DEVELOPMENT OF FULL ANNULAR COMBUSTOR FOR SMALL AIRCRAFT JET ENGINE IN JAXA TECHCLEAN PROJECT

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Abstract

In the TechCLEAN project of JAXA, experimental research has been being conducted to develop a combustor for a small aircraft engine. The combustor was tuned to show the behavior of the Rich-Lean combustion through tests under atmospheric and practical conditions. In parallel, an experimental facility to test full annular combustors under practical conditions was newly constructed in the spring of 2007. Through full annular combustion experiments under practical conditions, the combustors were tuned to show good combustion performance. The optimized full annular combustor finally achieved the reduction of NOx emissions to lower than 40% of the ICAO CAEP4 standard, also maintaining low CO and THC emissions and showing good exit temperature profiles and good lean blow-out performance. The process of development and optimization of the combustor is discussed in this report.

1 INTRODUCTION

In general, small and medium power aircraft engines must simultaneously satisfy several requirements, for example, high efficiency, environmental friendliness and cost effectiveness [1]. In April 2003, the New Energy and Industrial Technology Development Organization (NEDO) in Japan started a project "Research and development for an environment-friendly small aircraft engine" (so-called ECO engine) [2] to develop the technology to commercialize the next generation engines for affordable and environment-friendly small aircraft (approximately 50-passengers). The designed thrust of the engine is about 4kN and the pressure ratio is about 20. In October 2003, the Japan Aerospace Exploration Agency (JAXA) also started a project "Technology development project for clean engines" (so-called TechCLEAN project), in which research to develop advanced combustion technology was conducted aiming to reduce toxic exhaust gas components, especially NOx, from aero engine combustors. In the framework of the TechCLEAN project, JAXA has been supporting the ECO engine project and also developing an aero engine combustor of its own design. This combustor should satisfy specifications required for the ECO engine combustor, that is, reduce NOx emissions lower than 50% of the ICAO CAEP4 standard, aiming to precede the trend of NOx emissions shown in Fig.1. And also reduce CO and unburned THC emissions to those of 90% and ensure basic performance of aero engine combustors, such as ignition and blowout performance. The level of NOx emissions value achieved in this research is also shown in Fig.1

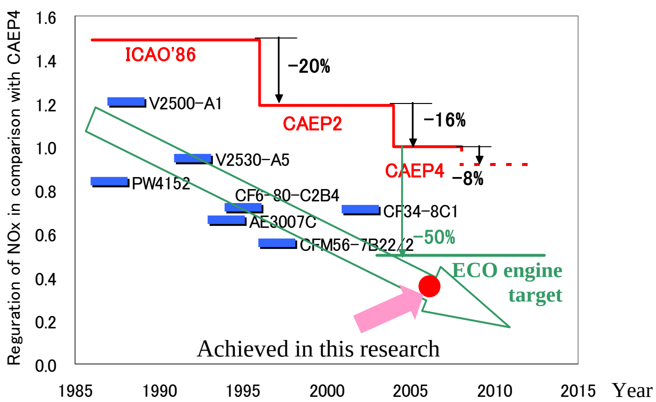


Fig. 1. Comparison of target and achieved level of NOx reduction with ICAO standards.

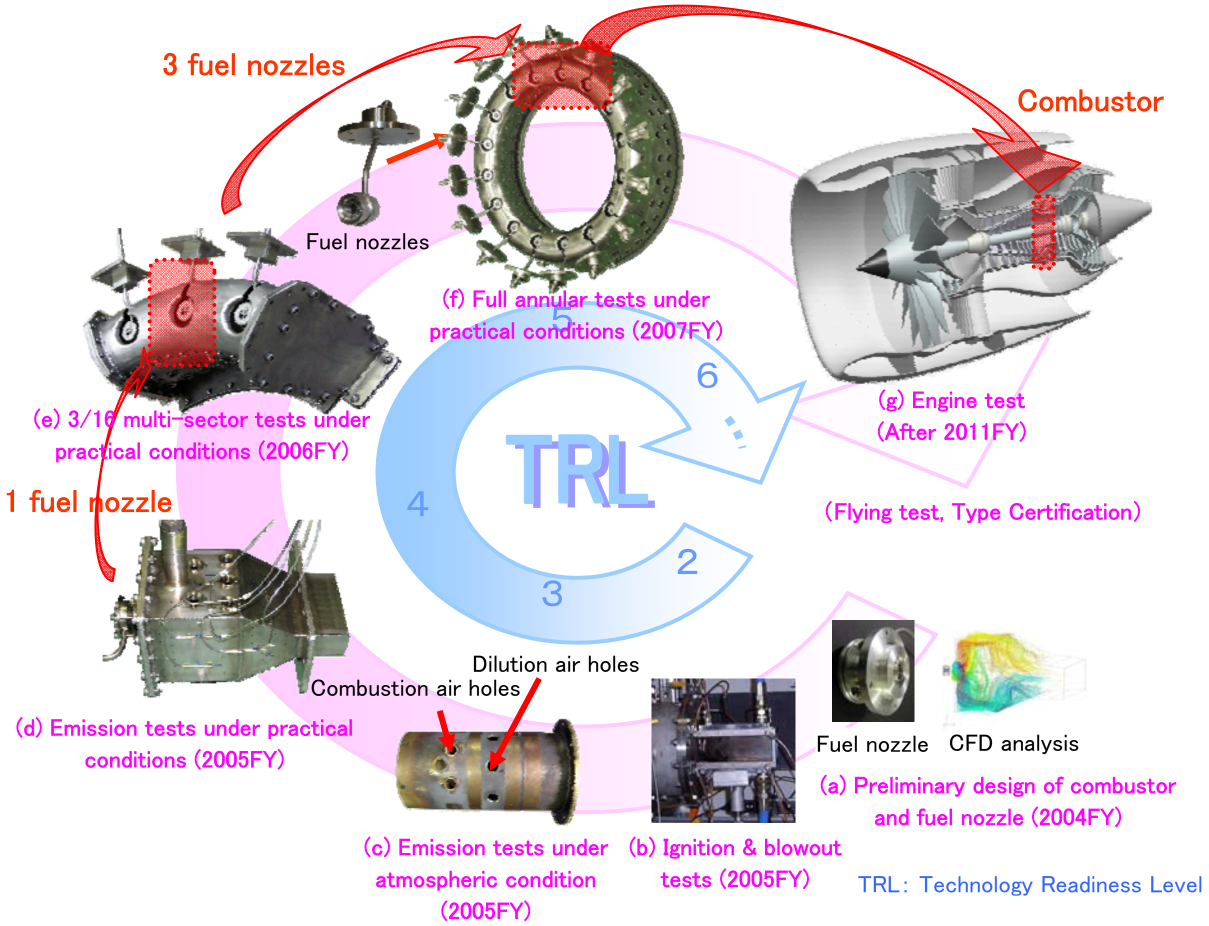


Fig. 2. Overview of development process of small aircraft combustor conducted in TechCLEAN project.

2 Development Process up to Multi-sector Combustor

2.1 Preliminary Design of Combustor

Figure 2 shows an overview of the development process of our combustor. Throughout this process, liquid kerosene was used as the fuel for combustion tests. The stages from (a) to (e) in Fig.2 were already discussed in previous reports [3,4], but to make smooth introduction to the full annular combustor tests, some discussions related to the design concept of the combustor and brief review of each stage are presented here. Figure.3 shows a cross-sectional drawing of the combustor with description explaining the preliminary design concept. Since one of the targets of this engine is to reduce the direct operating cost (DOC), the engine should be lightweight and simply structured. So the combustor is confined into a small space, and its fuel supply system is also required to be simple. While the reduction of NOx emissions is also required with high combustion efficiency over a wide range of operating conditions [5]. The overall equivalence ratio of the combustor varies from 0.10 (at the idle condition) to 0.35 (at the full load condition). To ensure ignition and blowout performance under the idle

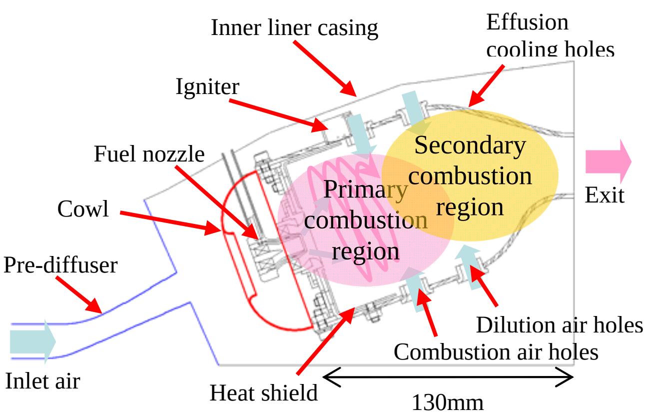


Fig. 3. Schematic cross-sectional drawing of target combustor with description of design concept.

Table 1. Comparison of emission summation in ICAO LTO cycle among SSU, MSU, FA combustors and target level in percentage figures of ICAO CAEP4 standard.

	NOx	THC	CO
Target	50.0%	90.0%	90.0%
SSU1	44.3%	92.9%	37.8%
MSU1	43.6%	168.5%	87.2%
MSU2	40.9%	3.5%	54.6%
FA1-1	45.3%	11.0%	57.0%
FA1-2	38.1%	16.3%	60.1%

condition, the local equivalence ratio in the primary combustion region should be in the vicinity of 1.0, so the amount of the air flow from the fuel nozzle should be about 10% of the total air flow. This means that the summation of combustion, dilution and cooling air should be 90% of the total air flow. Yet at the take-off condition, this air flow ratio makes the local equivalence ratio in the primary combustion region approach 3.0, which means a very fuel rich combustion condition. Even under this condition, sufficient combustion efficiency and low NOx emissions are required simultaneously. To satisfy these requirements, the Rich-Lean combustion approach [6] was utilized for this combustor. Because, as mentioned before, we should choose a simple and cost effective fuel nozzle for this combustor, we applied the concept of single fuel supplied airblast type nozzle proposed by Parker-Hannifin [7].

In the combustor concept mentioned above, two factors should play significant rolls; the enhanced mixing in the primary combustion region, and the tuning of the air mass flow ratio among the fuel nozzle, the primary and secondary combustion regions and the wall cooling. A lot of research has been done on these factors [8-14], and also in our research, large portion of effort has been concentrated on them.

2.2 Combustion Tests by Single-sector Combustors

In the following atmospheric tests, rectangular (Fig.2b) and tubular (Fig.2c) combustors which correspond to 1/16 region of the target annular combustor (which has 16 fuel nozzles) were tested. It aimed to assure the basic performance

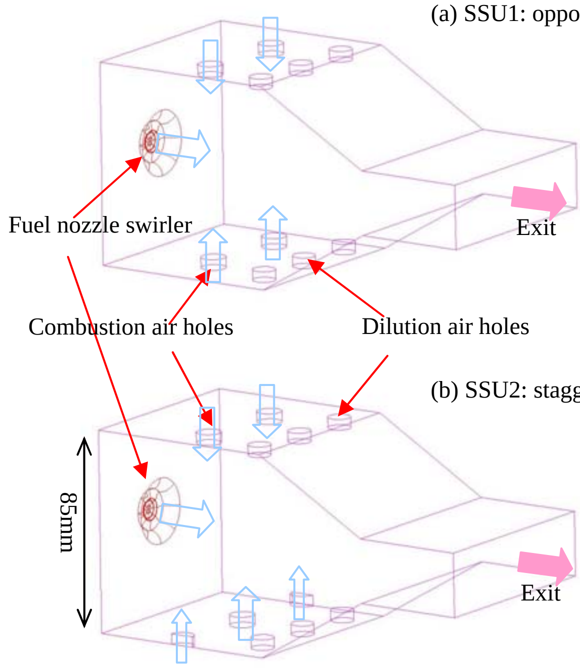


Fig.4. Schematic drawing of configuration comparison between two rectangular single-sector combustors SSU1 and SSU2.

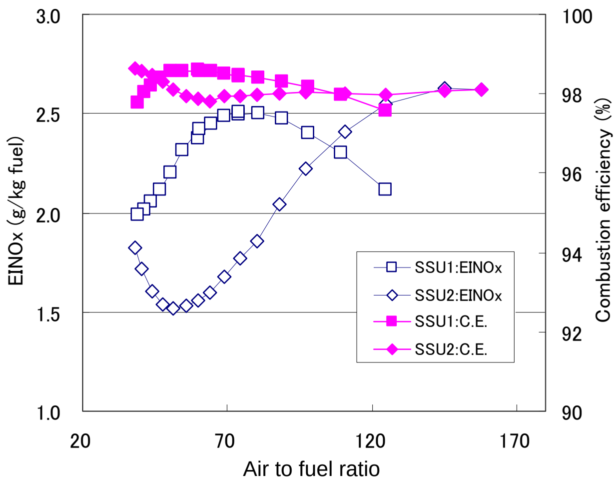
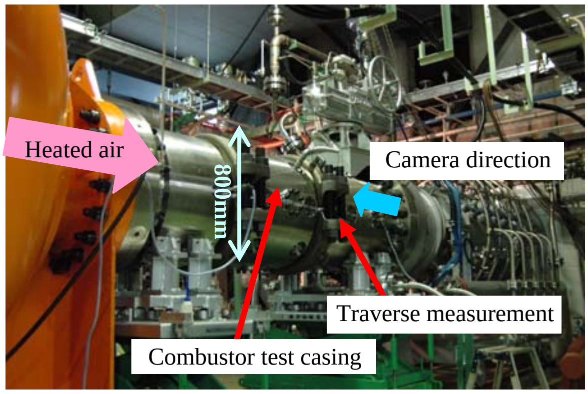


Fig.5. Emission characteristics of rectangular single-sector combustors SSU1 and SSU2 under atmospheric condition (open symbols: EINOx, solid symbols: combustion efficiency).

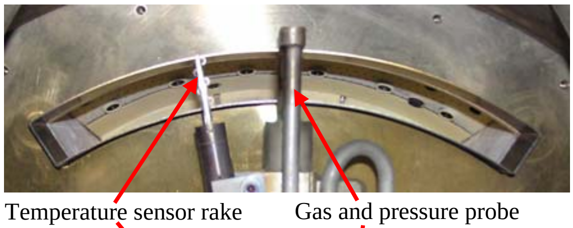
required for the aeroengine combustors, ignition and LBO (Lean Blowout), by selecting positions of igniter and air holes. And the air mass flow ratio was tuned to show the Rich-Lean behavior, that is, reducing NOx emissions at low AFR (Air to Fuel Ratio) condition, also sustaining high combustion efficiency. For these tuning, emission tests with tubular combustors were conducted for more than 20 cases with different air hole locations and sizes.

Based on the air mass flow ratio designed through the preceding atmospheric tests, rectangular single-sector combustors were designed as shown in Fig.2d, which also correspond to 1/16 region of the target combustor. To compare emission results with the ICAO CAEP4 standard, combustion tests were conducted under the inlet temperature, pressure and mass flow rate which were set to simulate the operating conditions corresponding to the ICAO LTO (Landing and Take-Off) cycle; 7%, 30%, 85% and 100% thrust of MTO (Max Take-Off) design points of the target engine. In Table 1, the row of SSU (Single Sector Unit) shows the summation of emissions measured at each design point of the LTO cycle, shown in percentage figures of the ICAO CAEP4 standard. The level of NOx emissions was reduced to 44.3% of the ICAO CAEP4 standard and achieved the emission target, while the THC level exceeded the target slightly. It was caused by insufficient combustion efficiency at the 7%MTO condition. Thus for the design of following multi-sector combustors MSU (Multi-Sector Unit), the air mass flow ratio was tuned to promote the combustion of unburned fuel. On the other hand, two types of combustion air hole arrangements were applied for the SSU combustors as shown in Fig.4; (a) SSU1 with opposing arrangement and (b) SSU2 with staggered arrangement. Emission tests were conducted for both the SSU1 and SSU2 combustors under atmospheric conditions (with pressure loss 3.2% and inlet temperature 500K). Figure 5 shows NOx emissions and combustion efficiency of SSU1 and SSU2. EINOx means the emission index of NOx, that is, grams of NOx emitted per 1kg fuel, and the combustion efficiency is calculated from the analyzed gas concentration. As shown in this graph, for both combustors, NOx emissions were reduced in the low AFR (<70) range successfully, which is one of the advantages of the Rich-Lean combustion. And the SSU2 combustor showed a more rapid reduction of NOx in the low AFR range, even the combustion efficiency was sustained.

2.3 Combustion Tests by Multi-sector Combustors



(a) Photograph of "High-Temperature and Pressure Combustion Test Facility."



(b) Temperature sensor rake and gas sampling probe traverse measurement system at combustor exit.

(c) Photo image of traverse measurement in combustion test under 7%MTO condition.

Fig.6. Testing setup for multi-sector combustor under practical conditions.

Following the results of the tubular and rectangular single-sector combustor tests, multi-sector combustors MSU were designed, simulating 3/16 region of the target combustor with three fuel nozzles.

Combustion tests of MSU were conducted under the practical conditions using the "High-Temperature and Pressure Combustion Test Facility" which was developed by JAXA in 2005. Figure 6a shows the testing setup with the facility. The multi-sector combustors were put into the combustor inner liner casing with the pre-diffuser passage, and they were set into a high pressure combustor test casing. The inlet air conditions were set to 0.3-2.0MPa pressure, 400-700K temperature and 0.8-3kg/s air mass flow rate, according to the ICAO LTO cycle; 7%, 30%, 85% and 100% thrust of MTO (Max

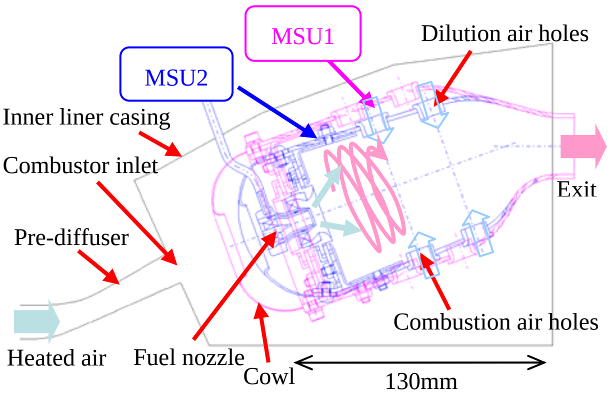
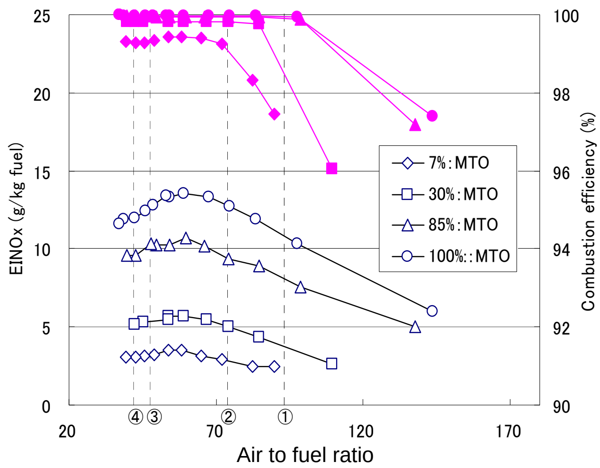
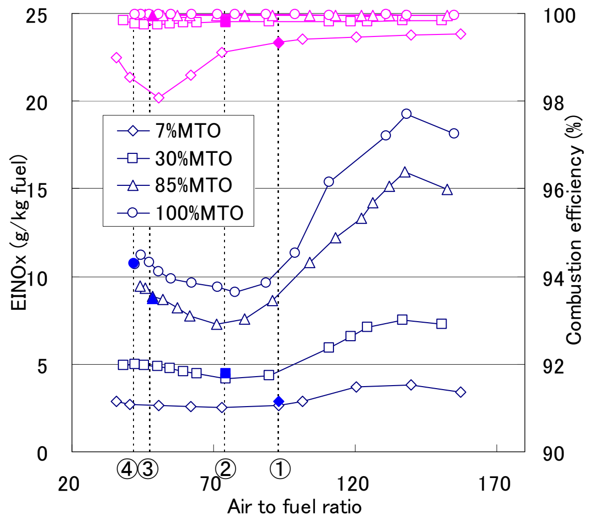


Fig.7. Schematic drawing of configuration comparison between two 3/16 multi-sector combustors MSU1 and MSU2.



(a) Emission characteristics of MSU1.



(b) Emission characteristics of MSU2.

Fig.8. Emission characteristics of multi-sector combustors MSU1 and MSU2 (open symbols: EINOx, solid symbols: combustion efficiency).

Take-Off) design points of the target engine. Exhaust gas, temperature and pressure distributions at the combustor exit were measured by a traversable five points collective hot-water-cooled sampling probe and a temperature sensor rake with five sensor points, located just below the combustor exit. Figure 6b shows the temperature sensor rake and the gas sampling probe. The sampled gas was led through the heated sampling line to the gas-analyzer HORIBA MEXA-7100D which measured the concentrations of CO, CO2, HC (as CH4), NO, and NOx by standard gas analysis procedures: chemiluminescence for NO, nondispersive infrared absorption for CO and CO2, flame ionization for HC, and paramagnetic analysis for O2. Soot was also measured by the "Bacharach True Spot Smoke Test Kit". The gas sampling procedure was based on the standard of the ICAO [15]. Furthermore, combustion behavior was observed by a direct monitoring system consisting of a CCD camera through a periscope downstream of the combustor. Figure 6c shows a sample photo image from the combustor exit, captured under the 7%MTO condition. These real time measurement and observation capabilities under high temperature and pressure conditions gave us useful information to improve the design of the multi-combustors.

Similar to the SSU combustors, two types of combustion air hole arrangement were applied to the MSU combustors; MSU1 with opposing arrangement and MSU2 with staggered arrangement. Figure 2e shows the photograph of the combustor liner and three fuel nozzles of the MSU2, and Fig.7 shows the overlapped schematic drawing of cross section of MSU1 and MSU2.

For the MSU1 combustor, the height of the liner was extended to the vicinity of the inner liner casing to increase the combustion volume (1.2 times of the rectangular single-sector combustor). And the simplification of the cowl configuration increased the pressure loss at the inlet edge of the liner, and relatively increased the inlet air through the fuel nozzle swirlers. This caused the dilution of the primary combustion region. Figure 8 shows NOx emissions and combustion efficiency of MSU1 and MSU2. In these graphs, each vertical dotted line noted as ①-④ shows the designed AFR at each condition of the LTO cycle; 7%, 30%, 85% and 100%MTO respectively. The blank symbols are values measured downstream of one nozzle only, varying the fuel mass flow and AFR, and the filled symbols in Fig.8b are results of the traversed measurements averaged at the target AFR value of each LTO cycle condition. Figure 8a shows that the excessive dilution of the combustion region led to the insufficient combustion efficiency in the high AFR range. In comparison with the ICAO CAEP4 standard, as shown in Table 1, NOx emissions of MSU1 were reduced by 43.6% of the ICAO CAEP4 standard, which achieved the target level, but the THC emission reduction was not sufficient at all.

Taking into account the results of MUS1, successive multi-sector combustor MSU2 was designed. The difference between the MSU1 and MSU2 configurations are shown in Fig.7. The cowl was modified to an aerodynamically smoother configuration to reduce pressure loss at the edge of the combustor liner, aiming to improve the air flow to the combustion and dilution air holes. The combustor volume was reduced to that of the rectangular single-sector combustor, and the size of the dilution air holes was enlarged 1.22 times to enrich the primary combustion region. Figure 8b shows the results of the MSU2, and we can see as expected, that the combustion efficiency was improved to sufficient level, owing to the sufficient fuel rich combustion. Comparing Fig.8a with Fig.8b, we can see that the difference is similar to that of SSU1 and SSU2 shown in Fig.5. That is, with the decrease of AFR, the EINOx plots of MSU1 and SSU1 increase at first, then have maximum values and decrease. On the other hand, the EINOx plots of MSU2 and SSU2 also increase and have maximum values at higher AFR, then decrease, have minimum values and increase again. In many cases, combustion test results obtained under atmospheric and practical conditions do not necessarily show same tendency, but for this case shown above, the modification inferred from the atmospheric test results successfully lead to improve the combustion performance under practical conditions. Finally, in comparison with the ICAO CAEP4 standard, NOx emissions of MSU2 were reduced by almost 40%, and THC and CO emissions were reduced much lower than the standard. The target of emission reduction was sufficiently achieved in the development stage of multi-sector combustor.

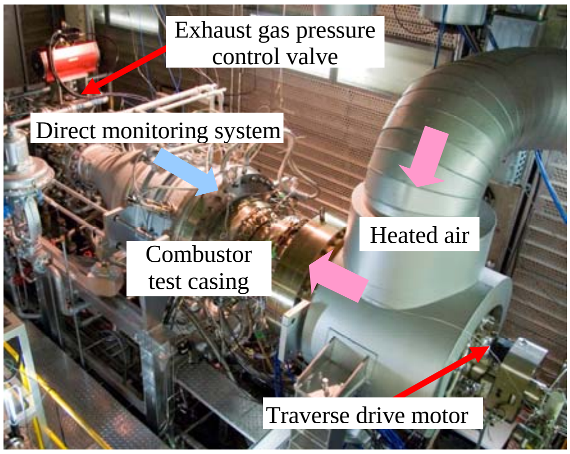


Fig.9. Photograph of "High-Temperature and Pressure Full Annular Combustor Test Facility."

3 Full Annular Combustor Tests Under Practical Conditions

3.1 Full Annular Combustor Test Facility

Based on the design of the multi-sector combustor MSU2, full annular combustors were designed. Figure 2f shows a photograph of the full annular combustor linear, equipped with 16 fuel nozzles. The outer diameter of the combustor linear is about 560 mm.

Combustion tests of the full annular combustors were conducted under the practical operating conditions at the "High-Temperature and Pressure Full Annular Combustor Test Facility" which was newly developed by JAXA in the spring of 2007. A photograph and a cross sectional drawing of the combustion test section are shown in Fig.9 and Fig.10. The inlet air conditions are set to each condition of the ICAO LTO cycle of the target engine as described in the multi-sector section.

And this test facility also has a traversable measuring system at the combustor exit and three direct monitoring systems located downstream of the combustor. As shown in

Fig.11, exhaust gas concentration, pressure and temperature distributions at the combustor exit are measured by the gas sampling and pressure probes and two temperature sensor rakes. They are mounted on the rotating disk located at the combustor exit. Each probe and rake has five sampling points in the radial direction. The disk can be rotated within a range of ±185 degrees with the accuracy of 0.5 degrees. Sampled gas from the collective 5 points probes is led through the traverse shaft, being kept warm by pressurized hot water (3MPa, 430K). The concentration of the exhaust gas is measured by the same procedures mentioned in the multi-sector section. By this traverse measurement system, detailed distribution of the temperature, pressure and gas concentration at the combustor exit can be obtained in both radial and circumferential directions. And these data are used to check the uniformity of the exit profile and to improve the air flow distribution of the combustor to satisfy the requirements from the turbine blade design.

This facility is also equipped with three direct monitoring systems 200 mm downstream of the combustor exit, consisting of water cooled industrial rigid borescopes which are connected to three CCD cameras. Figure 12 shows sample photo images from the combustor exit at three different positions, taken at the 7%MTO condition. This direct monitoring system enables us to check the combustion behaviour even under the high-temperature and high-pressure conditions. Then we can obtain

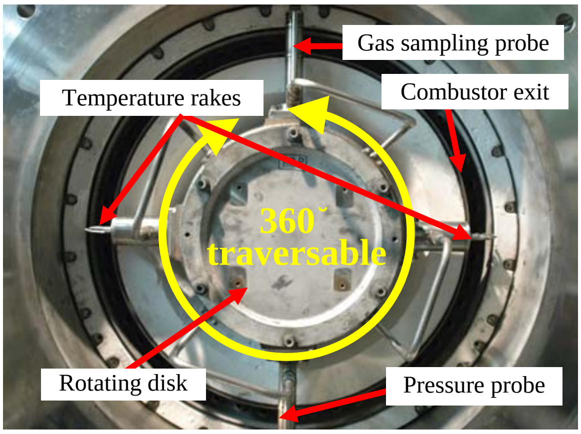


Fig.11. Temperature rakes, gas and pressure sampling probes traversable at combustor exit.

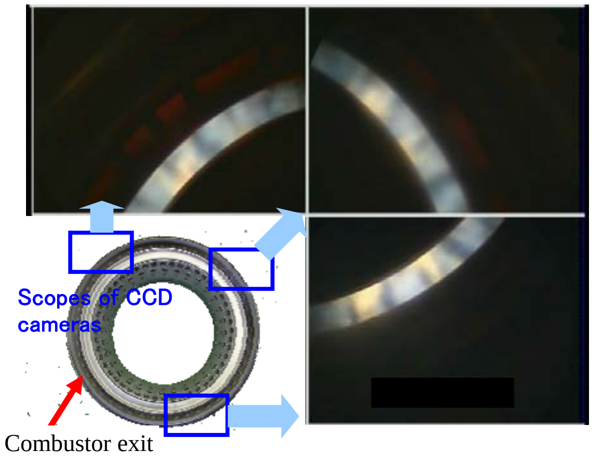


Fig.12. Photo images of combustion from downstream of combustor exit under 7%MTO condition.

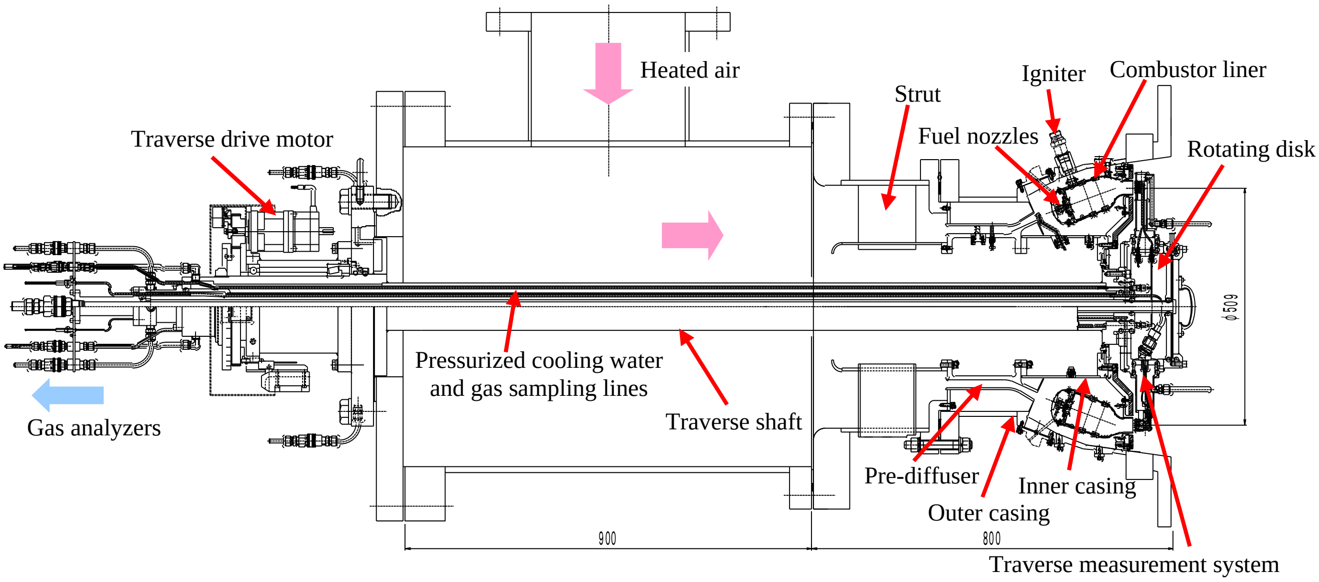
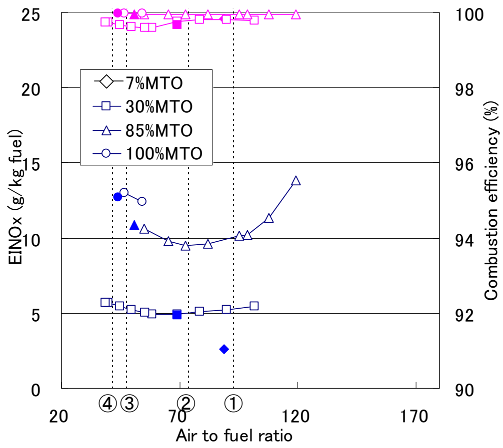


Fig.10. Cross-sectional drawing of combustion test section (including traverse system).

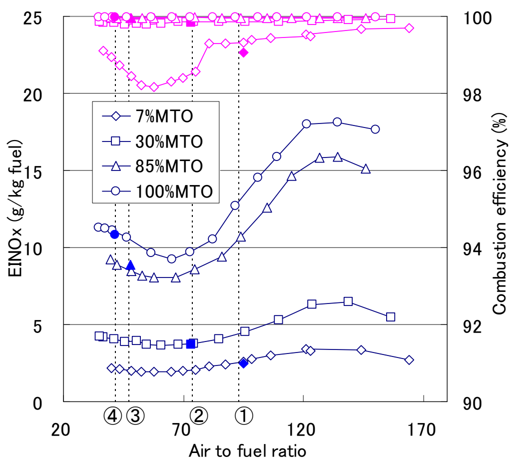
some useful information to improve the combustor, especially for reducing ununiformity of combustion and for checking flame stability under LBO conditions. In addition, soot emission is also measured by the Bacharach smoke meter, and combustion oscillation is checked by pressure transducers with resonance tubes.

3.2 Improvement Process of Full Annular Combustor

Two types of full annular combustor FA1-1 and FA1-2 were designed and tested by the newly developed test facility mentioned above. The combustion test of FA1-1 was conducted as a performance test of the test facility, so the test conditions were not set exactly to the ICAO LTO cycle of the target engine. Even so, we found some data which assure good performance of the full annular combustor FA1-1. Obtained NOx emissions and combustion efficiency under the vicinity of the LTO cycle conditions; 7%, 30%, 85% and 100% MTO; are shown in Fig.13a. As mentioned above, there are some gaps between the set AFR values and target AFR values (corresponds to vertical dotted lines ①-④ in Fig.13a, from 7% to 100%MTO conditions). The emission values at the target AFR values are estimated from the blank symbols, and summation of the emission values over the LTO cycle are shown in Table.1 in comparison with the ICAO CAEP4 standard. The obtained emission values are below the target values, but the NOx value slightly becomes worse than that of MSU2. Comparing the EINOx plots of the 85%MTO condition in Fig.8b and Fig.13a, especially in the AFR range from 50 to 100, the plot of Fig.13a seems to become broader and shift higher. On the other hand, the total combustor pressure loss was reduced from 5.8% to 3.85%, which was caused by the difference of geometry between MSU2 and FA1-1. From these two issues, we guessed that the mass flow ratio through the fuel nozzles, which have lower discharge coefficient than other air holes on the linear, was slightly decreased, and length of the primary combustion region got short. And this caused the increase of NOx emissions and broadened



(a) Emission characteristics of FA1-1.



(b) Emission characteristics of FA1-2.

Fig.13. Emission characteristics of full annular combustors FA1-1 and FA1-2 under practical conditions. (Blue symbols: EINOx, red symbols: combustion efficiency, filled symbols: traversed average)

the AFR range. So, aiming to modify the plots of Fig.13a closer to that of MSU2 shown in Fig.8b, in the design of secondary annular combustor FA1-2, the size of the combustion and dilution air holes was reduced to 0.94 times. This modification successfully adjusted the mass flow ratio to that of MSU2, and the emission plots shown in Fig.13b became closer to that of MSU2 in Fig.8b. And for the summation over the LTO cycle, which is shown in Table 1 and Fig.14, even THC and CO slightly increased from that of FA1-1, NOx emissions were successfully reduced to 38.1% of the ICAO CAEP4 standard.

For the purpose of checking emission performance in comparison with the ICAO CAEP4 standard, measurements for the filled symbols in Fig.13 are enough. Yet additional measurements for the blank symbols give useful information about emission characteristics of the combustor. As shown above, those additional measurements enabled the improvement from the FA1-1 to FA1-2 combustor.

And as earlier mentioned, temperature distribution at the combustor exit is also one of the very important performance required from the design of turbine blades. The newly developed test facility has an ability to measure the distributions in detail, by the traversable probes and rakes. Figure 15 shows the circumferential exit temperature distribution measured by the temperature sensor rakes and averaged over the five points in the radial direction, under the 100%MTO condition. And the ratio of the set AFR and the analyzed AFR calculated from the measured gas concentration is also shown in Fig.15. This ratio indicates the uniformity of the fuel distribution at the combustor exit. In addition, as other indexes of the exit temperature distribution, profiles of R.T.D.F. (Radial Temperature Distribution Factor) and P.T.F. (Peak Temperature Factor) calculated at each radial span by following equations are also shown in Fig.16 for the 100%MTO condition.

$$R.T.D.F. = \frac{T_{4rav} - T_{4av}}{T_{4av} - T_{3av}}, \quad P.T.F. = \frac{T_{4\max} - T_{4av}}{T_{4av} - T_{3av}} \qquad (1)$$

Here, T3 and T4 mean combustor inlet and exit temperature, and subscript "av" means average over all region and "rav" means circumferential average at a radial span. These profiles are within the required range from the turbine blade design and limitation (which cannot be shown on this paper), and P.T.F. calculated over all spans is successfully suppressed to 0.19. And in addition, in the emission profiles in Fig.13b, the blank symbols which show values being measured downstream of one nozzle only, and the filled symbols which show the average values of the traversed measurements over 360 degrees at the target AFR of each LTO cycle condition are very close, and this also indicates good exit concentration profile.

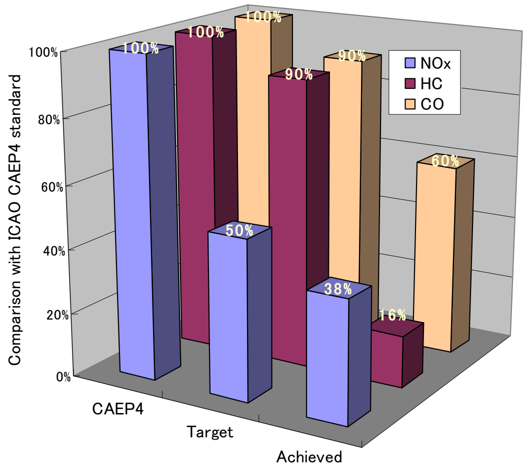


Fig.14. Emission comparison in ICAO LTO cycle between achieved value by full annular combustor FA1-2 and target level based on ICAO CAEP4 standard.

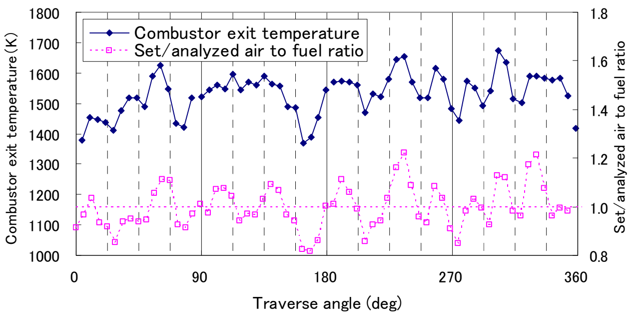


Fig.15. Circumferential profiles of temperature and AFR ratio at combustor exit of FA1-2 under 100%MTO condition.

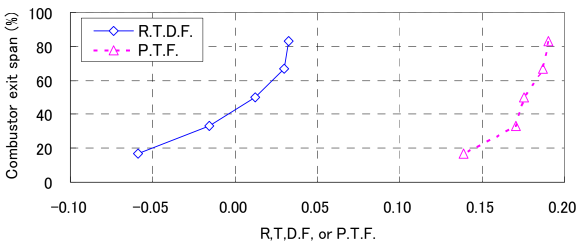


Fig.16. Radial profiles of temperature at combustor exit of FA1-2 under 100%MTO condition.

And for other performance, the stability of the flame (LBO performance) was assured up to 200 AFR under the 7%MTO condition. And soot emission suppressed to 16.6 SAE smoke numbers. And the pressure loss from the inlet to the exit of the combustor was modified to 4.5%. And there was no serious combustion oscillation during the tests.

4 Summary

In the TechCLEAN project of JAXA, a series of experimental research has been being conducted to develop a small aircraft engine combustor, aiming to reduce NOx emissions lower than 50% of the ICAO CAEP4 standard. The designed full annular combustor achieved NOx reduction to 38.1% of the ICAO CAEP4 standard. Achieved NOx reduction level is shown in Fig.1 in comparison with the ICAO standards and the emission levels of current commercial engines of similar power range.

Through these combustor experiments, we demonstrated that, even though applying a simple airblast fuel nozzle system to a small aircraft combustor, the combustor can be designed to show the Rich-Lean behavior and achieve sufficient combustion performance as an aircraft combustor, including low NOx emissions, by enhanced mixing in the primary combustion region and the optimization of air mass flow distribution. In the design of following combustors tested on a demo engine, we are going to make the most of the results of this study.

Nomenclature

AFR	Air to Fuel Ratio
CAEP	Committee on Aviation Environmental Protection
CFD	Computational Fluid Dynamics
DOC	Direct Operating Cost
EINOx	Emission Index of NOx
ICAO	International Civil Aviation Organization
LBO	Lean Blowout
LTO	Landing and Take-Off
MSU	Multi-Sector Unit
MTO	Max Take-Off
P.T.F.	Peak Temperature Factor
R.T.D.F.	Radial Temperature Distribution Factor
SSU	Single-Sector Unit
THC	Total Hydrocarbon

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