Research Report

Low-NOx Combustion Technology

Yoichiro Ohkubo

Abstract

Simple-cycle and recuperated-cycle micro gas turbines (MGT) were developed for use in cogeneration systems. A simple-cycle MGT is better suited to applications that require steady heat energy (steam) more than electric power. A recuperated-cycle MGT, however, can be used for those applications that need both electricity and heat energy.

Firstly, lean premixed combustion with a multistage fuel supply was investigated for a 300-kWe class simple-cycle MGT. An NOx emission level of less than 15 ppm (O_2 = 16 %) with town gas as the fuel was demonstrated when the equivalence ratio of the primary lean pre-mixture was held at a constant value of less than 0.6 and the pilot fuel constituted about 10 % of the total fuel flow rate. Secondly, to investigate low-NOx combustion for a 50-kWe class recuperated-cycle MGT, we examined lean premixed combustion that produces a NOx level of less than 10 ppm (O_2 = 16 %) with town gas and also lean premixed, pre-vaporized combustion with kerosene that produces a NOx level of less than 20 ppm (O_2 = 16 %).

Keywords

Low-NOx, Lean premixed combustion, Lean premixed pre-vaporized combustion, Combustor, Gaseous fuel, Liquid fuel, Micro gas turbine, Recuperated-cycle GT, Cogeneration system

1. Introduction

The continuous combustion of a gas turbine combustor simultaneously offers both low NOx and low CO/HC emissions, and the combustion technology does not require an exhaust after-treatment device. This, in fact, is one of the main advantages of continuous combustion over a reciprocating engine. Furthermore, clean combustion can be realized with many different types of fuel.

One type of conventional continuous combustion is diffusion combustion, in which the fuel is injected directly into the combustion chamber where it mixes with air. Because the flame stability is very good, diffusion combustion has been adopted for use in an automotive gas turbine that can operate over a wide range of equivalence ratios. The exhaust emission characteristics of diffusion combustion are influenced by both the operating conditions and the fuel properties. For example, the 300-kWe class simple-cycle micro gas turbine (MGT) commercialized by TOYOTA Turbine and Systems (TT&S) has a maximum NOx emission level of around 100 ppm. Unfortunately, reducing the NOx emissions leads to large amounts of unburnt components (such as CO and HC) being exhausted, as shown in **Fig. 1**. In general, it is difficult to reduce NOx emissions while maintaining a high combustion efficiency, because there is a tradeoff between the amount of unburned hydrocarbons (CO, HC) and the NOx emissions.

When a gas turbine is incorporated into a cogeneration system, the NOx emissions must be less than 70 ppm (O_2 = 16 %), as required by Japan's Air Pollution Control Act. Furthermore, a lower and more demanding NOx emission figure is applied in large cities, as shown in **Fig. 2**. For example, Aichi imposes a limit on NOx emissions of 35 ppm (O_2 = 16 %) with gaseous fuel, and 50 ppm (O_2 = 16 %) with liquid fuel.

There are several technologies, such as water or steam injection, that can be applied to satisfy these severe NOx regulations. These particular technologies are collectively known as "wet diffusion combustion" and work by lowering the combustion temperature and thus limiting the formation of thermal NOx. **Figure 3** shows one example of the design used to inject steam into the combustion chamber. A nozzle through which steam is injected is provided in the vicinity of the fuel injector. The NOx emission levels are controlled by varying the amount of steam, and are

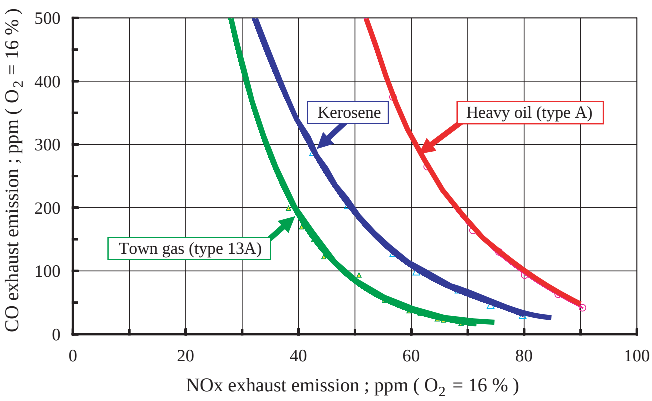


Fig. 1 NOx and CO emissions exhausted from a diffusion combustor.

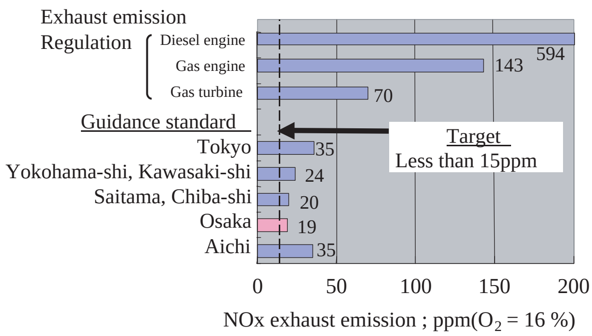


Fig. 2 NOx emission regulations in Japan.

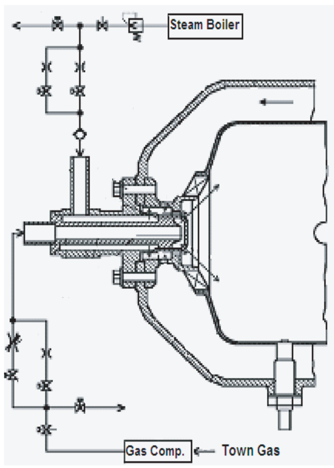


Fig. 3 Schematic of a diffusion combustor with steam injection.

less than 40 ppm (O_2 = 16 %) for a fuel to steam weight ratio of around 1. **Figure 4** compares NOx emissions both with and without steam injection when kerosene is being used as the fuel. The NOx emissions fall as the flow rate of the steam is increased, but there is a limit on the extent to which the NOx emissions can be reduced because there is a corresponding increase in the amount of CO emissions.

Further reductions in the NOx levels to less than 20 ppm (O_2 = 16 %) are required in giant cities such as Tokyo and Osaka. This level cannot be achieved by wet diffusion combustion. Lean premixed combustion, however, offers a means of achieving both low NOx and low CO emissions.

On the other hand, demand to be able to use town gas as a fuel is increasing because it produces lower levels of CO_2 emissions. Unlike liquid fuel, gaseous fuel allows us to achieve low NOx levels when it is applied to lean premixed combustion.

This paper describes the concept of the dry low-NOx combustors and the test results for a 300-kWe class simple-cycle and a 50-kWe class recuperated-cycle MGT.

2. Concept of lean premixed combustion

Conventional combustion, namely, diffusion combustion or spray combustion, has a particular advantage in that the ideal air-fuel mixture will always be formed at some point within the diffusion flame even if the fuel flow rate changes, such that the fuel-air mixture burns at the optimum ratio of around 1. It is observed that a bell shaped flame is formed in the center of the combustion chamber, as shown in **Fig. 5 (a)**. The bell-shaped flame becomes slender as the fuel flow rate falls, and widens as the fuel flow rate increases. As a result, the diffusion flame burns stably over a wide range of equivalence ratios.

The main technology that sustains the low-emission combustion[1-4] is lean premixed combustion. This involves forming a pre-mixture of air and fuel beforehand, which is then burned in the combustion chamber. The lean premixed flame has a uniform spread and forms a blue flame in the combustion chamber, as shown in **Fig. 5 (b)**. The flammable limit of lean premixed combustion closely depends on the equivalence ratio. For example, CO emissions increase at an equivalence ratio of less than 0.45. On the other hand, NOx is produced exponentially with temperature when the equivalence ratio is higher than 0.7. Given these preliminary considerations, the mixture temperature

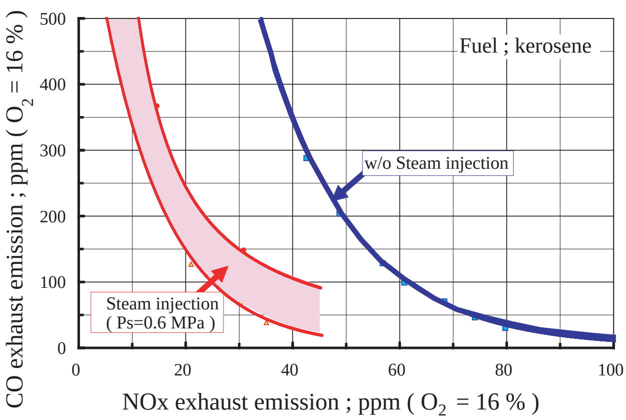


Fig. 4 Comparison of NOx/CO emission characteristics with and without steam injection.

Fig. 5 (a) Spray combustion flame. (Using kerosene as the fuel)

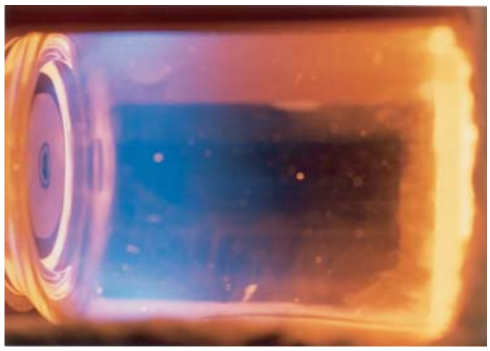


Fig. 5 (b) LPP combustion flame. (Using kerosene as the fuel) needs to be higher than 1250 ^{o}C to oxidize methane within 1 ms, which is the residence time of the mixture in the combustion chamber, but lower than 1550 ^{o}C to reduce the NOx emissions when a perfect mixture is formed. Actually, the upper temperature should be less than 1450 ^{o}C because the fuel and air are partially mixed. To attain this narrow temperature window between 1250 ^{o}C and 1450 ^{o}C, a specially designed combustion device is necessary. Several methods for stabilizing the lean premixed flame have been proposed. One is combined combustion in which a small diffusion flame (called the pilot flame) is formed in the central region of the lean premixed flame. Another proposal involves multistage combustion in which the combustion chamber is divided into many smaller chambers with each zone of lean premixed combustion being controlled separately and optimally.

When developing a combustor, it is important to take the operating conditions of the gas turbine into consideration. The operating conditions for a recuperated-cycle MGT are different from those of a simple-cycle MGT. The combustor inlet air temperature (CIT) is about 280 ^{o}C in a 300-kWe class simple-cycle MGT (compression ratio 6.5), while it is about 600 ^{o}C in a 50-kWe class recuperated-cycle MGT (compression ratio 3.5). The rotational speed of the turbine axis does not vary in the 300-kWe class MGT that is typically used to power a conventional generator. It is varied, however, in the 50-kWe class MGT as this type is well suited to directly powering high-speed generators. For the 50-kWe MGT, the most suitable equivalence ratio depends on the fuel flow rate, which is obtained by changing the air flow rate in proportion to the rotational speed. The combustor for the 300-kWe class MGT features multistage combustion, that is a simple load operating system that controls only the fuel flow rate, and which does not rely on any variable geometry for the airflow control.

It is relatively easy to realize lean premixed combustion with gaseous fuels such as town gas or LPG. But, prevaporization is necessary to achieve lean combustion with liquid fuels such as kerosene or gas oil. Given this fact, the combustor for a liquid fuels will have a complex structure.

3. Lean premixed combustion for simple-cycle micro gas turbine

3. 1 PDLP combustor

We employed multistage lean premixed (LP) combustion to achieve low NOx emissions with a high combustion efficiency over a wide operating range. To this end, we developed a pilot flame assisted double-swirler lean premixed (PDLP) combustor[5-6] to provide low-emission combustion for the 300-kWe class simple-cycle MGT. A cross-section of the 300-kWe class MGT with the PDLP combustor is shown in **Fig. 6**.

The PDLP combustor, shown in **Fig. 7**, has a central diffusion combustion zone, with the primary and secondary lean combustion zones in series. The diffusion flame formed by the pilot nozzle is intended to stabilize the lean premixed flames

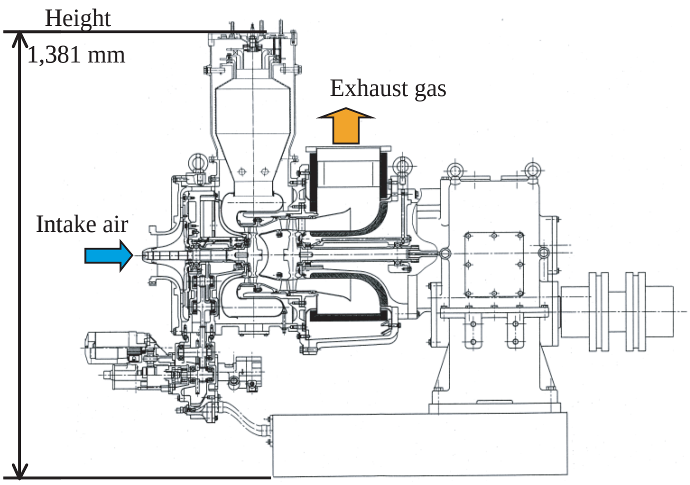


Fig. 6 Cross section of 300-kWe class simple-cycle & two-shaft MGT.

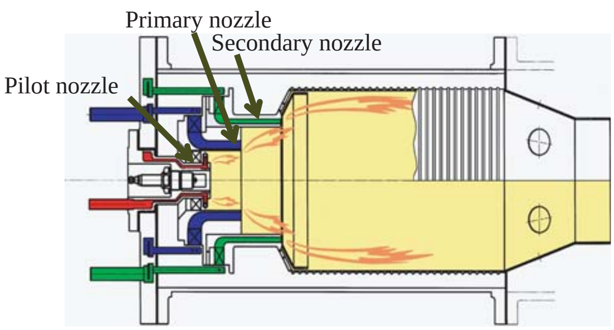


Fig. 7 PDLP combustor for a 300-kWe class simple-cycle MGT.

generated by the primary or secondary annular nozzles. The amount of pilot fuel must not exceed 10 % of the total fuel flow rate to suppress the formation of thermal NOx as much as possible without the risking flame instability.

3. 1. 1 Flame holding and combustion

A spark ignitor is set in the center of the pilot burner to ensure stable ignition. The pilot fuel is injected in both the axial and radial directions. In the first case, it is axially injected into the pilot burner region to form a flame kernel. In the second case, it is radially injected so as to spread a lean diffusion flame. These diffusion flames anchor the primary and secondary lean premixture flame, as follows.

The pilot burner has an axial vane swirler for which the swirl number is 0.8. The primary and secondary nozzles have a radial vane swirler at the inlet to each nozzle. These three swirlers form a co-swirling flow that rotates in the same direction. The swirl number is 1.2 for the primary and 1.0 for the secondary flow. The injectors for the primary and 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.

3. 1. 2 Heat-resistant measures

A unique characteristic of this combustor is that part of the primary lean premixed combustion duct is made of Si_3N_4 ceramic, and the combustion liner is cooled by turbulent air convection that is promoted by small ribs that protrude from the liner surface. No cooling air is introduced. High-velocity external cooling air is required to keep the wall temperature low enough. The shoulder wall of the combustion liner has many cooling holes but these are configured in such a way that the secondary premixture is not excessively diluted with air.

The Si_3N_4 ceramic duct can endure a temperature of 1400 ^{o}C. The use of the ceramic duct ensures that the unit is durable at primary equivalence ratios in excess of 0.7, even though the equivalence ratio is designed to be less than 0.6. The ceramic duct and small ribs are employed to withstand the thermal load and ensure a long service life.

3. 1. 3 Fuel schedule

Figure 8 shows the fuel schedule for a range of engine speeds. When starting the engine, the pilot fuel is injected to form a diffusion flame. After the formation of the pilot diffusion flame, as judged from the rotational 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-load mode, both the pilot and primary fuel are supplied up to half of the maximum power. While the pilot fuel flow is held constant throughout the operation range, the primary fuel flow, as controlled by a metering valve, is increased according to the engine load. In the high-load mode (half to full load), the secondary fuel is added to the pilot and primary fuel and controlled according to the load. When the equivalence ratio of the primary lean premixture is held below 0.6, very little thermal NOx is generated.

Fuel injection in the engine control map is scheduled depending on the electric power, as shown in **Fig. 9**. Secondary fuel feed begins at half of the full power and is controlled according to the increase in the electric power. In the high-load mode, the primary fuel is controlled so as to maintain a constant equivalence ratio of around 0.5 because little thermal NOx forms at low combustion temperatures. In practice, we modified the primary fuel in the high-load mode according to the engine inlet air temperature (EIT) and the engine speed because the inlet air density varies.

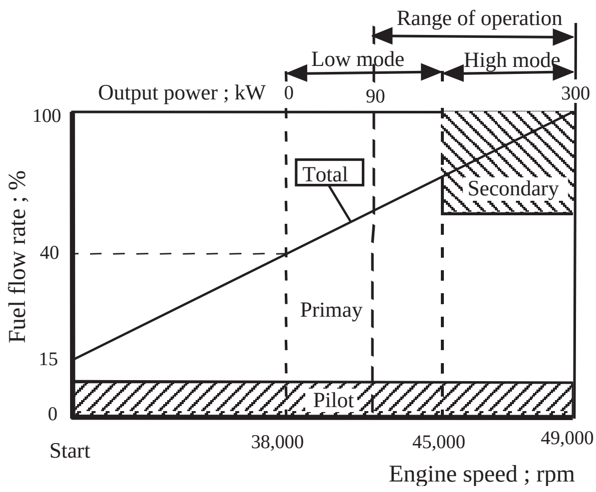


Fig. 8 Fuel schedule for a range of engine speed in the 300-kWe class simple-cycle & two-shaft MGT.

3. 2 Test results

3. 2. 1 Combustion characteristics

A gas turbine test was conducted on an engine bench. The exhaust gas was sampled at the turbine outlet duct and the NOx, CO, HC and O_2 emission levels were measured. The NOx emissions and combustion efficiencies of the PDLP combustor are plotted in **Fig. 10**, relative to those of a diffusion combustor with steam injection.

In the high-load mode range from 150 kWe to 300 kWe, we achieved a low NOx output of less than 10 ppm (O_2 = 16 %). No acoustic noise or vibration occurred across the entire operation range of the PDLP combustor. At a power output of 150 kWe, a NOx level of more than 17 ppm (O_2 = 16 %) was produced since the primary equivalence ratio reached the maximum of around 0.7 with the shutoff of the secondary fuel. In the low-load mode below 150 kWe, the NOx emissions increased in almost linear proportion to the primary equivalence ratio or the output power. Combustion efficiencies in excess of 99.5 % were maintained over a wide power range above 90 kWe.

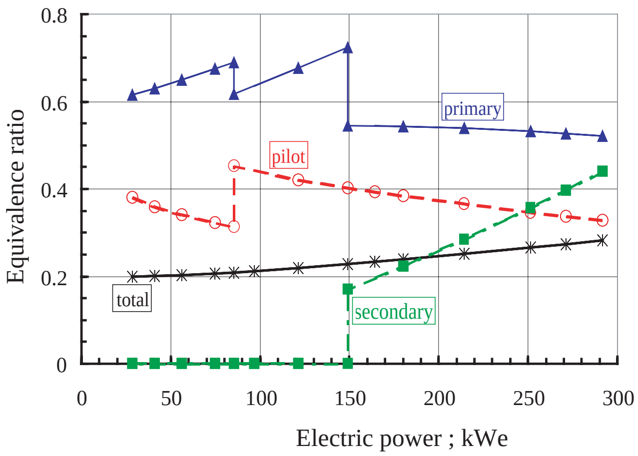


Fig. 9 Equivalence ratio controlled by fuel injection in the 300-kWe class simple-cycle & two-shaft MGT.

3. 2. 2 Field tests

We carried out a field test of the 300-kWe MGT during one year, and the total run time was 6,200 hours. The gas temperature at the inlet to the gas generator turbine (TIT) increases during the rated operation, without control, with an increase in the EIT. Therefore, it is necessary for the output power to be controlled in order to keep the TIT constant. For an EIT above 15 ^{o}C, the output power fell linearly by 2.8 kWe for every 1 ^{o}C increase in the EIT. The thermal efficiency and total efficiency decreased by 1.4 % and 1.7 %, respectively, for an EIT increase of 10 ^{o}C.

As shown in **Fig. 11**, NOx emissions relative to the EIT fall by 0.7 ppm for every 1 ^{o}C when the EIT is above 15 ^{o}C, but the output power falls to maintain a constant TIT. For this reason, the operated equivalence ratio of the primary and secondary fuel becomes lean as the EIT increases, in spite of the constant TIT. For an EIT below 15 ^{o}C, the output power is controlled to maintain a constant maximum power of 295 kWe. NOx emissions increase by 1.5 ppm per 1 ^{o}C, because the equivalence ratio of each of the three fuel lines increases as the thermal efficiency and air density decrease. As a result, the

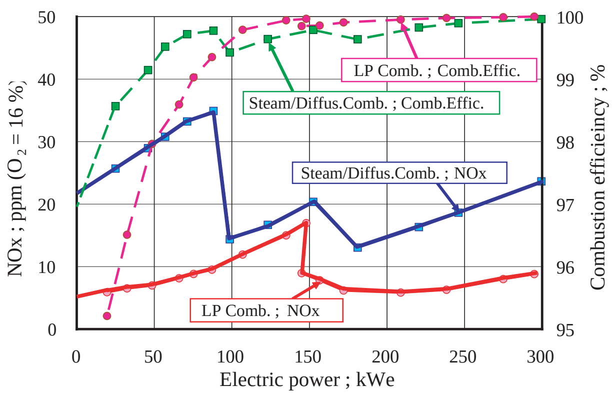


Fig. 10 NOx emissions and combustion efficiencies of the PDPA combustor, compared with those of a diffusion combustor with steam injection.

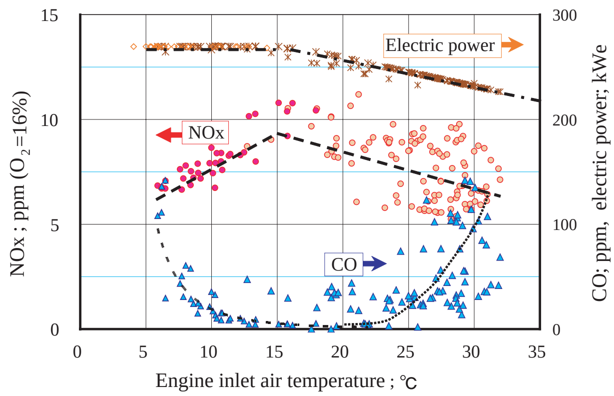


Fig. 11 NOx emission characteristics of a field test when fuel schedule is controlled by the engine inlet air temperature (EIT).

NOx emission peaks at around 10 ppm (O_2 = 16 %) at an EIT of 15 ^{o}C.

By the way, it is known that the NOx emission decreases accroding to the amount of the humidity in the atomosphere. When the NOx emissions in Fig. 11 were corrected by the reference equation,[7] NOx emissions increase by 0.2 ppm per 1 ^{o}C above 15 ^{o}C of the EIT, too.

4. Lean premixed combustion for a regenerative cycle micro gas turbine

4. 1 TLP combustor

This chapter explains LP combustion for a 50-kWe class recuperated-cycle MGT (**Fig. 12**) using gaseous fuel. The engine control for the MGT's low-emission combustor must be as small and simple as possible. The developed combustor employs a simple load operating system that controls the fuel flow rate and engine rotational speed, using neither a variable geometry (to control the air flow rate) nor multistage lean premixed combustion.

Figure 13 shows a cross section of a tandem-type lean premixed (TLP) combustor for gaseous fuels such as town gas or LPG. This combustor consists of a pilot nozzle with a bluffbody at its center and a coaxial annular nozzle for premixing the fuel, with a radial vane swirler at the inlet to the nozzle. The diffusion flame formed by the pilot fuel is intended to stabilize the lean premixed flame supported by the annular nozzle. The internal recirculation zone created by the swirling flow of the mixture downstream from the bluffbody is also indispensable to stabilizing the lean combustion flame.

The amount of pilot fuel must be held at less than 10 % of the total fuel flow rate to keep the amount of thermal NOx as small as possible without any flame instability. The gas fuel for premixing is injected through nozzles into the combustion air stream just upstream of the swirler vane. The fuel and combustion air are mixed and then introduced into the combustion chamber through the coaxial annular nozzle. The combustion liner is cooled by the turbulent air convection that is promoted by small ribs without introducing cooling air, which is the same technique as that explained in the previous chapter.

4. 2 Combustion characteristics

The engine control schedule is divided into three modes. Only the pilot fuel is supplied from start-up to the low electric power range (low diffusion combustion mode), both the pilot fuel and the premixing fuel are supplied in the middle range (medium mode of LP combustion, assisted by a pilot flame), and only the premixing fuel is supplied in the high load mode until full load (high LP combustion mode) is reached, as shown in **Fig. 14**.

In the high LP combustion mode, both the premixing fuel and air flow rate are controlled by means of a feedback signal to maintain a constant temperature at the turbine outlet. Actually, the air flow rate is varied according to the rotational speed of the compressor because the fuel flow rate is controlled according to the electric power demand. This means that the equivalence ratio of the lean pre-mixture is held almost constant at the combustor inlet. This variable speed operation is advantageous

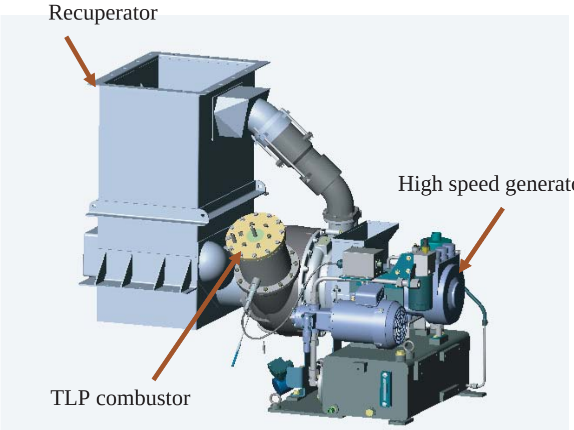


Fig. 12 50-kWe class recuperated-cycle MGT.

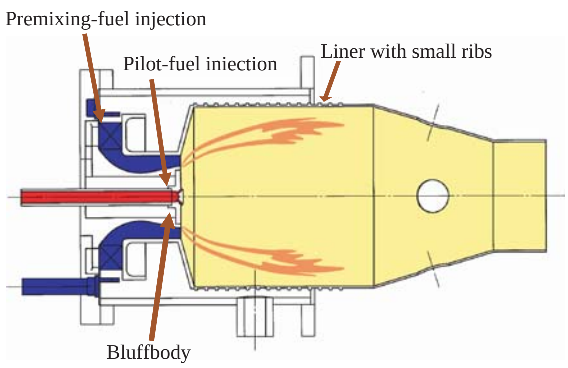


Fig. 13 TLP combustor for a 50-kWe class recuperated-cycle MGT.
(TLP: Tandem-type Lean Premixed Combustor)

in that it prevents the deterioration of the combustion efficiency under partial load conditions. The gas turbine is operated so as to maintain a certain exhaust gas temperature under high loads, so adequately low levels of emissions can be maintained over a wide range of output power.

The low load diffusion combustion mode is applied below 20 kWe. The medium LP combustion mode, assisted by the pilot flame, is suitable for loads between 20 kWe and 40 kWe, while the high LP combustion mode is optimized for loads between 40 kWe and full load. The NOx emissions are about 10 ppm (O_2 = 16 %) when LP combustion is assisted by a pilot flame and when the pilot fuel flow rate is set to around 10 % of the total fuel flow rate. Very low NOx levels of less than 10 ppm (O_2 = 16 %) are formed as a result of LP combustion. A combustion efficiency in excess of 99.5 % can be maintained

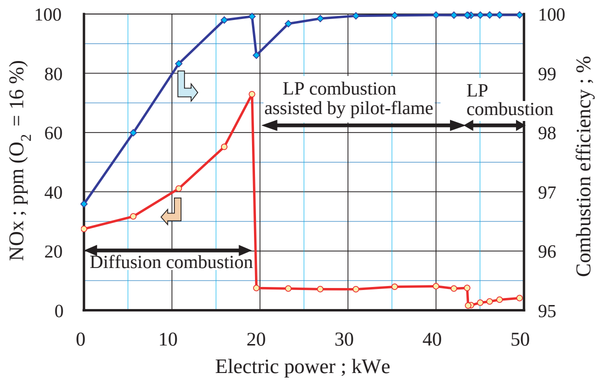


Fig. 14 NOx emission and combustion efficiency in the 50-kWe class recuperated-cycle MGT.

throughout all the modes. Variable speed operation is effective for improving not only the combustion efficiency but also the thermal efficiency under partial loads.

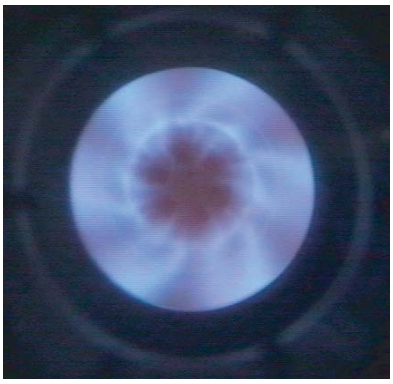
The characteristics of the pilot nozzle were selected to provide the rated power with only the pilot flame in order to ensure independent operation without a connection to the electric power grid. And also, the characteristics of the pilot nozzle affect both the ignition and the stability of lean combustion.

In order to improve the stability of the pilot flame and the deposition of soot on the surface of the bluffbody, the combustion test rig was used to observe combustion flameout. Flame out or unstable combustion at cold start occurred occasionally in the diffusion flame mode. As a result of our observations, we modified the shapes of the pilot nozzle and the bluffbody from those of the preliminary design. Photographs of the flame as viewed from downstream after the modifications in the two modes are shown in **Fig. 15**.

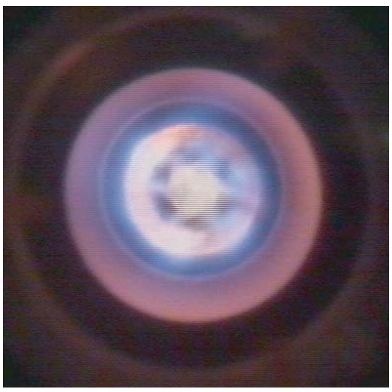
Moreover, the introduction of fresh air into a recirculation zone downstream of the bluffbody provides a very effective means of stabilizing the flame. Part of the compressed air from the compressor outlet is introduced through the pipe into the combustion chamber of the engine.

4. 3 Ignition characteristics

The diameter of the pilot injection hole has an influence on the ignition of the pilot flame and the stability of the lean premixed flame. By measuring



<Diffusion flame>



<Premixed flame assisted by pilot-flame>

Fig. 15 Photographs of the diffusion flame (Left) and the premixed flame with pilot-flame (Right), using town gas as the fuel.

the concentration in the vicinity of the spark plug gap, we can ensure stable ignition provided the velocity of the fuel injected from the pilot injector is high enough to reach the spark gap. So, the number and diameter of the pilot injector holes should be modified.

The relationship between the gaseous fuel concentration and ignition characteristics was investigated using an instrument that is based on the infrared absorption method for the time-resolved measurement[8] of the equivalence ratio in the vicinity of the spark gap. **Figure 16** shows a time history of the measured equivalence ratio in the vicinity of the spark plug gap at engine start-up. The equivalence ratio increases steeply approximately 0.3 seconds after the solenoid valves for total fuel cutoff are opened. And, it reaches its maximum level in 1 second, which is adjusted to the overall average equivalence ratio in the combustion chamber. Then, the equivalence ratio falls because the air flow rate increases with the rotational speed. The ignition test at start-up indicated an ignition timing of between 0.3 and 0.5 seconds after the valve was openedon 3 sec. in Fig. 16.

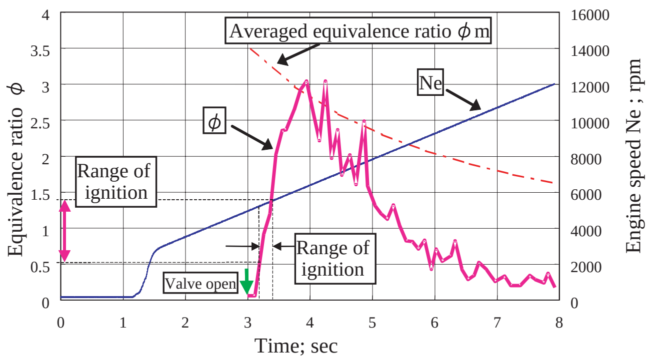


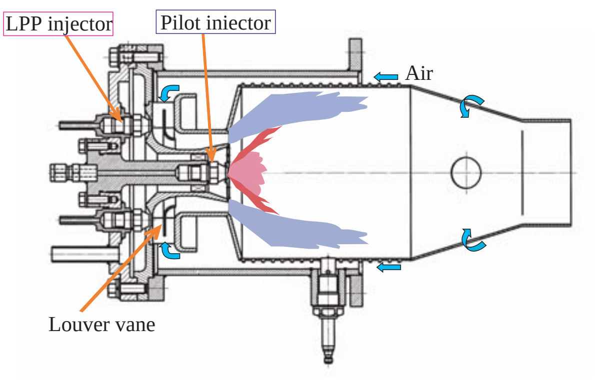
Fig. 16 Measurement of the equivalence ratio in the vicinity of the spark gap at the engine start-up.

5. Lean premixed prevaporized combustion for a recuperative-cycle micro gas turbine

5. 1 Design of TLPP combustor

To use liquid fuel such as kerosene or gas oil, the application of lean premixed prevaporized (LPP) combustion allows us to attain low levels of NOx. We developed a tandem-type lean premixed pre-vaporized (TLPP) combustor for the 50-kWe class recuperated-cycle MGT.[9] **Figure 17** shows the TLPP combustor. The TLPP combustor consists of a pilot spray injector with a bluffbody at its center and a coaxial annular premixing nozzle with a radial vane swirler at its the inlet, in the same way as for the TLP combustor for gaseous fuel. Although the TLPP combustor has approximately the same structure as the TLP combustor for gaseous fuel, it differs in the following aspects.

A louver vane is placed in the premixed, pre-vaporized passage to prevent the formation of high fuel concentrations. The prevaporizing passage is divided into two sections by the louver vane. Liquid fuel is injected from the swirl-type injectors towards the louver vane surface. This structure promotes spray evaporation and premixing as any comparatively large liquid droplets collide with the vane surface, and then evaporate completely within



(a) Cross section of TLPP combustor.

(b) Photograph of TLPP combustor.

Fig. 17 Tandem-type lean premixed pre-vaporized (TLPP) combustor.

about 1 millisecond after fuel injection.

There is a problem of deposits forming in the fuel passage and at the tip of the injector when the fuel injector is always exposed to an atmospheric temperature of around 600 °C. Compressor exit air at a comparatively low temperature (around 200 °C) is introduced into the injector tip to prevent overheating of the injector itself. A little pilot fuel is also injected to significantly improve the durability of the TLPP combustor but too much for cooling the injector itself, although the NOx emissions increase.

The fuel for premixing is injected, using four spray injectors, into the passage carrying the combustion air. The fuel flow rate to the pilot spray injector is controlled so as not to exceed around 12 % of the total fuel flow rate during LPP combustion assisted by the pilot flame. Compressed air is introduced from the circumference of the spray injector to promote atomization and to cool the injectors. We observed the spray impingement on the surface of the air passage wall at the air temperature of 600 °C, as shown in **Fig. 18**.

Only pilot fuel is supplied from start-up to a load of 20 kWe (low spray combustion mode), and both the pilot fuel and premixed fuel are supplied at loads over 20 kWe (high LPP combustion mode assisted by pilot flame).

5. 2 Combustion characteristics

Observations of the combustion flame are shown in **Fig. 19**. LPP combustion forms a blue flame in the annular region of the combustion chamber. LPP combustion assisted by a pilot flame forms a brilliant yellow flame that anchors the LPP flame.

Figure 20 shows the behavior of the NOx emission and the combustion efficiency for kerosene. With a pilot fuel flow rate of less than 12 % of total fuel flow rate, the NOx emission is less than 20 ppm (O_2 = 16 %) and the combustion efficiency is higher than 99.5 % over a power range of 20 kWe to 50 kWe. The lower pilot fuel flow rate is an effective means of reducing the NOx

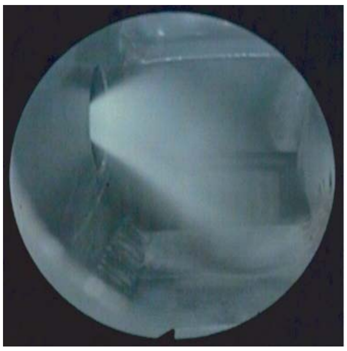


Fig. 18 Photograph of kerosene spray injected into the premixed prevaporized passage of TLPP combustor.
(Air temperature: 600 °C, Pressure: 0.3 MPa)

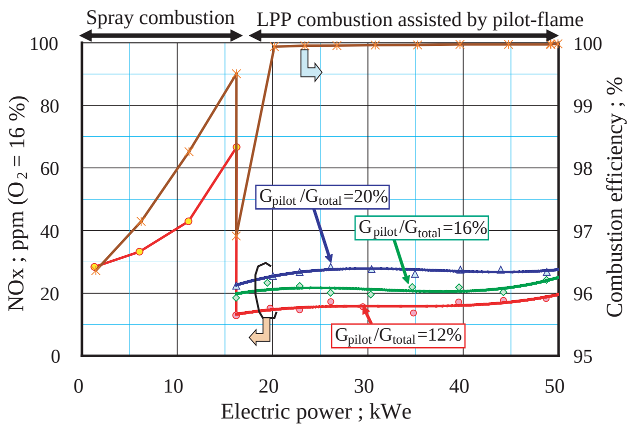


Fig. 20 NOx emission and combustion efficiency affected by pilot fuel flow rate in the range of the high LPP combustion mode (more than 15 kWe).

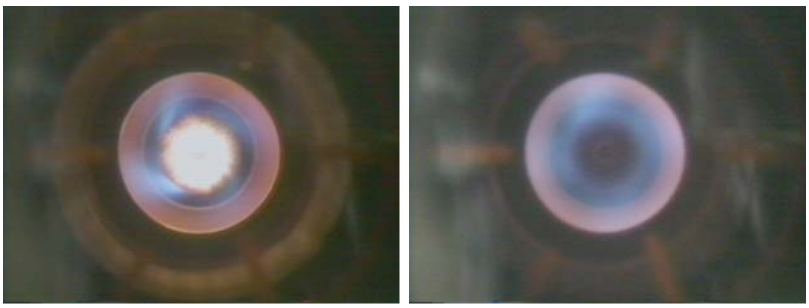


Fig. 19 Photographs of LPP combustion assisted by pilot-flame (Left) and LPP combustion flame without pilot-flame (Right), using kerosene as the fuel.

emissions. However, the combustion efficiency at a power output of around 15 kWe deteriorates because of the bad characteristics of the liquid atomization and prevaporization.

The pilot fuel is controlled by a feedback signal to adjust the engine load in the low spray combustion mode. But, the pilot fuel flow rate is held at around 12 % of the total fuel flow rate to stabilize the pilot flame in the middle and in the high mode of pilot flame assisted LPP combustion.

Figure 21 shows a comparison of the NOx emissions for kerosene and gas oil. Although the NOx emissions for kerosene are higher than those for gas oil in the low mode below 15 kWe of spray combustion, both NOx emission levels are almost the same in the medium and high mode of LPP combustion that is assisted by the pilot flame.

6. Summary

Lean premixed combustion was investigated as a means of simultaneously realizing low NOx emissions and high combustion efficiencies for gaseous or liquid fuels. To overcome the inherent characteristic in that lean premixed combustion can be stabilized only in a narrow range of equivalence ratios, the uniformity of the fuel-air premixture and the controllability of the lean premixed combustion were improved by using three types combustors, as follows.

(1) Multistage lean premixed combustion was investigated for a conventional simple-cycle micro gas turbine (MGT), using gaseous fuel such as town gas or LPG. The developed pilot flame assisted double swirler type lean premixed (PDLP) combustor has a diffusion combustion zone at its center, with a primary and secondary lean combustion zone arranged in series. It is possible that the diffusion flame formed by the pilot nozzle stabilizes the lean premixed flames generated by the primary or secondary annular nozzle. Low NOx levels of less than 15 ppm (O_2 = 16 %) and combustion efficiencies in excess of 99.5 % are achieved over a wide range from 50 % to full load for a 300-kWe class simple-cycle MGT.

(2) Because modern MGTs directly power high-speed generators, the air flow rate is changed based on the rotational speed of the engine. A simple load operating system that controls both the fuel and air flow rates is easily applied to a tandem-type lean premixed (TLP) combustor using gaseous fuel. Low NOx levels of less than 10 ppm (O_2 = 16 %) and combustion efficiencies in excess of 99.5 % are achieved over a wide range from 40 % to full load for a 50-kWe class recuperated-cycle MGT.

(3) Lean premixed prevaporized (LPP) combustion was investigated in order to enable the use of liquid fuel such as kerosene or gas oil. The structure devised for the TLPP combustor promotes spray evaporation and premixing within about 1 millisecond after fuel injection at the air temperature of 600 ^{o}C. Low NOx levels of 20 ppm (O_2 = 16 %) and higher combustion efficiencies are also achieved over a wide load range from 40 % to full load for the 50-kWe class recuperated-cycle MGT.

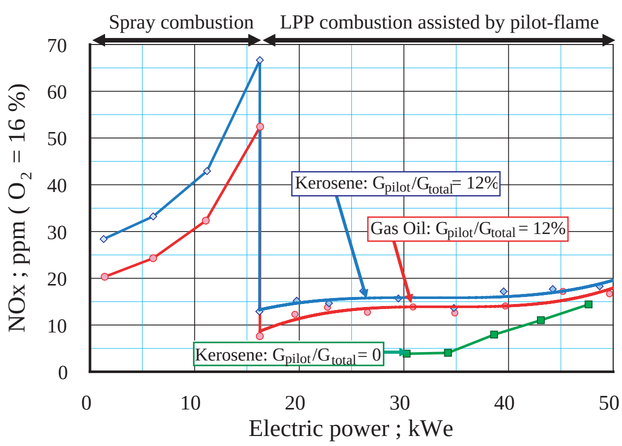


Fig. 21 NOx emissions using kerosene as the fuel compared with those of gas oil.

References

1) Mori, M., Ishizuka, A., Miyahara, M. and Kuwabara, S. : "Development of Double Swirler Low NOx Combustor for Gas Turbine", 20th CIMAC G03, (1993), London
2) Hosoi, J., Watanabe, T., Toh, H., Mori, M., Sato, H. and Ishizuka, A. : "Development of a Dry Low NOx Combustor for 2MW Class Gas Turbine", ASME Pap., No. 96-GT-53(1996)
3) Ichikawa, H., Kumakura, H., Sasaki, M. and Ohkubo, Y. : "Development of a Low Emission Combustor for a 100-kW Automotive Ceramic Gas Turbine (IV)", ASME Pap., No. 97-GT-462(1997)
4) Bhargava, A., Kendrick, D. W., Casleton, K. H. and Maloney, D. J. : "Pressure Effect on NOx and CO Emissions in Industrial Gas Turbines", ASME Pap., No. 2000-GT-97(2000)

5) Sato, H., Hase, K., Tokumoto, T., Ohkubo, Y., Azegami, O., Idota, Y. and Higuchi, S. : "Development of a Dry Low Emission Combustor for 300 kW Class Gas Turbine", 23rd CIMAC, Hamburg, (2001)
6) Ohkubo, Y., Azegami, O., Idota, Y., Sato, H. and Higuchi, S. : "Development of Dry Low-NOx Combustor for 300kW Class Gas Turbine Applied to Co-generation Systems", ASME Pap., No. 2001-GT-83(2001)
7) Hung, W. S. Y. and Agan, D. D. : "The Control of NOx CO Emissions from 7-MW Gas Turbines with Water Injection as Influenced by Ambient Conditions", ASME Pap., No. 85-GT-50(1985)
8) Ohkubo, Y., Idota, Y. and Azegami, O. : "Measurement of Equivalence Ratio in Spark Plug Gap for Low Emission Combustor", 30th GTSJ Annual Conf. Pap., Oct.9-10, (2002), 115-120
9) Azegami, O., Ohkubo, Y., Idota, Y,. Higuchi S. and Okabayashi, K. : "Development of Dry Low Emission Combustor for 50kW Class Gas Turbine", Asian Congr. on Gas Turbines 2005, Nov.16-18, (2005)

(Report received on Dec. 16, 2005)

Yoichiro Ohkubo

Research fields : Gas Turbine and reciprocating engine, Combustion, Fuel injection and atomization

Academic degree : Dr. Eng.

Academic society : Jpn. Soc. Mech. Eng., Gas Turbine Soc. Jpn., Soc. Autom. Eng. Jpn., Combust. Soc. Jpn., Int. Inst. Liquid Atomization and Spray Systems-Jpn.

Award : Paper Award of Gas Turbine Soc. Jpn. (1991)
Technical Award of Combust. Soc. Jpn. (1996)