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DEVELOPMENT OF DRY LOW-NOX COMBUSTOR FOR 300 KW CLASS GAS TURBINE APPLIED TO CO-GENERATION SYSTEMS

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ABSTRACT

A 300 kWe class gas turbine which has a two-shaft and simple-cycle has been developed to apply to co-generation systems. The gas turbine engine is operated in the range of about 30% partial load to 100% load. The gas turbine combustor requires a wide range of stable operations and low NOx characteristics. A double staged lean premixed combustor, which has a primary combustion duct made of Si_3N_4 ceramics, was developed to meet NOx regulations of less than 80 ppm (corrected at 0% oxygen). The gas turbine with the combustor has demonstrated superior low-emission performance of around 40 ppm (corrected at 0% oxygen) of NOx, and more than 99.5% of combustion efficiency between 30% and 100% of engine load. Endurance testing has demonstrated stable high combustion performance over 3,000 hours in spite of a wide compressor inlet air temperature (CIT) range of 5 to 35 degree C.. While increasing the gas generator turbine speed, the flow rate of primary fuel was controlled to hold a constant equivalence ratio of around 0.5 in the CIT range of more than 15 C. The output power was also decreased while increasing the CIT, in order to keep a constant temperature at the turbine inlet. The NOx decreases in the CIT range of more than 15 C. On the other hand, the NOx increases in the CIT range of less than 15 C when the output power was kept a constant maximum power. As a result, NOx emission has a peak value of about 40 ppm at 15 C.

INTRODUCTION

Local environmental regulations in Japanese large cities are imposing severe NOx limits of less than 80 ppm (O_2=0%) on small or micro gas turbine systems. Co-generation systems using the gas turbine have been increasing because of the high total thermal efficiency. A low NOx combustion system with initial and low running costs is specifically required to increase the number of micro gas turbine systems.

Lean premixed (LP) combustion[1-5] is a promising technique for the reduction of pollutant emissions. It increases the application of gas turbines as an alternative to conventional diffusion flame combustion, which employs a water/steam injection for low NOx.

As simple control systems are required for micro gas turbine combustors, a pilot assisted LP combustor with multistage lean combustion nozzles may be one of the most suitable combustors. Although an ideal combustor of this type produces a homogeneous lean mixture, some developed lean premixed combustors do not have such low emissions because of imperfectly premixed or operating conditions affected by fuel control. Therefore, the fuel preparation and fuel control method is very important to realize low NOx combustion characteristics.

A pilot assisted, double staged, lean premixed (PDLP) combustor was developed to achieve low NOx and high combustion efficiency in the power range of 90 kWe to 300 kWe. The original concept of the combustor was presented by Mori et al[1] (1993). This combustor has the diffusion flame combustion zone at the center, the primary and secondary lean combustion zones in series. It is a unique characteristic of this combustor that a part of the primary lean premixed combustion duct is made of Si_3N_4 ceramics, and the combustion liner is cooled by turbulent promoted air convection effected by small ribs at the liner surface. They are introduced in order to withstand heat and assure long-life endurance.

In this paper, the concept of a pilot assisted, double staged, lean premixed combustor is described and the results of engine tests and a trial run of 3,000 hours are discussed.

NOMENCLATURE

CO	Carbon monoxide emissions	: ppm
kWe	kilo-Watt of electric power	: kW
NOx	Oxides of nitrogen emissions	: ppm
ppm	Parts per million by volume	
T_0, CIT	Compressor inlet air temperature	: degree C.
TIT	Turbine inlet gas temperature	: K
ηcc	Combustion efficiency	: %
ηe	Thermal efficiency	: %
fpil	Pilot nozzle equivalence ratio	
fpri	Primary nozzle equivalence ratio	
fsec	Secondary nozzle equivalence ratio	
ftot	Total equivalence ratio	

DESIGN OF DOUBLE STAGED LEAN PREMIXED COMBUSTOR

The design specifications of a low NOx combustor are listed in Table 1. Based on preliminary considerations, the mixture temperature needs to be higher than 1500 K to oxidize methane in less than 1 msec and lower than 1800 K to minimize NOx emission. To satisfy this temperature window, a pilot assisted, double staged, lean premixed (PDLP) combustor illustrated in Figure 1 was designed. The combustor employs a simple load operating system that controls only the fuel gas flow rate, thereby using no variable geometry for airflow control.

This PDLP combustor consists of a pilot nozzle at the center, a primary and secondary annular nozzle in series. It is expected that the diffusion flame stabilizes lean premixed flames generated by the primary or the secondary annular nozzles, as the pilot nozzle forms a diffusion flame. The amount of pilot fuel needs to be restricted to under 10% of the total fuel flow rate to decrease the formation of thermal NOx as much as possible without flame instability.

The pilot burner has a spark ignitor in the center to ensure stable ignition. The pilot fuel is injected to axial and radial directions. One is axially injected into the pilot burner region to form a flame kernel. The other is radially injected to spread a lean diffusion flame. These diffusion flames anchor the primary and secondary lean premixture flame.

The pilot burner has an axial vane swirler whose swirl number is 0.8. The primary and secondary nozzle has a radial vane swirler set at the inlet of each nozzle. Three swirlers form co-swirling flow with the same rotation. The swirl number is 1.2 for primary and 1.0 for secondary. The injectors of primary fuel or secondary fuel are spaced circumferentially at the inlet of each swirler vane. The fuel and air are mixed sufficiently while the mixture is introduced through the swirler into the combustion chamber. The swirling flow of the mixture creates an internal recirculation zone, which stabilizes the flame and combustion. A duct for primary premixed combustion is made of Si_3N_4 ceramics which endures at a temperature of 1700 K. This ceramic duct assures the durability at a primary equivalence ratio of over 0.7, but the equivalence ratio is designed to be less than 0.55.

The PDLP combustor, which is a reverse flow circular type can, is cooled by air convection promoted turbulence without the introduction of a cooling air. A high external cooling air velocity is required to keep the wall temperature low enough. The shoulder wall of the combustion liner has many holes to cool itself and dilute the secondary premixture with air. The flow splits of Table 2 are estimated from cold flow effective area measurements for each of the combustor passages.

The liner length is approximately equal to 1.5 times the liner diameter. The volume of the combustion zone is so large that a residence time of around 15 msec is designed to be enough to completely burn CO and hydrocarbons.

Figure 2 indicates the fuel schedule. While starting the engine, double solenoid valves for total fuel cut are opened and the pilot fuel is injected to form the diffusion flame. After the formation of the diffusion flame is confirmed by the criteria of rotation speed and exhaust temperature, the primary fuel is supplied to accelerate the engine.

The fuel injection schedule is divided into two ranges. In the low mode, the pilot and primary fuel is supplied in the range until a half of the maximum power. The pilot fuel flow passed through an orifice is kept almost constant and the primary fuel flow controlled by a metering valve is increased according to engine load. In the high mode of electric power from a half to full load, the secondary fuel is added to pilot and primary fuel and mainly controlled according to the load. When the equivalence ratio of lean premixture is kept lower than 0.6, it is expected to form little thermal NOx. The primary fuel flow rate is corrected by the CIT conditions in order to keep a constant primary equivalence ratio of around 0.5 in the CIT range of more than 15 C. However, the primary metering valve is kept constant in the CIT range of less than 15 C, because the output power holds the maximum power. In this CIT range of less than 15 C, the primary equivalence ratio increases until about 0.5 while the CIT increases. The maximum of secondary equivalence ratio is limited below the primary equivalence ratio of 0.5.

In this paper, town gas (CH_4 88.5vol%, C_2H_6 4.6 vol %, C_3H_8 5.4 vol % and C_4H_{10} 1.5 vol %) was used as a fuel.

300 KW CLASS GAS TURBINE ENGINE

A 300 kW class gas turbine with a two-shaft was newly developed by TOYOTA Turbine and Systems Inc.. Figure 3 shows a cross-section of the TG312 engine with a conventional combustor. The photograph of the engine is shown in Figure 4. The engine specifications are given in Table 3. This engine has been applied to various types of co-generation systems. In a co-generation package, an electric generator driven by this engine is combined with a heat recovery steam generator. In the other chiller package, a turbo refrigeration machine driven by this engine is combined with an exhaust heat absorption refrigeration machine. Thermal efficiency and total efficiency of electricity and steam generation in a co-generation system are shown in Figure 5. At full load operation, electric power of 290 kWe and steam of 850 kW are generated.

This engine usually employs a diffusion flame combustor whose NOx emissions are reduced by steam injection. The steam flow controlled by double staged orifices was supplied from the heat recovery steam generator to a fuel nozzle. The steam is injected into the primary combustion zone to effectively reduce thermal NOx. NOx emission in the power range from 100 kWe to 300 kWe is maintained lower than 100 ppm (O_2=0%), when the steam at full load is injected in a steam-fuel ratio of 0.8. There is no steam injection in the power range below 75 kWe because this system is required to achieve NOx levels of 150 ppm (O_2=0%). On the other hand, NOx emissions of this diffusion combustor with steam injection cannot be expected to be compatibly low at less than 80 ppm (O_2=0%) with high combustion efficiency in the wide range of operations.

TEST RESULTS

The injection fuel in an engine test is scheduled according to the electric power increasing, shown in Figure 6. The secondary fuel appears at a half of the full power and is controled according to the increase in the electric power. In the high mode, the primary fuel is controlled to keep constant equivalence ratio of around 0.5 because little thermal NOx forms under low combustion temperature. The exhaust gas was sampled at the turbine outlet duct and NOx, CO, HC and O_2 was measured.

Combustion Characteristics

A gas turbine engine test was conducted in an engine bench. The NOx and combustion efficiencies of the PDLP combustor are plotted in Figure 7, compared with those of diffusion combustor with steam injection.

In the high mode range of 150 kWe to 300 kWe, the low NOx of less than 40 ppm (O_2=0%) is achieved. An acoustic noise or vibration did not occur in the DPLP combustor which had the same rotation swirler. At the power of 150 kWe, NOx of more than 70 ppm (O_2=0%) is exhausted since the primary equivalence ratio reaches the maximum of about 0.7 because of the disappearance of secondary fuel. In the low mode range of below 150 kWe, the NOx emissions increase in almost linear proportion to the primary equivalence ratio or the output power. The high combustion efficiencies of more than 99.5% are kept widely in the power range of above 90 kWe.

The emission characteristics of the high mode in which fuel is supplied from three fuel lines are compared with those of the low mode in which fuel is supplied from two fuel lines, shown in Figure 8. The relationship of NOx and CO in the high mode does not indicate a trade-off relationship like that in the low mode. In the high mode, the thermal NOx is formed in the pilot and primary combustion zone and CO is mainly formed in the secondary combustion zone because secondary equivalence ratio is changed from 0.15 to 0.45.

Wall temperatures of the combustion liner increase in proportion to the electric power. Although there is a maximum temperature of 1000 K on the middle surface of the liner wall at full power, surface temperatures of the liner wall are kept almost uniform without hot spots. Wall temperature of the liner shoulder is 50 K lower than that of the middle of the liner.

3,000 Hours test run

A long-run engine test at rated speed was conducted using a co-generation package. The exhaust emissions of NOx, CO, HC and O_2 were measured continually by a gas-sampling device. The measured data at 10 minute intervals was averaged per day.

In the first stage, the gas turbine system was started in the morning and stopped in the evening (Daily Start and Stop: DSS). This DSS test run was operated up to 500 hours for 60 days. In the next stage, the gas turbine system was started on a Monday morning and stopped on a Friday evening (Weekly Start and Stop: WSS). The WSS test run was operated for 25 weeks. The total time of the trial test run was more than 3,000 hours. The primary ceramics duct has no damage except for a change of color of the inner surface. The temperature of the liner wall indicated around 850K for the test run, although it was exactly influenced by CIT conditions.

In Figure 9, the records on NOx, electric power and CIT are shown according to run times. The CO data is shown in Figure 10. The data changes unevenly, but nevertheless still appears to indicate a certain trend. While the CIT increases, NOx and electric power decreases by degrees. When the CIT decreases, NOx and electric power increases. At the time of 2,250 hours, the engine was changed to inspect the gas generator parts, but the running PDLP combustor was not changed. On the other hand, CO trend has been opposed to the trend of NOx on the whole, but there are some differences in detail.

The gas temperature at the inlet of the gas generator turbine (TIT) increases in the same rated operation without control when the CIT rises. Therefore, it is necessary for the output power to be controlled in order to keep constant TIT. In the range of incoming air temperature above 15 C, the output powers were linearly decreased by 2.8 kWe per 1 K while increasing incoming air temperature, shown in Figure 11. Thermal efficiency and total efficiency decrease by 1.4% and 1.7% respectively per 10 K in proportion to the CIT.

In Figure 12, the data of NOx in relation to the CIT decreases by 0.7 ppm per 1 K in the CIT range of more than 15 C, when the output power is decreased to keep a constant TIT. This is the reason why the operated equivalence ratio of primary and secondary becomes barely leaner as the CIT rises, in spite of the constant TIT. In the CIT range of below 15 C, the output power is controlled to keep a constant maximum power. NOx increases by 1.5 ppm per 1 K, because the equivalence ratio of each of the three fuel-lines increases as thermal efficiency and air density decreases. As a result, NOx emission has a peak value of about 40 ppm at 15 C.

On the other hand, the data on CO in Figure 13 indicates the inverse tendency of NOx shown in Figure 12. It looks like the dispersed data represent the CO formation depending on the other parameter together with the strong relations to CIT. The CO emission has a low value of about 5 ppm at 15 C, as the reverse trend of NOx data.

Now, it is described above that NOx and CO is formed in a different lean combustion field. The NOx mainly depends on primary combustion, shown in Figure 14. The NOx in relation to primary combustion has approximately a linear increase of 0.16 ppm per 1 K. The NOx compared with the regulations is sufficiently low in the range of primary combustion temperature of less than 1800 K.

The relationship between NOx and CO shows an inverse tendency on the whole, but the dependence between NOx and primary combustion temperature is smaller than that of CO.

The relationship between NOx and CO emissions is a unique characteristic, plotted in Figure 15. The CO data against NOx are not dispersed and almostly formed into two groups. One is a group in CIT less than 15 C, and the other is a group in CIT above 15 C. The data compared between one and the other results in that the difference mainly depends on the power or fuel control affected by CIT.

SUMMARY

Since 1998, TOYOTA Turbine and Systems Inc., TOYOTA Central R&D Labs., Inc. and TOKYO Gas Co., Ltd. have collaborated in a development of a dry low-NOx combustor for a two-shaft gas turbine. This engine has been applied to various types of co-generation systems. The combustor using town gas as fuel was designed by employing a pilot assisted, double staged, lean premixed (PDLP) combustion concept. A trial test of the PDLP combustor was completed over 3,000 hours.

The test results are summarized as follows.

(1) The PDLP combustor has been successfully adopted to achieve a low NOx level of 40 ppm (O_2=0%) in a simple cycle gas turbine with two shafts.

(2) In the range of 150 kWe to 300 kWe, the NOx levels lower than 40 ppm (O_2=0%) are achieved because the primary equivalence ratio is set around 0.5 and the secondary equivalence ratio is controlled by a maximum of 0.5.

(3) In the range of compressor inlet air temperature (CIT) more than 15 C, NOx emissions decrease by 0.7 ppm per each 1 K of CIT, when the output power is restricted by CIT in order to keep the constant turbine inlet temperature. In the CIT range of less than 15 C, NOx emissions increase by 1.5 ppm per each 1 K, while the output power is kept at a constant maximum power. NOx emission has a peak value of about 40 ppm (O_2=0%) at 15 C.

(4) CO emissions increase exponentially in the CIT range of less than 15 C and CO emissions decrease exponentially in the range of CIT at above 15 C , although the data was dispersed. The CO emission has a low value of about 5 ppm (O_2=0%) at 15 C.

(5) NOx emissions are sufficiently low in the range of primary combustion temperature less than 1800 K. Those increase almost linearly by 16 ppm per primary combustion temperature of 100 K. CO emissions decrease exponentially and have a relatively weak dependence of primary combustion temperature between 1700 K to 1800 K.

(6) The PDLP combustor has been developed to be adopted a ceramic primary duct and a combustion liner with small ribs to be cooled by turbulent promoted air convection. This combustor proved no trouble in a trial run for over 3,000 hours.

REFERENCES

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[4] Vandervort, C.,L., 2000, “9 ppm NOx/CO Combustion System for “F” class Industrial Gas Turbine”, ASME paper 2000-GT-86.

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Table 1 Combustor Design Specification and Target

Combustor Inlet Air	1.98 kg/s
Combustor Inlet Air Pressure	0.6 MPa (abs)
Combustor Inlet Air Temperature	550 K
Full Load Equivalence Ratio	0.28
Fuel LHV	Town Gas : 41.6 MJ/m^{3}N
NOx Target 100 – 50 % Load 50 - 0 % Load	 < 60 ppm (@ O_2=0%) <120ppm (@ O_2=0%)
Combustion Efficiency Target 100 – 50 % Load 50 – 30 % Load	 <99.5 % < 99 %

Table 2 Open Area Ratios of Combustor Nozzles

Pilot Nozzle	12.8 %
Primary Nozzle	24.5 %
Secondary Nozzle	24.2 %
Cooling Air	4.7 %
Dilution Air	33.8 %

Table 3 TG312 Engine Specification

Cycle	Simple
Shaft	Two
Gas Generator Speed	49,000 rpm
Power Turbine Speed	35,000 rpm
Compressor	Centrifugal, Single
Compressor Turbine	Axial, Single
Power Turbine	Axial, Single
Output Power	315 kW
Pressure Ratio	6.0 : 1
Weight	1,100 kg
Exhaust Gas Temperature	863 K

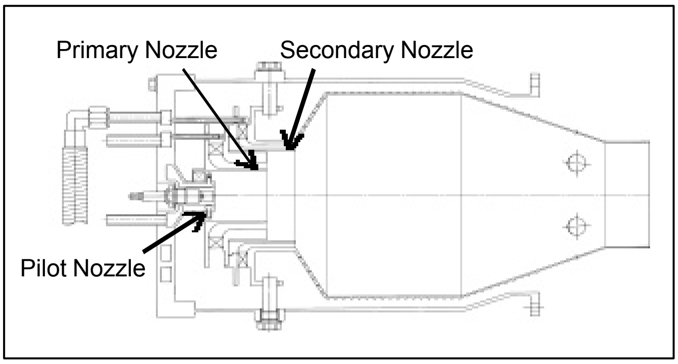

Figure 1 Schematic of pilot assisted, double staged Lean Premixed combustor

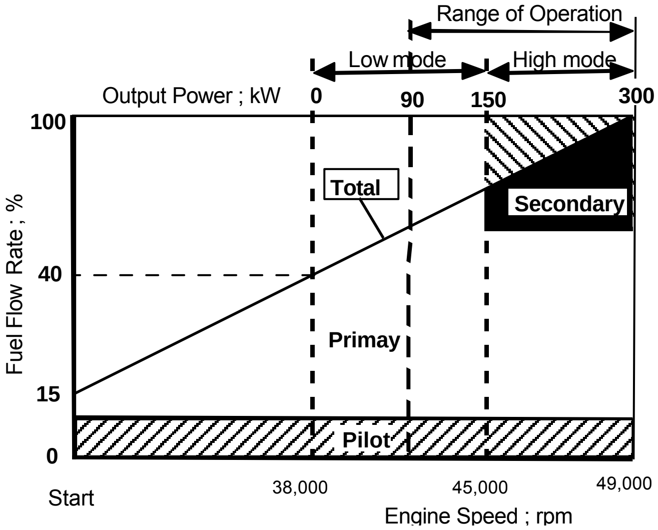

Figure 2 Schematic of fuel supply schedule

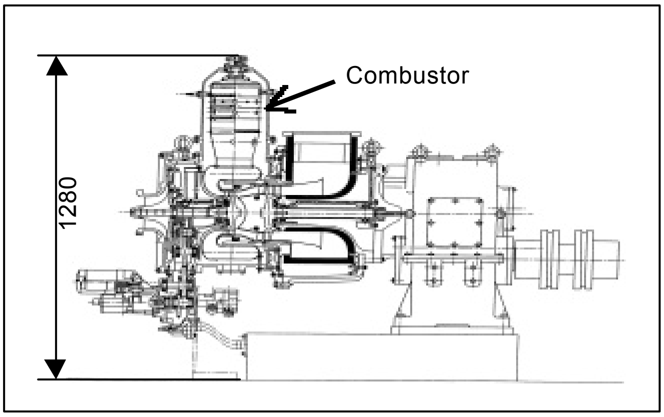

Figure 3 Schematic of TG312 gas turbine engine

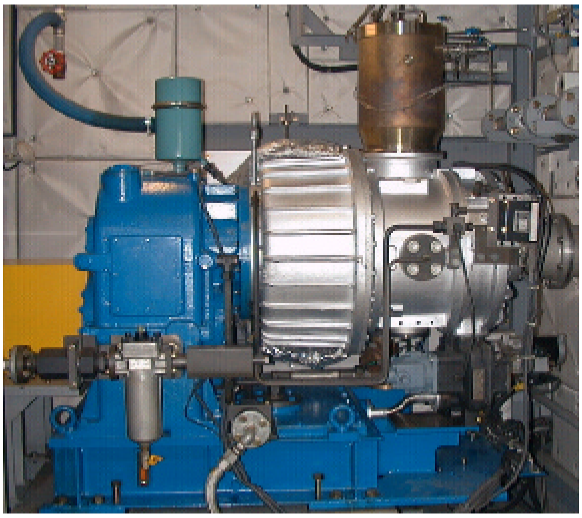

Figure 4 Photograph of TG312 gas turbine engine

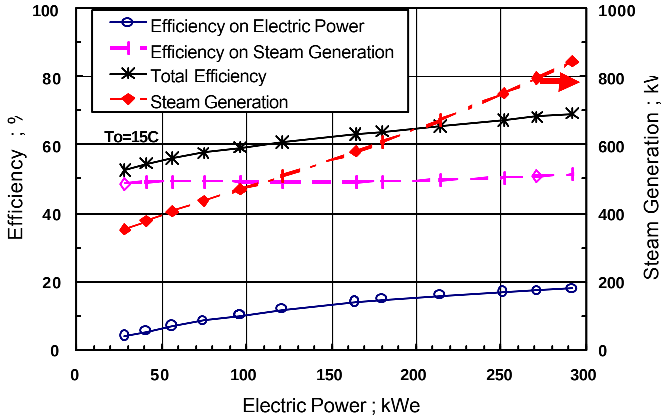

Figure 5 Outline characteristics of TG312 cogeneration system

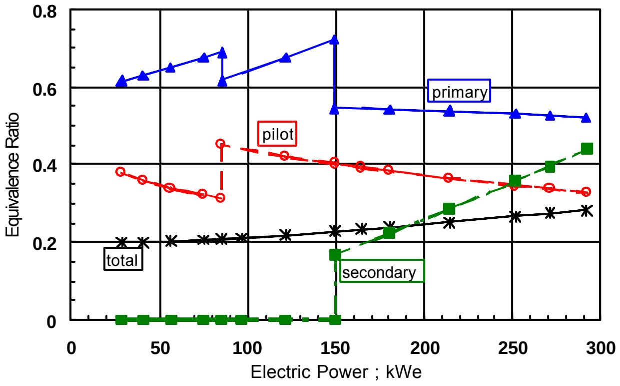

Figure 6 Schematic of fuel control schedule in TG312 gas turbine engine

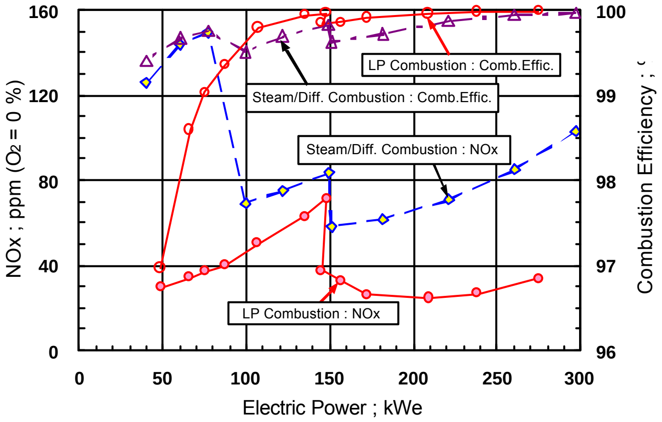

Figure 7 Characteristics of engine exhaust emission compared between LP combustor and diffusion combustor with steam injection

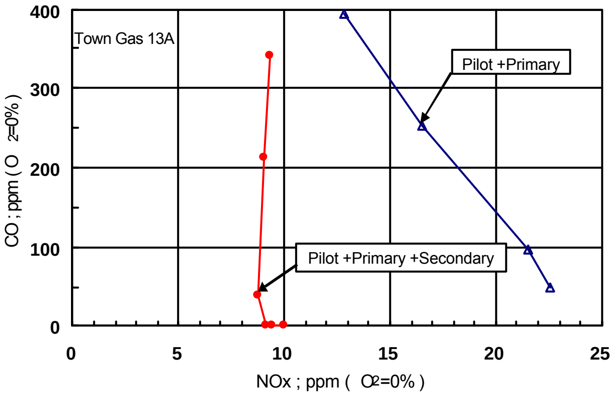

Figure 8 Combustion characteristics of three fuel supply compared with those of two fuel supply

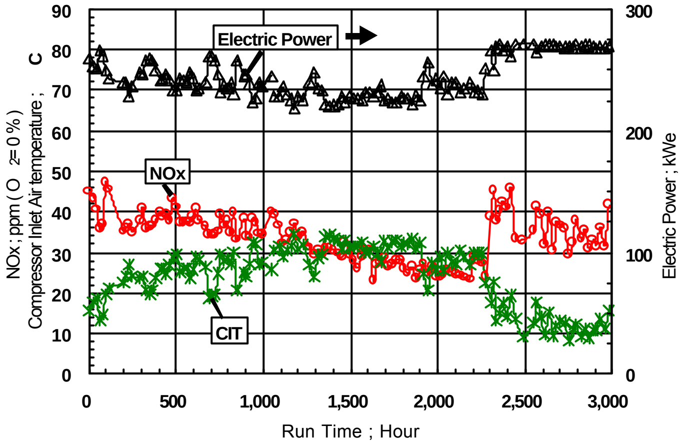

Figure 9 Record of NOx, CIT and Power in long-run test

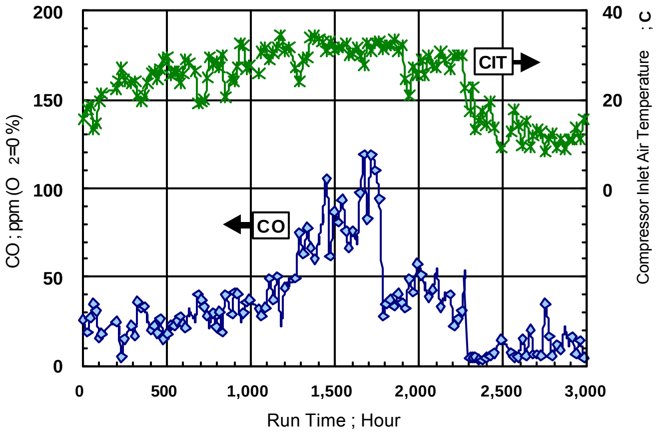

Figure 10 Record of CO and CIT in long-run test

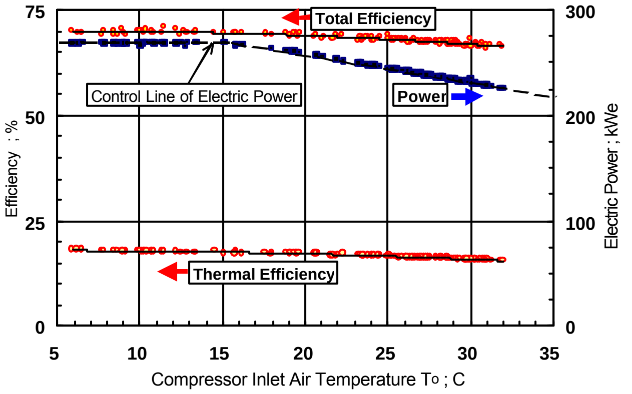

Figure 11 Characteristics of thermal efficiency and electric power controlled by CIT

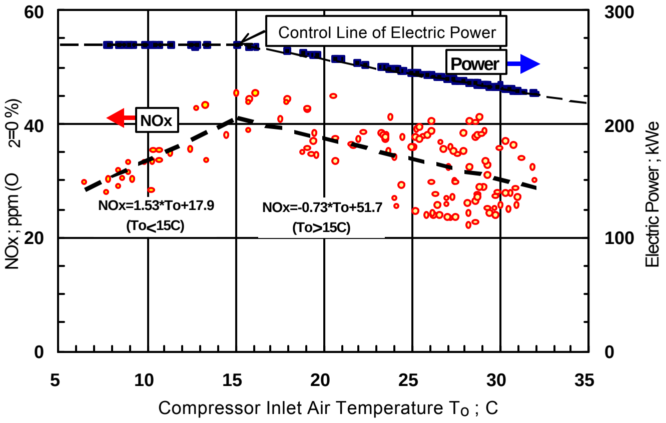

Figure 12 NOx emission characteristics of trial test run

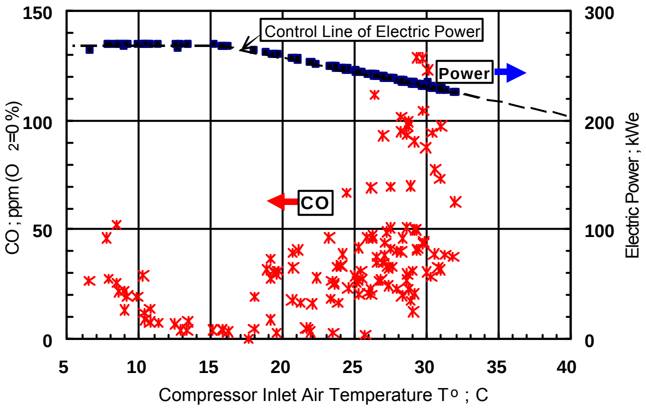

Figure 13 CO emission characteristics of trial test run

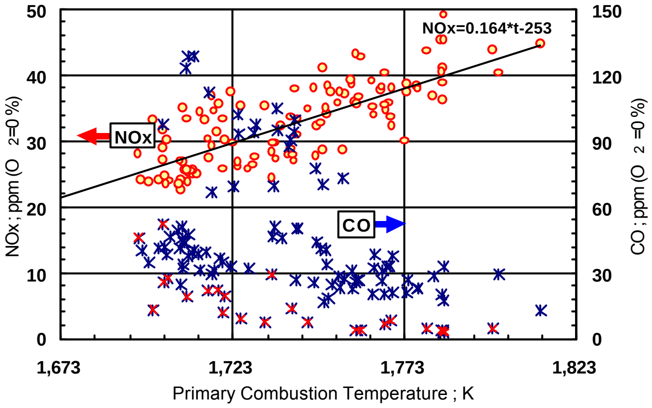

Figure 14 NOx and CO emissions versus primary combustion temperature

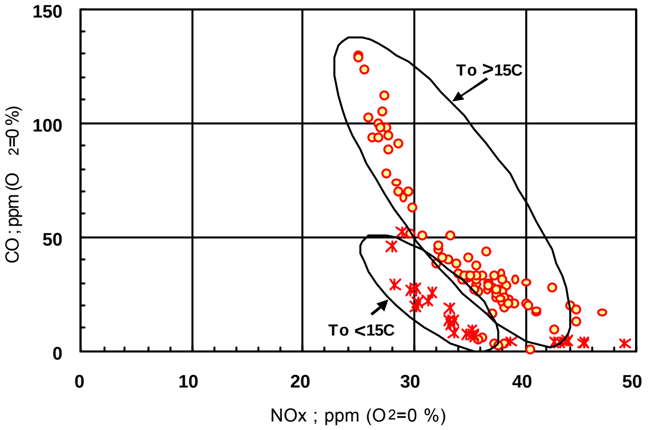

Figure 15 Relationships between NOx and CO emissions in CIT of less than 15 C and above15 C