THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

97-GT-462

DEVELOPMENT OF A LOW-EMISSION COMBUSTOR FOR A 100-kW AUTOMOTIVE CERAMIC GAS TURBINE (IV)

Masafumi Sasaki, [1] Hirotaka Kumakura, [1] Hiroyuki Ichikawa [1]
Youichiro Ohkubo, [2] Yuusaku Yoshida [3]
Japan Automobile Research Institute, Incorporated
Tsukuba, Japan

ABSTRACT

A low emission combustor, which uses a prevaporization-premixing lean combustion system for the 100-kW automotive ceramic gas turbine (CGT), has been subjected to performance tests. A second combustor prototype (PPL-2), which incorporates improvements intended to overcome a flashback problem observed in an initiel combustor prototype (PPL-1), had been tested. Now combustors with further improvements accomplished to the PPL-2 prototype, is tested.

Test results of the PPL-2 combustor showed that, increasing the air distribution ratio in the lean combustion region to aviod flashback, and by providing a uniform flow layer at the entrance of the combustion region so as to supress flashback, were effective in expanding the stable combustion range by substantially improving the flashback characteristics.

To improve the flashback characteristics further more, we have redesinged the bluffbody and the swirl chamber so as to obtain uniform flow of the mixture, in the prevaporization premixing zone.

Test results shows that the flashback characteristics has been greatly improved, and a wide stable combustion range, needed to operate the 100-kW CGT engine, was obtained.

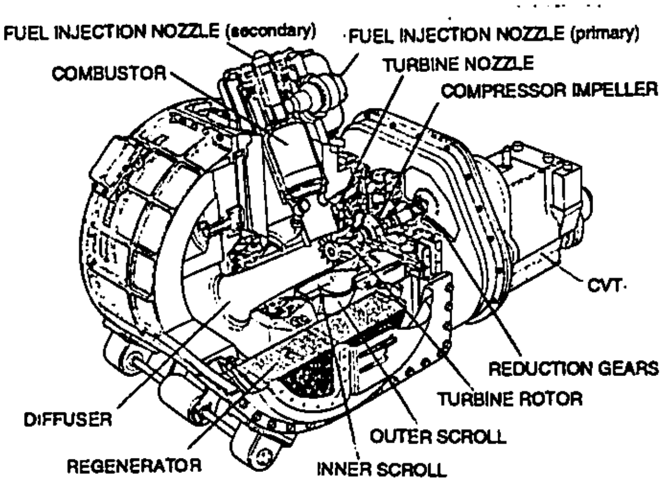

Figure 1 Construction of the 100-kW CGT engine

1. Nissan Motor CO., Ltd.
2. Toyota Central R&D Labs Inc.
3. Japan Automobile Research Institute Inc.

NOMENCLATURE

A/F air fuel ratio
λp exess air ratio in combustion region
(EI) emission index g/kg-fuel
L, Load engine load %
Ga air flow rate g/s
Pa combustor inlet pressure MPa
Ta combustor inlet temperature K
Gf fuel flow rate g/s
Gfp fuel flow rate of the primary nozzle g/s
P fuel pressure

INTRODUCTION

The Petroleum Energy Center in Japan has been working on the development of a ceramic gas turbine (CGT) for automotive application since fiscal 1990 in a project supported by the Ministry of International Trade and Industry. The ceramic gas turbine engine is seen as a promising next-generation automotive powerplant because of its multifuel capability, low emission levels and potential for improving thermal efficiency through the application of ceramics. Together with members of the petroleum industry, the Japan Automobile Research Institute, Inc. (JARI) is participating in this project and is responsible for developing the CGT engine. The construction of the CGT engine is shown schematically in Fig. 1. This 100-kW engine adopts a single-shaft regenerative turbine and is designed to operate at a turbine inlet temperature of 1623 K (1350°C). The target set for engine efficiency is 40%, and the emission performance objective is to meet Japan's 10-15 mode emission standards for passenger cars without using an aftertreatment system.

In order to maintain acceptable part-load fuel economy, the CGT engine is built with two high-efficiency regenerators, which results in an exceptionally high combustor inlet temperature, Tin, of 1150-1300 K. Because such a high inlet temperature promotes the formation of thermal oxides of nitrogen (NOx), a critical development issue is to control NOx emissions.

The CGT development project has adopted a prevaporization-premixing lean combustion (PPL) system for the engine combustor [1]. The results of steady-state combustion tests conducted with an initial combustor prototype (PPL-1) indicated that the emission performance objective could be achieved [2]. A second combustor prototype (PPL-2) was then designed and built which incorporated improvements to overcome problems that had been identified in the PPL-1 combustor. Tests conducted to measure the steady-state performance of the PPL-2 combustor confirmed that it met nearly all the performance requirements for the CGT engine combustor[3]. The PPL-2 combustor was then further upgraded to create an improved version, which will be referred to here as the improved PPL-2 combustor.

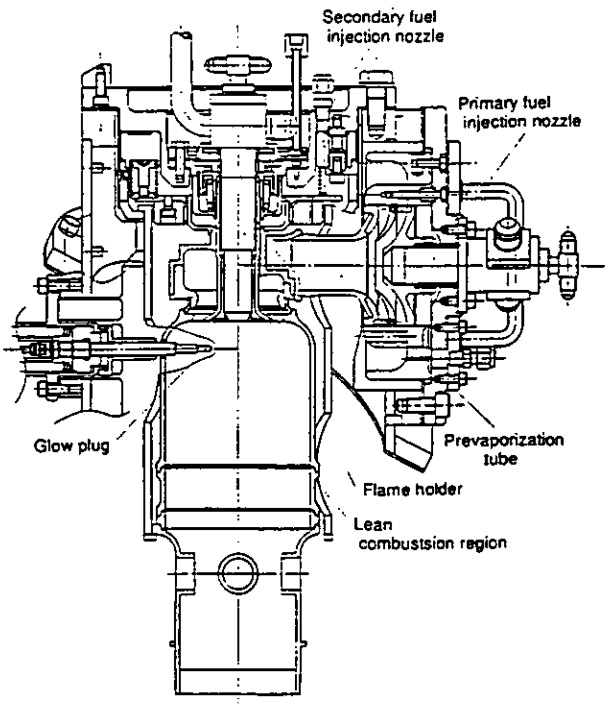

Figure 2 Construction of the PPL combustor

This paper describes the enhanced combustion performance obtained with the improved PPL-2 combustor in the high load region along with the results of emission performance tests that included transient operation. The direction of future work is also indicated.

During the tests, kerosene was used as fuel.

IMPROVEMENT OF PPL COMBUSTOR

Figure 2 is a schematic showing the construction of the PPL combustor. The results nf steady-state combustion tests conducted on the PPL-1 combustor indicated that the flashback characteristic of the combustor had to be improved in order to expand the stable combustion range. That result was factored into the design of the PPL-2 combustor. The geometry of the inlet to the prevaporization tube was substantially changed to reduce the pressure loss associated with the generatioo of swirl, making it possible to increase the air distribution ratio in the primary (lean) combustion region. In addition, air was introduced to dilute the boundary layer near the throat wall going into the combustor. These measures were effective in expanding the stable combustion range by greatly improving the flashback characteristic.

However, it was clear that the flashback characteristic would have to be improved even more to secure a stable combustion range for the combustor with a sufficient margin in all operating regions relative to the required engine operating conditions. It was also evident that carbon deposits on the inner surfaces of the combustor would have to be prevented under full-load operation.

This section describes the improvemeots made to the combustor construction and the improvement of the flashback characteristic in the low load region with the aim of resolving those issues.

Improvement of PPL combustor construction

An improved combustor design was developed with three major objectives in mind for improving the flasbback characteristic. The first was to increase the air distribution ratio in the lean combustion region. The second was to reduce uneven mixture flow in the prevaporizatino region by improving the flow characteristic from the prevaporization tube to the lean combustion region. The third objective was to reduce the variation in the mixture flow velocity distribution from the prevaporization region into the lean combustion region.

In the previous paper it was reported that the prospect of assuring lean combustion stability in the low load region was confirmed by the test results [3]. Accordingly, it was decided to discontinue the variable mechanism that had been provided upstream of the prevaporization tube to adjust the air introduction openings in the lean combustion region for the purpose of obtaining lean combustion stability. That change was intended to reduce pressure losses, thereby increasing the air distribution ratio in the lean combustion region to suppress flashback.

Flow visualization experiments were conducted to ascertain the mixture flow characteristics in the swirl chamber. The results indicated that the mixture flow was uneven and stagnated just after flowing into the swirl chamber from the prevaporization tube. The same characteristics were observed in the annular throat of the combustor from the swirl chamber to the lean combustion region.

Since the basic shape of the swirl chamber would have to be radically redesigned in order to improve the mixture flow at the inlet to this chamber, it was decided to put that design change on hold.

To improve the mixture flow in the annular throat at the inlet to the lean combustion region, the shape of the flame holder forming the inner wall of the swirl chamber was redesigned so that the flow velocity would increase monotonically. A flow visualization experiment was conducted to confirm the effect of that design change, and the results indicated that flow stagnation in the annular throat had been improved. This flow improvement achieved a more uniform mixture flow velocity into the lean combustion region, and an experiment was conducted to verify the resultiag effect on improving the flashback characteristic.

Improvement of flashback characteristic

The automotive CGT engine combustor operates on a prevaporization-premixing lean (PPL) combustion mode alone up to the highest load conditions of the 10-15 mode test, which covers nearly the entire load distribution projected for everyday use. In the higher load range, it operates on a hybrid combustion mode that combines diffusion combustion with PPL combustion. Figure 3 shows the flashback and blow-off limits in relation to the combustor inlet temperature under the highest load conditions for PPL combustion alone.

The notation Gfpmax in the figure indicates the maximum fuel flow rate of the primary fuel injection nozzle used for PPL combustion.

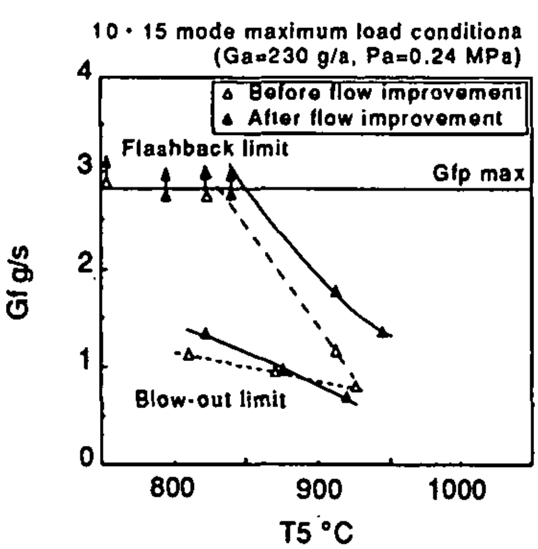

Figure 3 Combustor inlet temperature vs. stable combustion range

It is clear from the figure that flashback shows noticeably high sensitivity to the combustor inlet temperature, as the tendency for flashback to occur increases sharply as the combustor inlet temperature rises.

Before the mixture flow in the swirl chamber was improved, a sufficient stable combustion range was obtained relative to the design fuel flow rate when the combustor inlet temperature was around 800°C. However, when the combustor inlet temperature exceeded 900°C, the stable combustion range virtually disappeared. After the mixture flow was improved, however, it is clear that the flashback characteristic was substantially improved.

It was initially feared that improving the mixture flow would cause the blow-out characteristic to deteriorate. However, excluding the region of a low combustor inlet temperature, there were no signs of deterioration in the blow-out characteristic.

These results confirmed that improving the mixture flow from the swirl chamber into the lean combustion region had a large effect on improving the flashback characteristic. In future work, it is planned to expand the margin of the stable combustion range against flashback and blow-out, taking into account the characteristics of these phenomena and the air temperature level at the combustor inlet under actual engine operation.

TRANSIENT EMISSION PERFORMANCE

One of the major development aims set for the automotive CGT engine is to meet Japan's 10-15 mode emission standards for passenger cars without using an aftertreatment system. The results of steady-state combustion tests conducted with the PPL-1 and PPL-2 combustors indicated that both units had the potential to achieve this

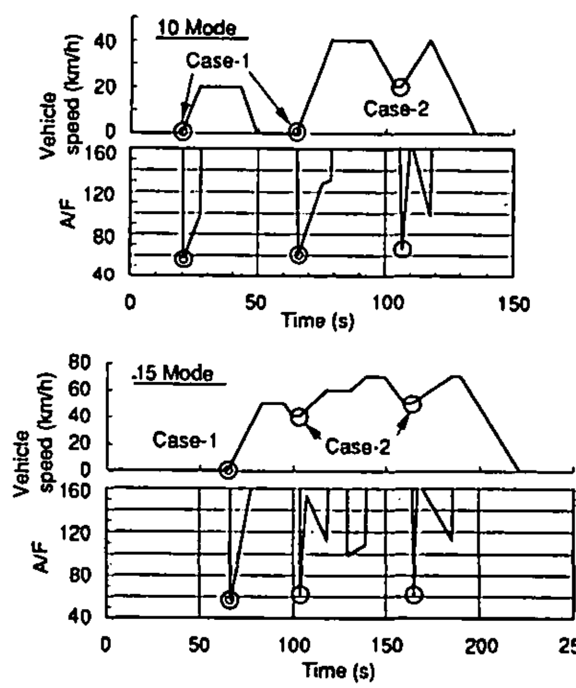

Figure 4 10 and 15 mode operating conditions

ENGINE SPEED rpm	CASE 1	CASE 2
AIR FLOW g/s	131	168
AIR PRESSURE MPa	0.17	0.2
AIR TEMPERATURE ℃	800	800
AFTER ACCELERATION (A/F)	52	60

Table 1 Transient test conditions

emission performance objective under quasi- steady-state operation.

As shown in Fig. 4, however, under 10 and 15 mode operation there are points where the air-fuel ratio suddenly becomes rich during acceleration, which could result in a decline in emission performance. Therefore, in order to verify the emission performance of the PPL combustor, it was necessary to conduct emission tests that ultimately included transient operating conditions as well. A typical procedure for measuring emission performance under transient operation is to cnllect exhaust samples in bags while the engine is operating at the specified test mode conditions. In this project, however, as we did not have the necessary continuously variable transmission for simulating the operating parameters, it was not possible for the engine to trace the test mode operating conditions.

Figure 4 shows the results of a dynamic characteristics analysis conducted for 10 and 15 mode operation. It was found that there were two general pstterns for the sudden increase in the fuel amount (i.e., lower A/F ratio) during acceleration. One pattern is for acceleration from idling (Case 1) and the other psttern is for acceleration from a certain vehicle speed (Case 2). These acceleration patterns during test mode operation were then taken into account in setting transient operating conditions for simulating the acceleration conditions only on the basis of an increase in the fuel flow rate. Transient emission performance tests were then conducted under those conditions.

Table 1 shows the transient test conditions for simulating the acceleration conditions.

High-response NOx analyzer used in transient emission tests

The fuel flow rate and exhaust components had to be measured with ultra-fast responsiveness and high accuracy in order to obtain accurate emission measurements under transient operation with the CGT engine, as it could not trace the test mode operating conditions. The fuel flow rate was obtained by using a fast-acting pressure pickup to measure the combustion pressure.

Because no device existed that could meet the requirements for NOx measurement, an ultra-high response exhaust analyzer (Bex4100Hss made by Best Instruments Co., Ltd.) was newly developed for use in the tests. The internal volume nf the device from the sampling probe to the analyzer proper was minimized as much as possible while maintaining high accuracy, in order to accomplish accurate measurements with ample responsiveness even for minute exhaust samples. As a result, it can analyze exhaust samples at a response speed of less than 50 msec. A schematic of the transient emission test apparatus is shown in Fig. 5.

Transient emission test results

Transient emission performance is shown in Fig. 6. The solid line represents emission data obtained in steady-state combustion tests conducted on the PPL-1 and PPL-2 combustors in isolation. So long as emission data measured during engine operation do not deviate from this curve, it confirms that the 10-15 mode emission standards can be met. Moreover, NOx emission levels measured under any arbitrarily chosen test conditions can also be plotted in this figure hy first correcting the data according to comhustor inlet temperatures and combustion pressure sensitivities found separately [2].

The open squares indicate the steady-state emission performance of the engine, which is equal to the steady-state emission results measured for the combustors hy themselves. The "+" and "x" symbols indicate the results of the transient emission test. It is seen that emission performance during acceleration coincided with the steady-state emission characteristic. In short, the results confirmed that the PPL comhustor by itself can meet the 10-15 mode emission standards even under transient operating conditions.

It is planned to measure the emission levels of the engine under actual transient operation in future work to ohtain final confirmation that the engine is also capable of clearing the 10-15 mode emission standards.

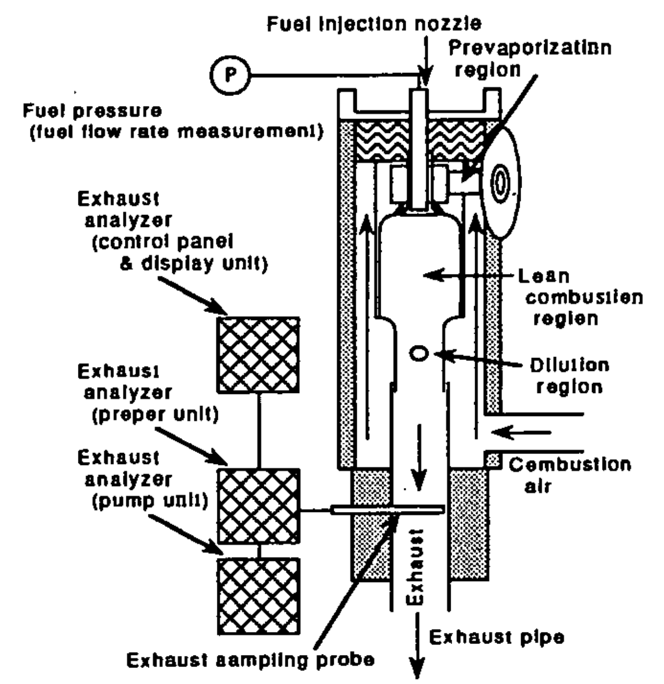

Figure 5 Schematic of transient emission test apparatus

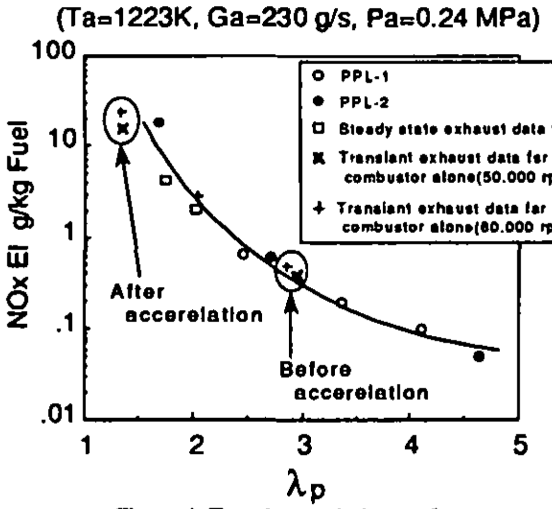

Figure 6 Transient emission performance

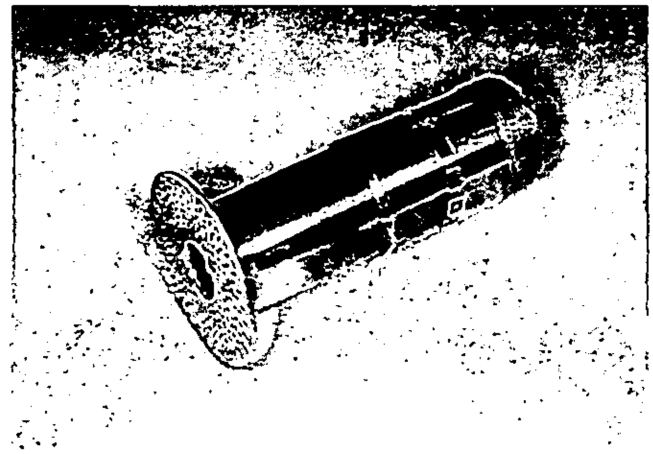
Figure 7 Flame holder

IMPROVEMENT OF HIGH-LOAD COMBUSTION PERFORMANCE

As a result of the combustion tests conducted with the PPL-2 combustor, it was found that carbon deposits occurred on the inner surfaces of the combustor when it was operated under the planned operating condition (A/F=70) at full load. This section describes the measures taken to prevent the occurrence of carbon deposits in the combustor under high load operating conditions, especially at full load.

Measure against carbon deposits (1)

Carbon deposits were found only on the downstream end of the flame holder in the PPL-2 combustor. It was decided to increase localized dilution of the mixture at that location as a means of preventing carbon buildup.

The downstream end of the flame holder in the PPL-2 combustor was designed with 200 small holes, 1 mm in diameter, through which fresh air was discharged in the direction of the lean combustion region. That measure had been adopted to prevent carbon deposits from forming on the downstream end of the flame holder.

Holes for introducing air were newly provided in the sides of the flamo holder, as shown in Fig. 7. Part of the air for combustion was then discharged into the lean combustion region through the flame holder as a further means of promoting greater localized mixture dilution at the downstream end of the flame holder. That improvement achieved carbon-free operation in the high load region above 60% at the planned operating condition of A/F=70 or lower.

Figure 8 shows the stable combustion range of the improved PPL-2 combustor. It is clear that the stable combustion range of this improved PPL-2 combustor fully covers the combustion conditions (= design operating point) required by the CGT engine. It should be noted that the lean combustion limit is defined here as the point of 99.5% combustion efficiency. The actual blow-off limit is located much more toward the lean combustion side.

These results confirmed that the improvements made to the PPL-2 combustor would achieve the required specifications, provided that the engine attained the combustor inlet air temperature as planned.

Measure against carbon deposits (2)

In the course of developing the engine it was found that a larger fuel quantity than the planned fuel flow rate was required in nrder to achieve the rated nperating conditions. Among other factors, that requirement stemmed from the effect of heat Insses that occurred from the engine.

Specifically, it was necessary to operate the engine on a richer air-fuel mixture of less than A/F = 70 in the high load region above 90% load in order to attain a turbine inlet temperature, TiT, of 1350°C. As a result, it was necessary to take some other measure to prevent carbon deposits.

It was evident that the effect of localized mixture dilution at

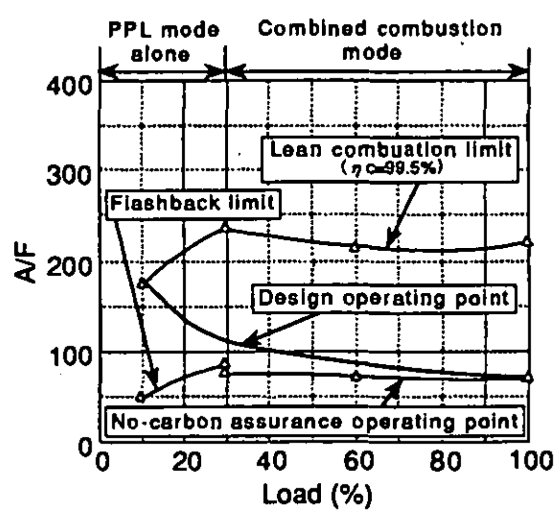

Fig. 8 Stable combustion range of the improved PPL-2 combustor

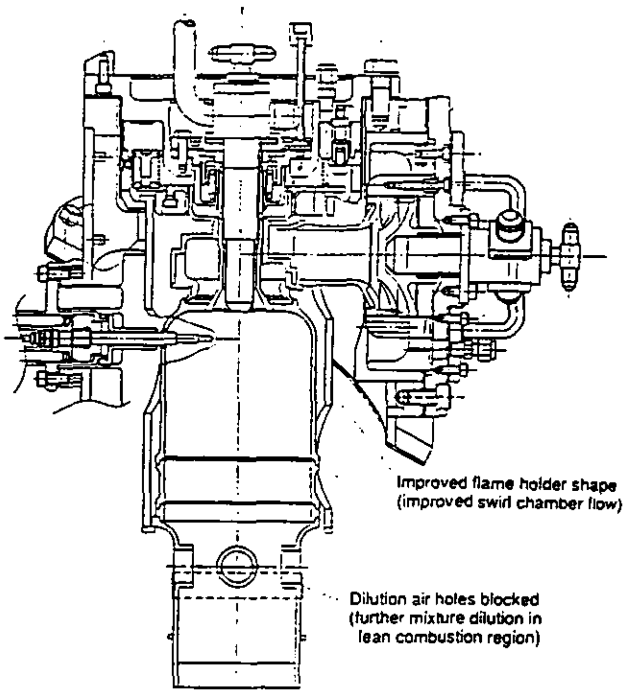

Figure 9 Construction of the A/F=60 type PPL-2 combustor

the downstream end of the flame holder was limited. Therefore, it was decided to further dilute the mixture in the lean combustion region by increasing the air distribution ratio in that region. Additionally, the fuel supply distribution between the two fuel injection nozzles was optimized for the combined combustion mode. That was done by reducing the ratio of fuel supplied from the fuel injection nozzle for diffusion combustion, which was observed to have a large effect on carbon deposit formation, and by increasing the

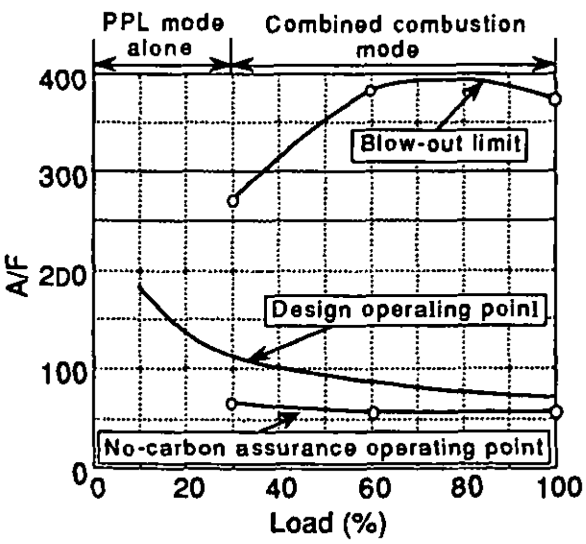

Figure 10 Stable combustion range
of the A/F=60 type PPL-2 combustor

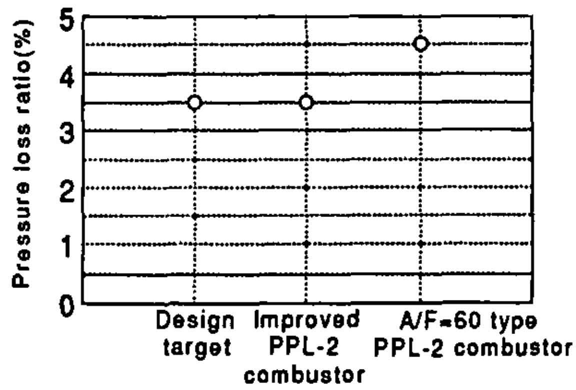

Figure 11 Comparision of pressure loss ratio

ratio of fuel supplied from the fuel injection nozzle for PPL combustinn.

Further dilution of the mixture in the lean combustion region was accomplished by blocking some of the air introduction holes in the dilution region. The measures explained earlier for improving the flashback characteristic also worked to improve this characteristic under high load conditions, allowing the fuel supply distribution for the combined combustion mode to be optimized.

Figure 9 illustrates the constructinn of the A/F=60-type PPL-2 combustor incorporating these improvements, and Figure 10 shows its stable combustion range. It is seen that the carbon-free performance of this combustor was improved in the medium to high load region. These measures to prevent carbon deposits made it possible to operate the engine at A/F=60 in the high load region above 90%, thereby achieving a turbine inlet temperature, TiT, of 1350°C with the present engine specifications. Although lean combustion stability was confirmed only in the load region above 30%, it was observed that there was a sufficient margin relative to the design operating point.

Pressure loss ratio of combustor

Figure 11 compares the pressure loss ratios of the improved PPL-2 combustor and the A/F=60-type PPL-2 combustor. As a result of the measures adopted to prevent carbon deposits under a high toad condition with the aim of obtaining a turbine inlet temperature, TiT, of 1350°C, the pressure loss ratio of the A/F=60-type combustor deteriorated by approximately 20% (1 percentage point) from the target value.

In future work, efforts will be made to improve the performance of the PPL combustor further, focusing on improvement of the flashback characteristic.

CONCLUSION

The flashback characteristic of the PPL combustor was improved by improving the mixture flow in the prevaporization region, making it possible to expand the stable combustion range.

Transient emission tests conducted on the PPL combustor alone using a high-response exhaust gas analyzer indicated that the same level of emission performance was obtained as under steady-state operation. This result suggests that it should be possible to meet Japan's 10-15 mode emission standards including transient operation.

The tendency for carbon deposits to form in the combustor under high load operation at a turbine inlet temperature, TiT, of 1350°C was substantially improved.

In future work, transient emission performance will be measured using an actual CGT engine to verify compliance with the 10-15 mode emission standards, and further efforts will be made to improve the performance of the PPL combustor.

REFERENCES

[1] Sasaki,M., Kumakura,H., Suzuki,D., "Low Nox Combustor for Automotive Ceramic Gas Turbine -- Conceptual design", ASME Paper 91-GT-369.

[2] Kumakura,H., Sasaki,M., Suzuki,D., Ichikawa,H., "Development of a low-emission combustor for a 100 kW Automotive ceramic gas turbine (II)", ASME Paper 94-GT-33.

[3] Sasaki,M., Kumakura,H., Suzuki,D., Ichikawa,H., Ohkubo,Y., Yoshida,Y., "Development of a low-emission combustor for a 100 kW Automotive ceramic gas turbine (III)", ASME Paper 96-GT-119.

[4] Sasaki,M., Kumakura,H., Suzuki,D., Sugiyama,K., Ohkubo,Y., "Development of a low-emission combustor for a 100 kW Automotive ceramic gas turbine (I)", ASME Paper 93-GT-63.

[5] Sasaki,M., Kumakura,H., Suzuki,D., Ichikawa,H.,"Development of a low-emission combustor for a 100 kW Automotive ceramic gas turbine", Yokohama International Gas Turbine Congress, 1995.