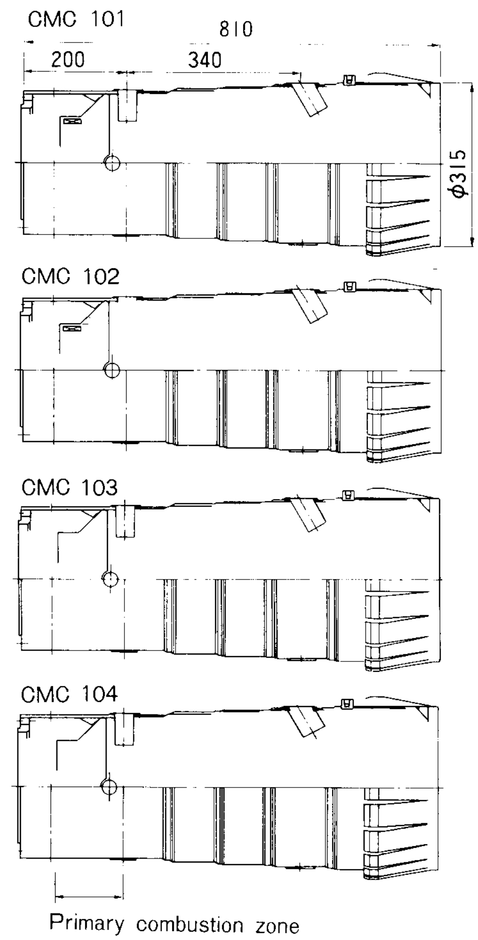

Fig. 5 Outline of each designed combustor

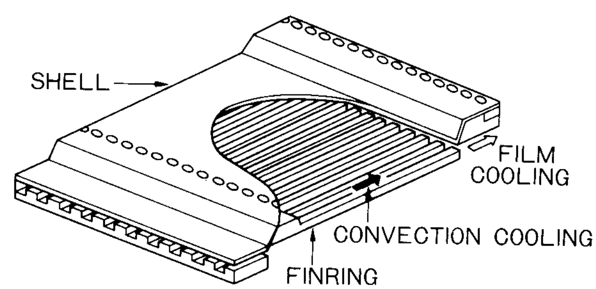

Fig. 6 Schematic of liner cooling scheme

ed as a wall cooling. The schematic of the cooling scheme is shown in Figure 6. An air flow distribution of the standard combustor is shown in Table. 3.

A combustor named CMC101 is a typical conventional combustor designed for coal-gasified fuel, with three primary-air scoops at the first liner and three secondary-air scoops at the fourth liner. In order to achieve stable combustion, the air ratio of the primary combustion zone was set at 0.9 without cooling air, that is, near the theoretical amount of air. In the case of combustor CMC102, to achieve a low NOx combustion, a primary air ratio was set at the fuel-rich 0.5 by removing the primary air scoops at the first liner. In the case of combustor CMC103 and that of combustor CMC104, to make the primary combustion zones even more fuel rich, the primary air ratios for the two combustors were set at 0.3 and 0.25, respectively, by closing the air swirler. Combustor CMC104 has six scoops at the fourth liner. An open area of the scoop is larger than that of CMC103. Primary air ratio is calculated from fuel gas flow and the air flow rate in primary combustion zone.

Table 3 Air flow distribution

Swirler air	17.6 %
Primary scoops air	18.0 %
Secondary scoops air	21.4 %
Liner cooling air	33.4 %
Transition piece cooling air	4.2 %
Transition piece sealing air	5.4 %

TEST RESULTS AND DISCUSSION

Combustion characteristics

Typical test results for combustors CMC101 ~ CMC104 are presented below. Inlet air temperature condition is 370°C and inlet fuel gas temperature is 360°C. The pressure drop of these combustors under full load condition are as follows; 4.1% (CMC101), 4.0%(CMC102), 4.3%(CMC103), 2.9%(CMC104). The residence time in the combustor is about 15 msec under full load condition.

The test results for combustor CMC103, which involved examining its combustion efficiency by lowering the calorific value of fuel gas, are illustrated in Figure 7. Primary zone equivalence ratio is 3 with the HHV of 1000 kcal/m^{3}N. Although the calorific value was lowered to 650 kcal/m^{3}N, it did not trigger a flame failure. Up to 800 kcal/m^{3}N, the combustion efficiency was 99.95 percent or higher, but began to decline thereafter. The results of the distribution of the surface temperature of the combustion wall are presented in Figure 8. When the calorific value was at 820 kcal/m^{3}N, the surface temperature inside the entire combustor was nearly uniform and stable combustion was maintained. On the other hand, when the calorific value was lowered to 740 kcal/m^{3}N, the wall temperature in the front half of the combustor was low and most of the combustion zones shifted to the rear of the combustor. Consequently, it can be argued that the combustion in the primary combustion zone was inadequate and this caused the combustion efficiency to decline. Possible causes include, in addition to deterioration of combustion capacity accompanying the decline in the calorific value of fuel gas, the increase in the amount of fuel flow and the reduction in the established air ratio.

Next, test results for combustors CMC101 ~ CMC104 regarding the influence air ratio has on CO emissions are illustrated in Figure 9. The conditions for air ratio 2 correspond to the rated load condition when the temperature at the exit of a combustor is set at 1300°C. Under these load conditions, the concentration of CO emission of combustors CMC103 and CMC104 is high when the fuel in a primary combustion zone is set at an excessively rich level. On the other hand, there is a noticeable CO emission of combustors CMC101 and CMC102, the basic combustor type, when the load level is low. The results shown in Figure 9, rear-ranged by using a primary air ratio, are presented in Figure 10. From the latter, we can see that the amount of CO emission is affected by a primary air ratio, and that the concentration of CO emission is extremely low where the primary air ratio ranged from 0.4 to 1.8, that is, in combustion zones characterized by a high flame temperature.

The results presented in Figure 11 are those obtained when the bypass valve is set in motion as a remedy for the lowering of combustion efficiency that occurs at lower load conditions. The high CO emission concentration of combustors CMC101 and CMC102 declined sharply to the concentration level of the other combustors in accordance with the opening of the bypass valve. It can be argued that this happened because the primary air ratio was set at an appropriate level by reducing the air flow into a combustor.

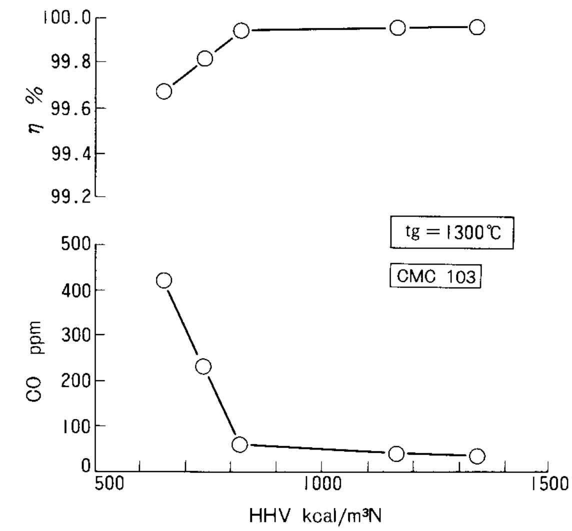

Fig. 7 Relation between the fuel heating value and combustion efficiency, CO emissions

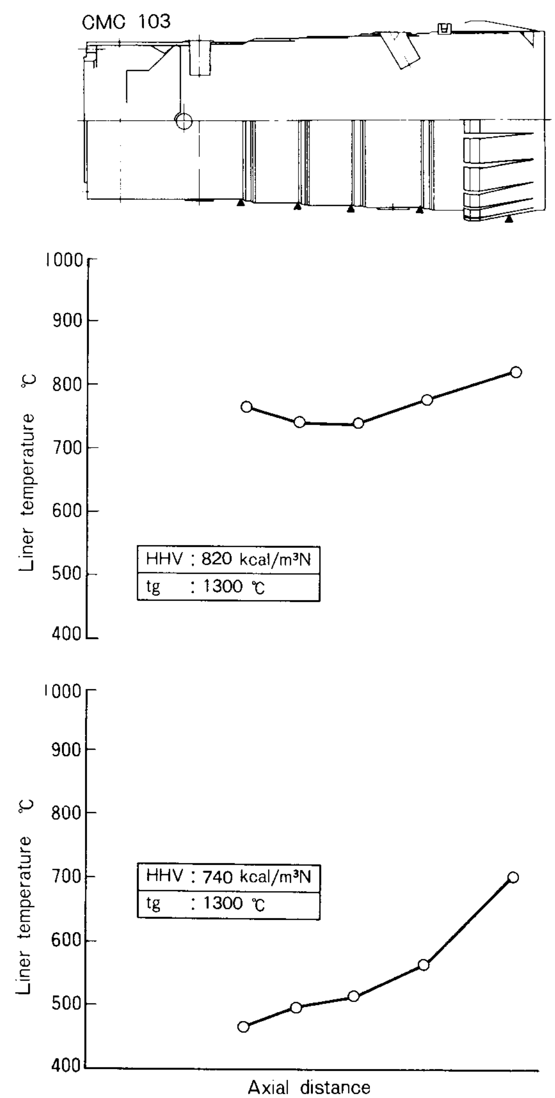

Fig. 8 Combustor wall temperature distribution

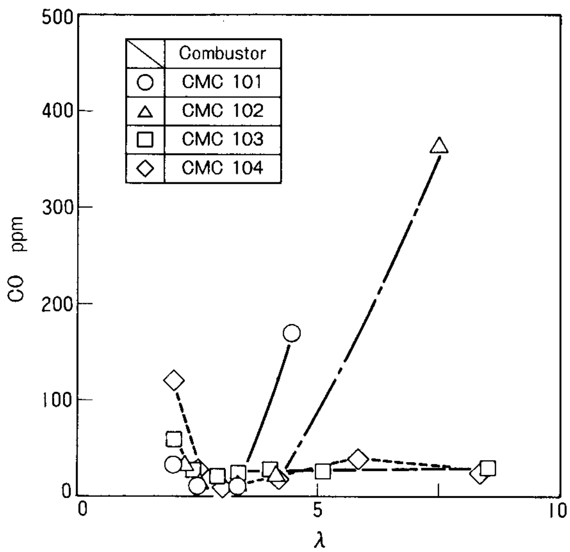

Fig. 9 Relation between air ratio and CO emission concentration

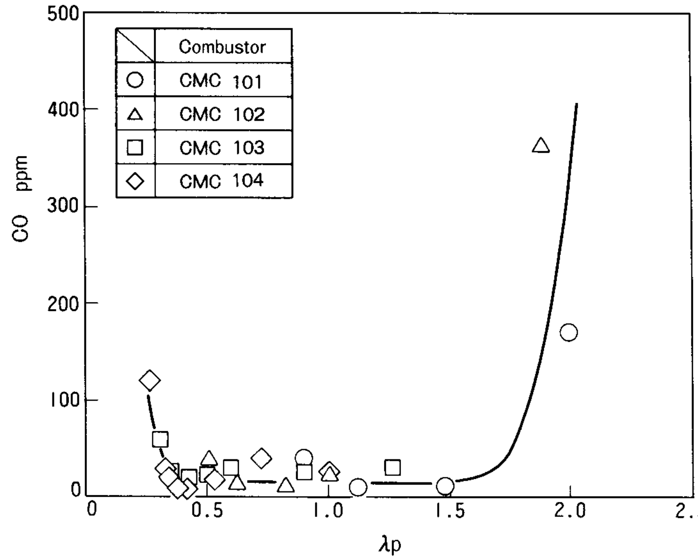

Fig. 10 Relation between primary air ratio and CO emission concentration

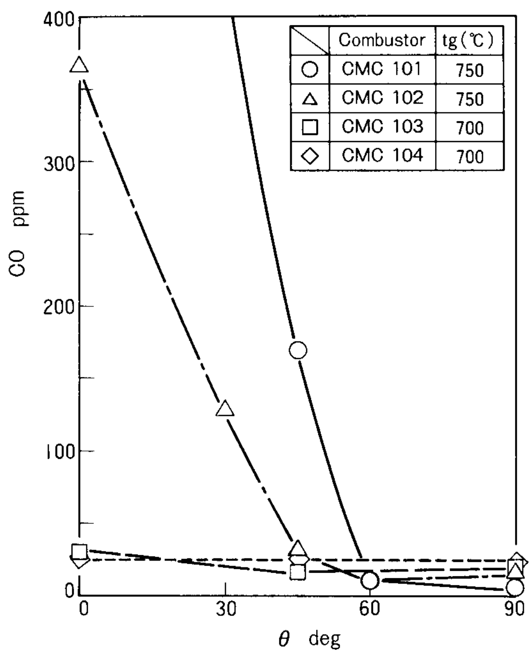

Fig. 11 Effect of bypass air on CO emission

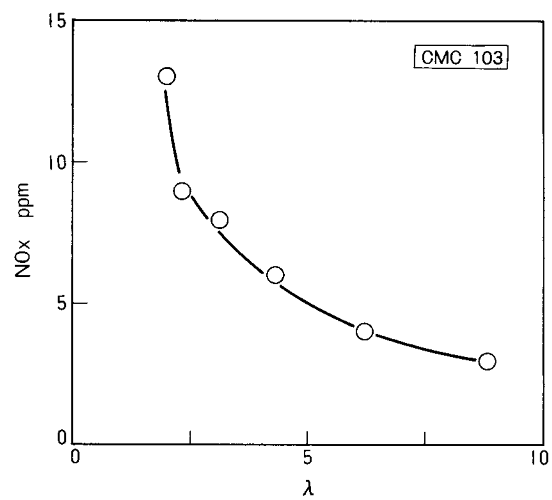

Fig. 12 Thermal NOx emission characteristics

Characteristics of NOx emission

As a preliminary investigation of the characteristics of fuel NOx emission, the results of thermal NOx emission are presented in Figure 12. The maximum concentration of thermal NOx under rated load condition was 13 ppm, or substantially lower than that of a higher calorific fuel.

Next, the concentration of NOx emission and the conversion rates from fuel-N to NOx are shown in Figure 13. These results were obtained by supplying the standard 1000 ppmv of NH_3 into the fuel as the fuel N contents.

From these results, we can see that a primary air ratio has a significant impact on the characteristics of NOx emission. This is manifested by the fact that the NOx level of a combustor is lower the richer the level at which its primary air ratio is set. Moreover, with combustors CMC101 to CMC103, the NOx conversion rate tends to indicate its minimum value when the rated point is $\lambda = 2$, and increases as the air ratio increases. On the other hand, combustor CMC104 has a different tendency: the NOx conversion rate begins to increase after it indicates its minimum value on the side where the fuel is slightly weaker ($\lambda = 2.5$) than the data obtained at the rated load point.

Figure 14 presents the characteristics of NOx emission when the NH_3 density in the fuel is changed under a set of rated load conditions. The NOx conversion rate decreased as the NH_3 density increased. Moreover, in the case of combustor CMC103, compared with combustor CMC101, the NOx conversion rate was reduced by about 30 percent within a wide range of NH_3 density. This clearly demonstrates the lowering effect that a rich-lean combustion method has on NOx emissions.

The effect of a primary air ratio on the conversion rate of NOx, which we examined by changing the bypass air valve under a set of rated load conditions, are illustrated in Figure 15. From this figure, we can see that the NOx conversion rate is smallest when the primary air ratio is in the vicinity of 0.4, and that, from this point on, it increases, whether on the side where the fuel is weak or where it is excessively rich. The fact that the most suitable primary air ratio for minimizing the NOx conversion rate exists in this way is consistent with the results of our basic experiment conducted using a diffusion burner[4]. This can be constructed as a result of the small amount of hydrocarbonic (CH_4) element found in the fuel having an effect on the NOx formation of the coal-gasified fuel mainly consisting of CO and H_2.

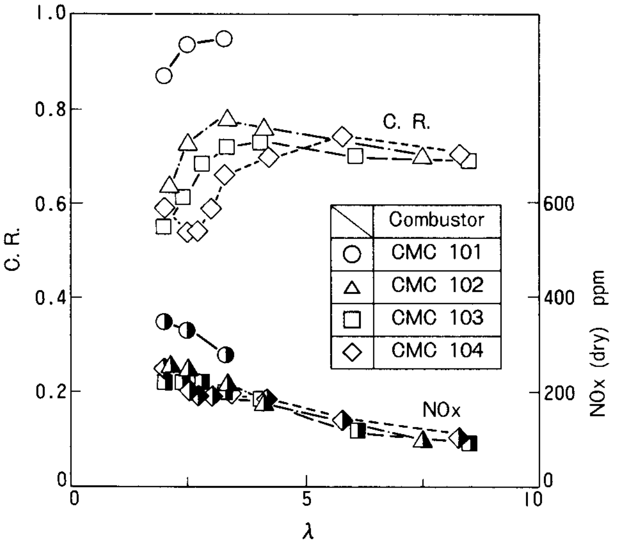

Fig. 13 Relation between air ratio and NOx conversion rate, NOx emission concentration

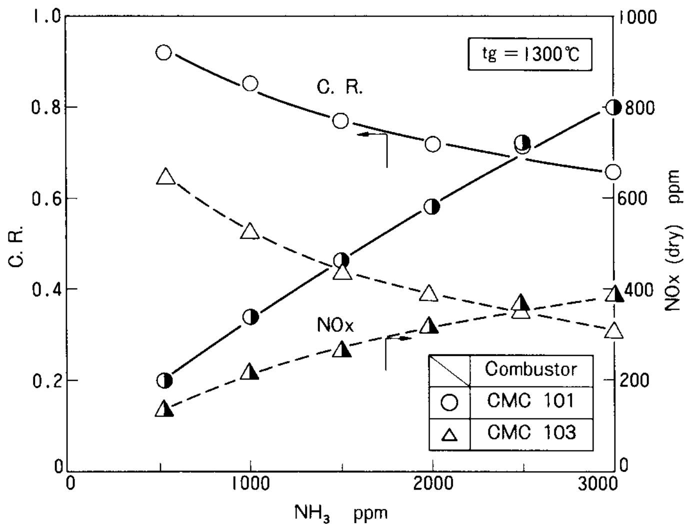

Fig. 14 Relation between NH_3 density in the fuel and NOx emission characteristics

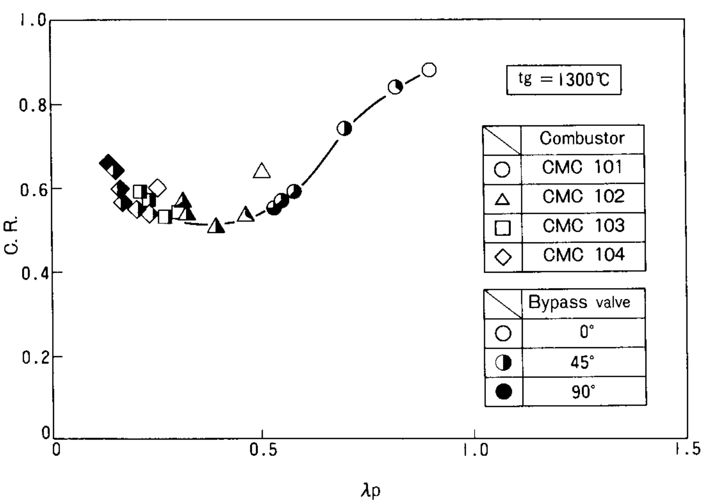

Fig. 15 Relation between primary air ratio and NOx conversion rate

CONCLUSIONS

A 150-MW, 1300°C(1573 K) class gas turbine combustor firing coal-gasified fuel has been designed, and combustion characteristics and NOx emission characteristics were investigated. The following results were obtained:

(1) A designed combustor has an excellent combustion efficiency of 99.6 percent even when the calorific value of a fuel drops to 650 kcal/m^3N.
(2) CO and NOx emissions can be estimated by the air ratio in primary combustion zone.
(3) The role of air bypass valve is important for low NOx combustion, and to give stable combustion at lower load conditions.
(4) Ammonia conversion to NOx is minimized with a optimum air ratio in primary combustion zone.

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