The Development of LPP Combustor for ESPR

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Abstract

An axially staged combustor equipped with an LPP combustion system and CMC liner walls has been investigated for stable combustion and low NOx emissions for the ESPR project.

Several fuel injectors were designed and manufactured for the LPP burner, and single sector combustor tests were conducted to evaluate fundamental combustion characteristics such as emissions, instabilities, auto-ignition, and flash back at typical operating conditions from idle to Mn 2.2 cruise.

The latest test results showed that the LPP burner had a good potential for the low NOx target. It was also found that the NOx emission level was greatly affected by a distortion in the air flow velocity field upstream of the LPP burner due to the diffuser and fuel feed arm.

The CMC material was investigated to apply for the high temperature and low NOx combustor. Annular combustor liner walls were manufactured with the CMC material, and they have been tested at low pressure conditions to evaluate the soundness of the material and the mounting and seal system.

This paper reports the latest research activities on the LPP combustion system and CMC liner walls for the ESPR project.

Introduction

The research and development of a low emission combustor for a Mn 2.2 supersonic aircraft engine has been undertaken under ESPR (Research and Development of Environmentally Compatible Propulsion System for Next-Generation Supersonic Transport) project in Japan. Supersonic aircraft are supposed to cruise in the stratosphere during supersonic flight, hence the effect of NOx emissions from the aircraft to ozone layer is concerned. NASA (National Aeronautics and Space Administration) reports that the NOx emissions exhausted from super sonic aircraft should be less than 5EI at cruise conditions to minimize the ozone layer destruction in the stratosphere [1]. Therefore, 5EI of NOx emissions is set as the major goal of the combustor development in the ESPR. This goal of 5EI.NOx is a challenging target to achieve for a combustor of an inlet and exit temperature of as high as 915 K and 1923K, respectively and the goal corresponds to 1/7 of the level predicted for a conventional combustion technology with a diffusion flame.

Fig. 1 shows the engine being studied in the ESPR. An LPP combustion system is considered to be one of the best key technologies to achieve very low NOx emissions. And the use of advanced heat resistance materials of CMC for high temperature combustion liners has a benefit for LPP combustion system due to less air necessary for liner wall cooling. Hence, an axially staged combustor with a combination of an LPP combustion system and CMC liner walls is investigated for the ESPR combustor (Fig. 2). This LPP low NOx combustion system has been being developed in collaboration among JAXA (Japan Aerospace Exploration Agency), Rolls Royce and KHI in this program.

LPP Combustion System Development

A flowchart of the R&D plan is shown in Fig. 3. Sequential phases in the development flow were planed and many tests have been executed in each phase. NOx emissions exponentially increase with combustion gas temperatures, therefore combustion regions must be kept under a certain mean temperature level without locally high temperature regions to suppress them. This can be achieved by lean premixed, pre-vaporized and uniform mixture produced by good LPP burners. For the sake of suitable mixture, LPP burners are to be developed through burner and single sector test to assess the potential for low NOx, non auto-ignition, and non-flashback firstly. Then multi sector combustion tests follow to assess other combustion characteristics such as light across, combustion instability and temperature traverse. Finally, a high pressure full annular combustor test follows for the purpose of evaluation and verification of the LPP combustion performance, such as emissions, auto ignition, flash back, light across, and combustion instability along the engine operation line being studied in the ESPR project. This main test is coming up in the final year of the program, this year.

Up until now, burner combustion tests and single sector combustor tests have been conducted up to M2.2 conditions to evaluate fundamental characteristics. The latest test results showed that the LPP burners had a good potential for the NOx target and that NOx emission level was greatly affected by a distortion in the air flow velocity field upstream of the LPP burners due to the diffuser, fuel feed arm and so on.

Combustor Design

The ESPR LPP staged combustor is shown in Fig.2. The main features are,

/ an axially staged combustor

/ LPP & diffusion hybrid pilot burners (16 off)

/ LPP main burners (16 off)

/ a bifurcated diffuser.

The combustor dimensions have been determined to be able to install the combustor into the existing HYPR HTCE demonstrator engine.

Combustion Test Results

Firstly, fundamental burner combustion tests were conducted to evaluate burner potential itself with the unit shown in Fig. 4, and it had no diffuser and fuel feed arm that should exist in actual engines. Following the fundamental burner tests, in order to assess emission characteristics in an engine, tests have been done with the combustor unit illustrated in Fig. 5 simulating a general engine configuration. The combustor had a diffuser, a robust feed arm to withstand a vibration when an engine is in operation. Either test was done at typical operating conditions from idle to Mn 2.2 cruise of ESPR engine at the high-temperature and high-pressure test facility of JAXA. Both units are 1/16 models of the full annular combustor.

The material of the liner walls was not CMC but heat resistant metal of HA188. The cooling scheme is a transpiration type. The amount of cooling air is 18% based on an airflow measurement. Firebrick is used for the sidewalls of the unit.

Burner potential assessment

Figure 6 shows NOx and combustion efficiency obtained for the unit shown in Fig. 4 at Mn2.2 cruise inlet pressure and temperature conditions as a parameter of primary AFR. The fuel split into the main, pilot LPP, and pilot diffusion was kept the same through the tests and the split was examined to minimize NOx emission at the specified AFR at Mn2.2 conditions. The results show NOx emission of 3.8 EI at the primary AFR of 25.4 based on 18% cooling air in this unit (AFR25.4=AFR31 x (1-0.18)). Considering that the test was performed with metal walls that need a certain amount of cooling air, the burners tested had a good NOx potential to achieve the target. Combustion efficiency was very close to 100% and there was no sign of flash back or auto ignition.

Single sector test results

Although the good burner potential has been acquired through the burner tests described the above, combustion characteristics in an engine combustor can be sensitive to flow field near the burner inlet such as an air velocity distribution caused by diffuser, and wakes from objects upstream of burners. Those flow distortions make the fuel/air mixing property worse and also induce undesirable flow fields in the pre-mixer duct for prevailing against flash back and auto ignition.

The tests have been done with the combsutor unit with a bifurcated diffuser and a pilot burner fuel feed arm (30mm diameter) just upstream of the main burners shown in Fig. 5. Figure 7 shows NOx emission characteristics as a parameter of primary AFR. The fuel split into main, pilot LPP and pilot diffusion was determined in the same manner as stated above. At M2.2 cruise conditions (AFR=25.4), it gave 16EI NOx which was much higher than that in the "clean" combustor described above that has no diffuser and no feed arm fitted. The flow field just upstream of the burners seemed to have a great impact on NOx emission characteristics, thus a great care should be taken to design a suitable flow field in front of burners.

The causes that made NOx emissions worse had been investigated. Figure 8 shows the NOx emission characteristics without the diffuser tested in the same condition as Fig. 7. Based on the result, the NOx level had not changed much or it was slightly lower with the diffuser. The air flow distortion caused by the diffuser was supposed to give a worse mixing property in terms of uniformity in radial direction, hence it created less homogeneous flame temperature region in the primary combustion zone. On the other hand, the total air feed into the burners gave more air going through the burner and that result in lower flame temperature in average. In this test, these two effects on NOx emission were supposed to cancel each other and that result in the similar NOx value.

Figure 9 shows NOx emission level tested in the combustor with a reduced pilot feed arm. The diameter of feed arm was originally 30 mm and in this test the parts simulating the arm was removed. Only thin fuel feed pipes (about 6mm) were exposed and they were located at just upstream of the main burner. The emission at 25.4 AFR went down from 16EI to 9EI NOx. The wakes from the objects just upstream of main burner was supposed to have a great effect on NOx value. When the diffuser and the feed arm simulating parts were removed, the combustor configuration became very similar. The specifications of swirl vanes and fuel injection holes were identical between two models except for fuel feed pipe arrangements. But comparing the test results shown in Fig. 6 and Fig. 9, there still seemed to have a big difference between two models. The causes for the difference are now under investigation.

Countermeasures to Achieve the Target

The following three items were to be considered for a further NOx reduction toward the target.

(1) Minimize wake affections to main burners

As already mentioned above, the wakes from the objects, especially the pilot feed arm, located upstream of burners had a great impact on NOx emission level. To minimize wake generation just upstream of the mains, a "Dog leg " feed arm shown in Fig. 10 was planned to employ to the combustor. With the "Dog leg" feed arm, it was expected that NOx will goes down to 9EI as shown in Fig. 11.

(2) Cooling air reduction

CMC material was originally planned to install into the full annular combustor test for the final assessment. Due to its strength problem, however, metal liner walls combustor was to be used instead of CMC walls. A shallow angled effusion-cooling scheme was employed for the metal liner due to its potential of the cooling effectiveness as tentative liner walls.

The liner was 3 mm thick with heat resistant material (C263) and effusion holes were 0.6mm in diameter with the angle of 17degree. Thermal paint tests (OG-6 Thermindix) had been done for this combustor with the effusion holes in the range of 0.54% - 1.0 % porosity at Mn2.2 cruise condition. The result indicated that the amount of cooing air from liner walls and heatsheild could be reduced to 12% in total. The metal liner currently used for the single sector unit had a transpiration-cooling scheme with 18% cooling air. Hence, if the cooling air was reduced from 18% to 12% and 9%, the NOx value was expected to go down to about 5EI and 4EI from 9EI respectively as shown in Fig.11. Based on the temperature distribution in the liners acquired through the thermal paint tests, the hole arrangement for each region is now being optimized.

(3) Further improvement in burners.

Several promising options to improve mixing of fuel and air were considered for the pilot burner. There were three main modifications in the pilot burners.

Firstly, the shape of swirl vanes was modified. The current swirl vane of the pilot burner was not parallel to the airflow at the inlet edge. This vane shape might cause a flow separation at the inlet edge of the vanes due to a sharp change in flow angle and therefore the wakes generated at the edge were possible to make mixing worse and induce flashback in the premixed duct. Hence, curved vanes were going to be employed to improve the mixing property.

Secondary, the number of the fuel injection holes was planned to reduce with the same hole diameter for the purpose of increasing the fuel feed pressure. Fuel would have a larger momentum and could even reach the outer region of the premixing duct. This modification was expected to improve mixing property in the entire premixing duct.

Thirdly, an atomizing lip was removed in the premixing duct. The purpose of this modification was the same as the second modification. By the deletion of the lip, fuel could reach further outer region in the premixing duct and that was expected to have more homogeneous mixing.

Latest Results and Future Plan

For the sake to achieve the 5EI target at Mn2.2 cruise conditions, currently the "Dog leg" feed arm, new burners and liner walls with reduced cooling air mentioned above were designed and manufactured for the single sector combustor unit. High pressure tests were performed at JAXA test facility to finalize the specifications of LPP low NOx burners. Figure 12 shows the latest results of the single sector tests. The cooling air was set as 9% for the combustor unit. 2.2EI NOx was successfully obtained at Mn2.2 cruise condition due to the countermeasures mentioned above. Combustion efficiency was of course almost 100% at the condition.

Multi sector tests were planned up to 0.6 MPa pressure condition at Mn2.2 inlet temperature of 915K at KHI test facility. The tests were planned to start after the burner specifications were determined in the single sector tests. Combustion instability is one of the characteristics of an LPP combustion system that may cause a serious damage to any combustor parts. The multi sector unit had a Helmholtz resonator system to damp the combustion instability in case it happens. The resonator chamber volume was designed to dump the magnitude of instability at a typical possible frequency for this size of ESPR combustor. The unit also has flashback detection sensors at the main burners to detect the likelihood of flashback especially when the combustor condition was not steady such as light across. The aim of these multi sector tests was to evaluate combustor characteristics that were not able to assess at the single sector unit such as light across, start ignition, temperature traverse and staging. And the second objective was to do a functional check on the resonator system and flashback sensors in advance for the preparation of the high-pressure full annular combustor tests at Rolls Royce. This multi sector tests have been finished and the data are analyzing now.

A full annular combustor test is planned at the end of February at Rolls Royce, Derby plant for the final assessment of the low NOx combustion system. Test specifications and procedure are currently discussed among JAXA, KHI and Rolls Royce and the test unit has been being prepared.

CMC Combustor Liner Development

CMC material has superior heat resistant properties than existing Nickel-based or Cobalt-based super-alloys which are conventionally used for a combustor liner of engine. The CMC material can be used at the temperature range more than 1000 deg C at which the existing metal material can not withstand. Therefore, CMC liner walls are expected to reduce cooling air significantly and that would lead to Low

NOx emission due to a lower flame temperature on LPP combustion.

Establishment of design and manufacturing technology for large size CMC combustir liner wall, improvement of CMC liner walls integrity, and the development of liner mounting system have been executed in ESPR project. Figure 13 shows ESPR combustor liner, outer liner walls and inner liner walls, and Fig. 14 shows the photograph of outer liner after cyclic test.

Acknowledgement

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References

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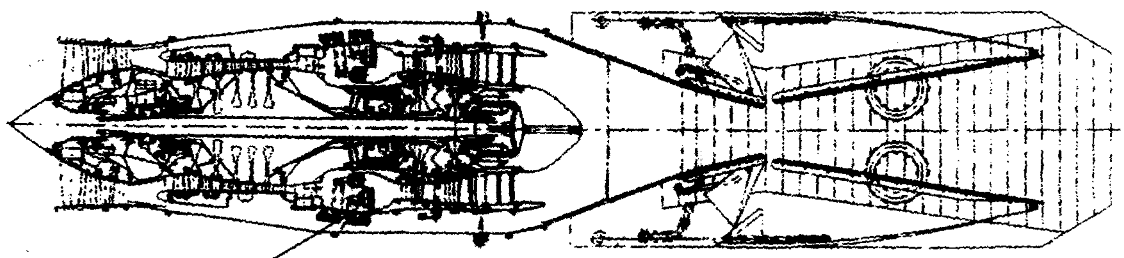
Nonenclature

CMC : Ceramics Matrix Composite
EI : Emission index g/kg fuel
FAR : Fuel Air Ratio
LPP : Lean Premixed Pre-vaporized
Mn : Mach number
P_3 : Combustor inlet air pressure MPa
T_3 : Combustor inlet air temperature K
T_4 : Mean combustor exit gas temperature K
W_{31} : Combustor inlet air flow rate kg/s



Axially staged LPP Combustor

Figure .1 ESPR Target Engine (Draft)

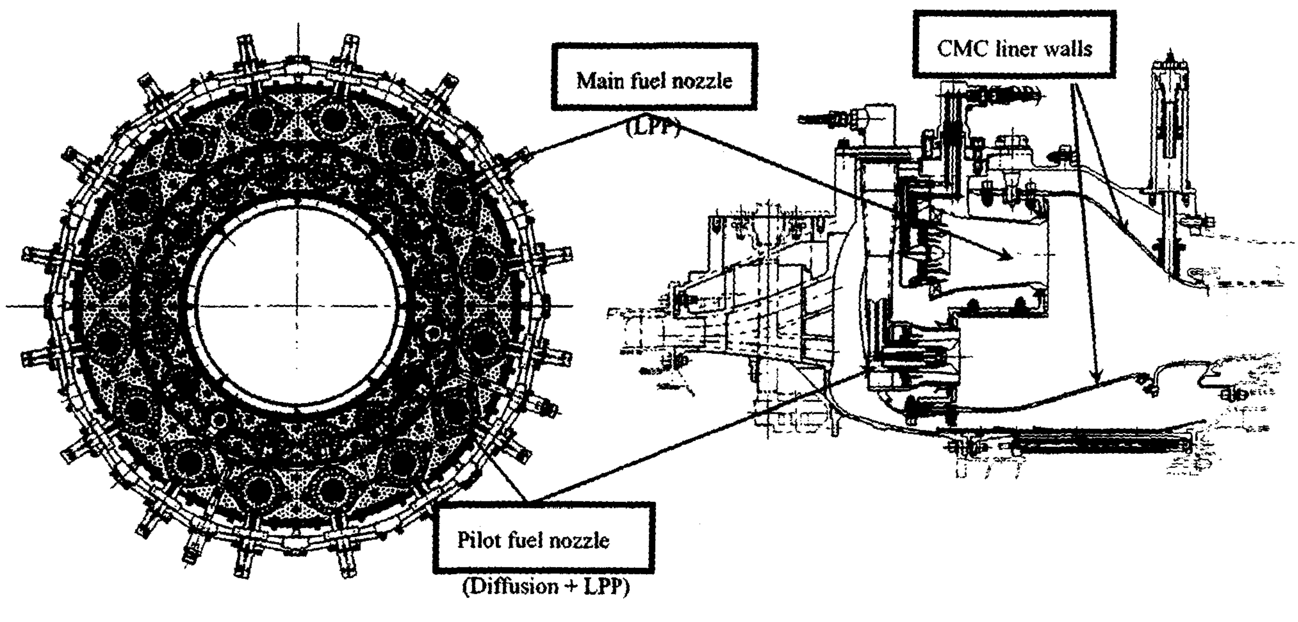


Fig.2 ESPR axially staged combustor

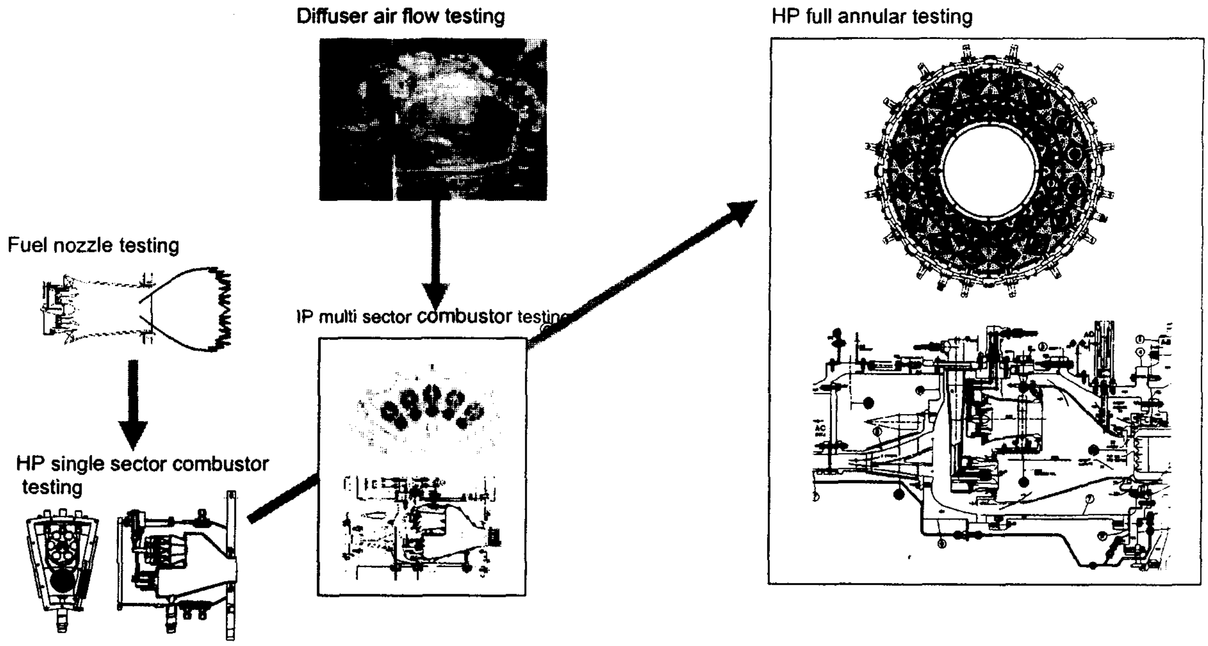


Fig.3 Research & Development plan

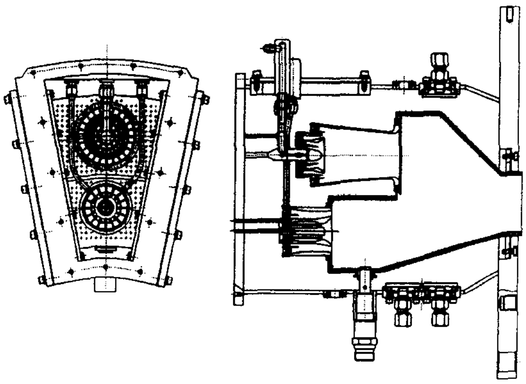


Fig.4 Single sector combustor test unit (Without diffuser and feed arm)

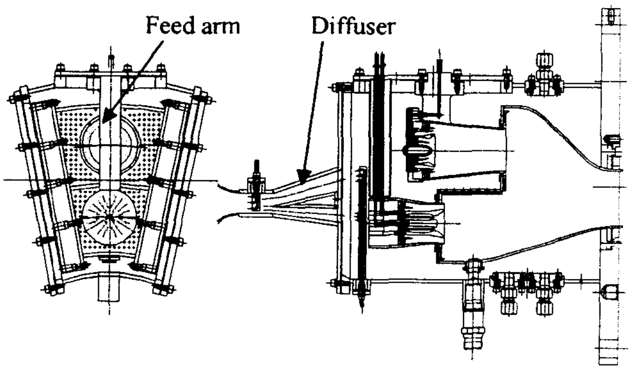


Fig.5 Single sector combustor test unit

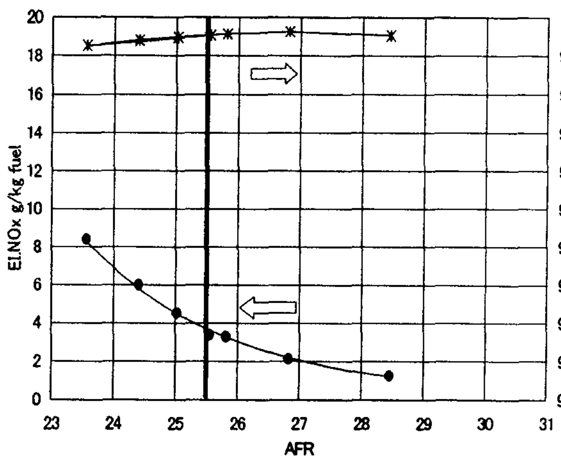


Fig.6 NOx and Combustion efficiency

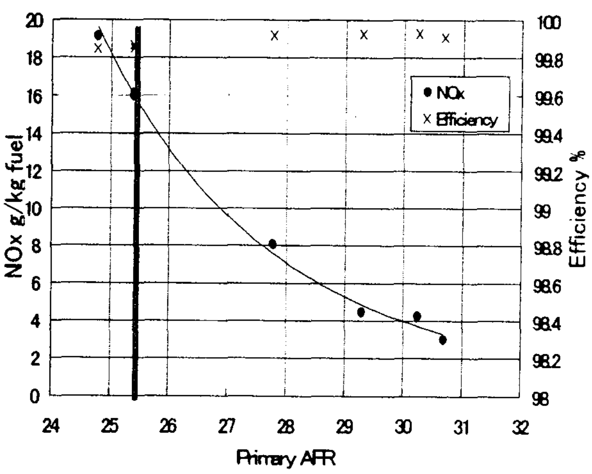


Fig.7 NOx emission and combustion efficiency (Engine simulated combustor)

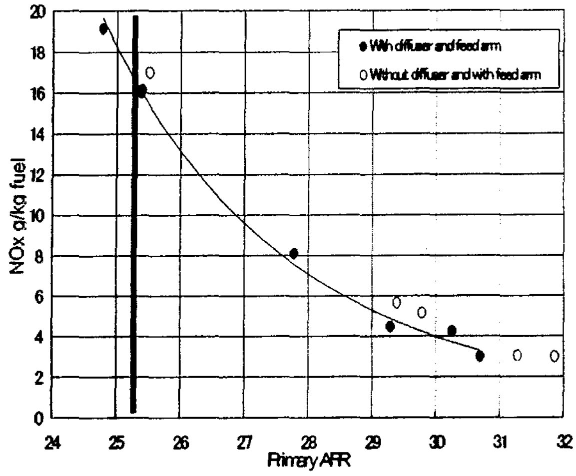


Fig.8 NOx emission comparison between the units with & without diffuser

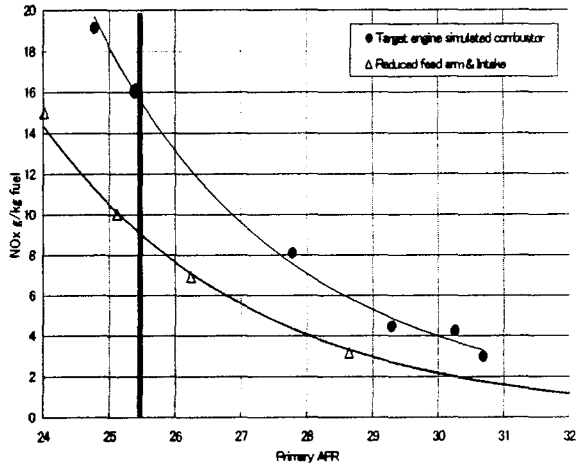
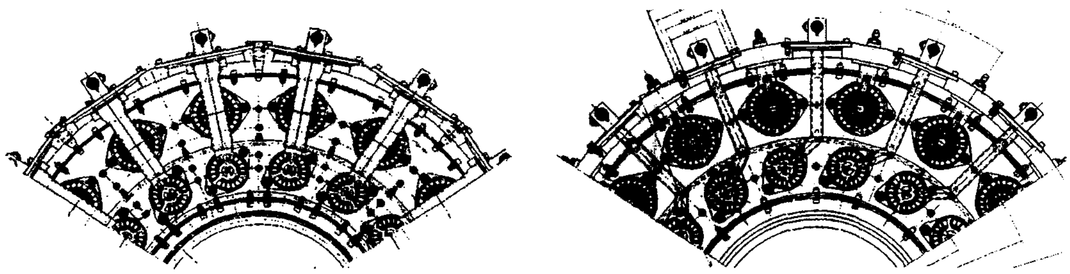


Fig.9 NOx emission comparison between the units with & without feed arm



Original

"Dog leg" configuration

Fig.10 Original feed arm configuration and "Dog leg" feed arm configuration

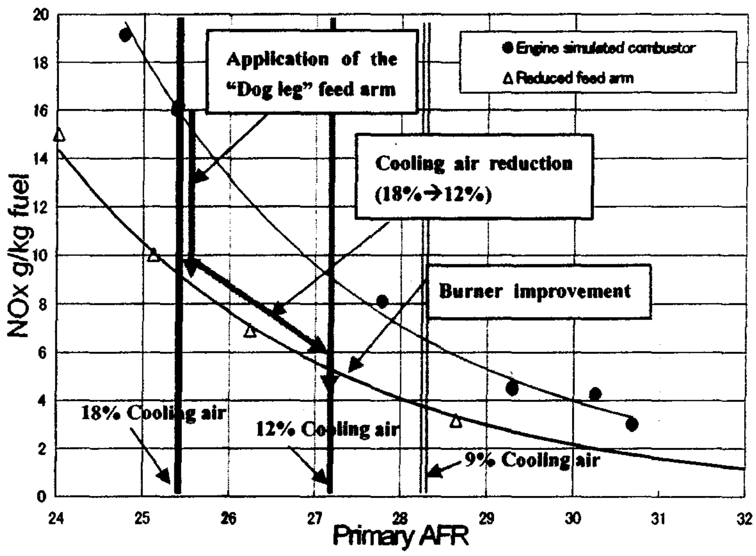


Fig.11 Countermeasures for futher NOx reduction plan

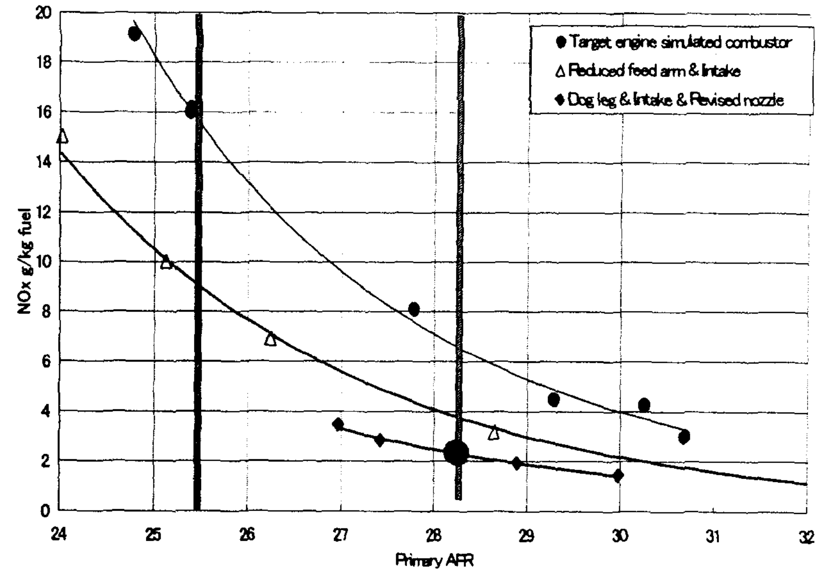


Fig.12 Latest single sector tests results

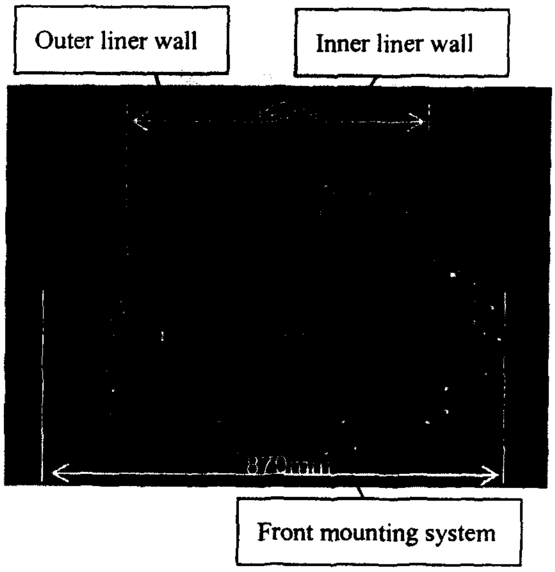


Fig.13 Photograph of CMC liner walls

Fig.14 CMC liner after cyclic test (300 cycle)