Proceedings of ASME Turbo Expo 2012
GT2012
June 11-15, 2012, Copenhagen, Denmark

GT2012-68468

DETAILED RESEARCH ON RICH-LEAN TYPE SINGLE SECTOR COMBUSTOR FOR SMALL AIRCRAFT ENGINE TESTED UNDER PRACTICAL CONDITIONS UP TO 3MPA

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ABSTRACT

In the TechCLEAN project of JAXA, experimental research has been 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. Finally, through full annular combustion experiments under practical conditions, the combustor was tuned to reduce NOx emissions to almost 40% of the ICAO CAEP4 standard, also sustaining low CO and THC emissions. To investigate the performance of the combustor in detail, parametric experiments were conducted with single-sector combustors under additional test conditions in addition to design conditions of the target engine. Also the performance as a combustor for higher-efficient aircraft engine is examined by increasing inlet air pressure and temperature up to 3MPa and 825K in combustion tests. Obtained results of emission characteristics are discussed in this report.

Keywords: small aircraft engine, single-sector combustor, practical conditions, NOx reduction, Rich-Lean.

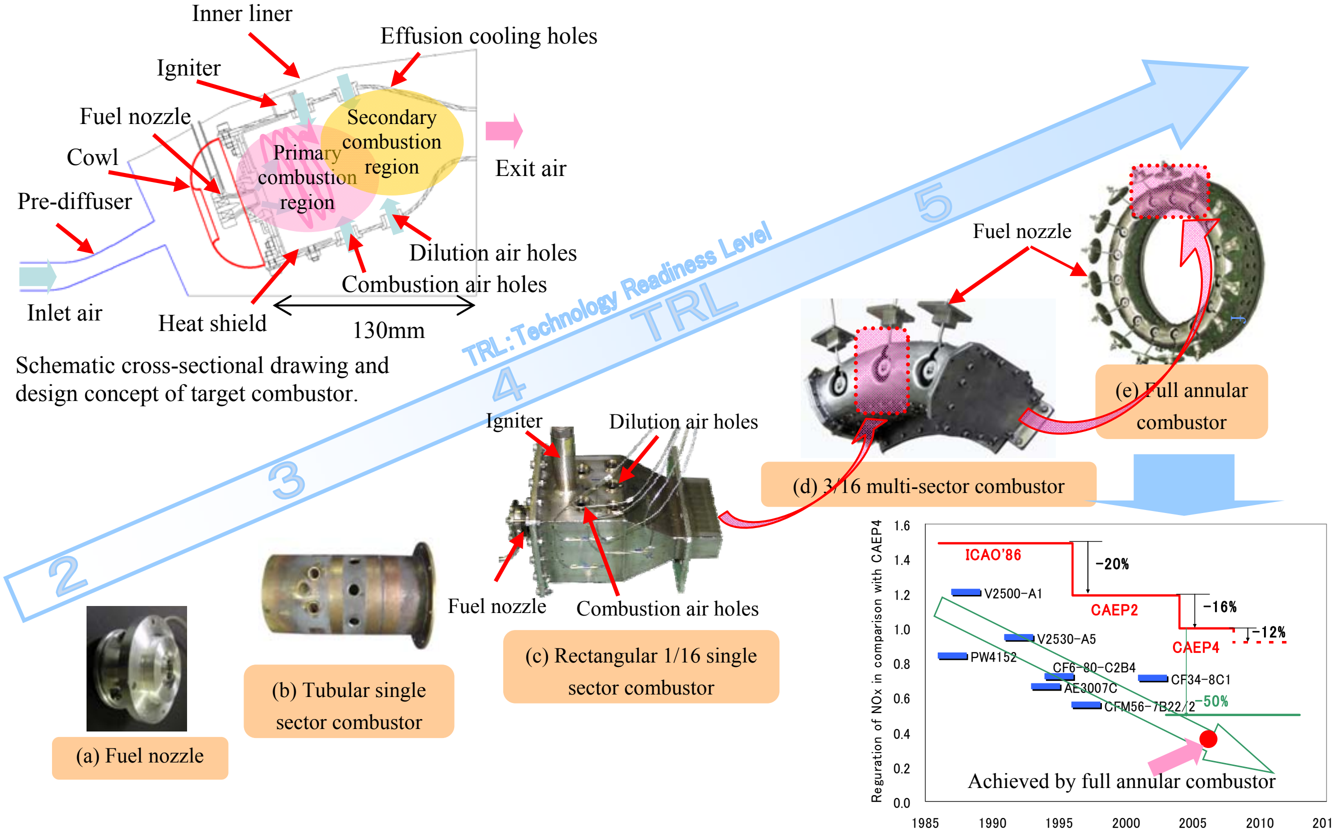
INTRODUCTION

In general, small and medium power aircraft engines must simultaneously satisfy several requirements, for example, high efficiency, environmental friendliness and cost effectiveness [1]. In October 2003, Japan Aerospace Exploration Agency (JAXA) started a project "Technology development project for clean engines" (so-called TechCLEAN project), in which researches to develop advanced combustion technology were conducted aiming to reduce toxic exhaust gas components, especially NOx, from aeroengine combustors. And in the framework of the TechCLEAN project, JAXA has been developing aeroengine combustors for an affordable and environment-friendly small aircraft (with approximately 50-passengers). The designed thrust of the engine is about 40kN and the pressure ratio is about 20. The target of the combustor development is to reduce NOx emissions lower than 50% of the ICAO CAEP4 standard, aiming to precede the trend of NOx emissions shown in the lower right of Fig.1. Also aiming to reduce CO and THC emissions to those of 90% and ensure basic performance of aero engine combustors, such as ignition and blow-out.

The overview of the development process of our combustor is shown in Fig.1 with TRL (Technology Readiness Level). We started from preliminary combustion tests with tubular combustors under atmospheric conditions. Then both model combustors and test conditions got closer to the target engine combustor step by step, and finally full annular combustors were tested under practical conditions and succeeded to reduce NOx emissions to 38.1% of the ICAO CAEP4 standard, which are also shown in the lower right of Fig.1.

But during the development process under practical conditions, combustion tests were only conducted under ICAO LTO (Landing and Take-Off) cycle conditions of the target engine, whose numerical value could not be presented in detail. So in this report, in order to obtain and report more detailed data which can be utilized for further combustor improvement, we conducted parametric combustion tests with single-sector combustors under inlet air temperature increasing from 450K to 800K with 50K intervals. Also inlet pressure and mass flow rate of inlet air were increased in accordance with inlet temperature along the design line of ordinary small engines. Furthermore, to prepare for increasing demand for higher-efficient aircraft engine, we also examined the combustor performance under increased inlet temperature and pressure up to 825K and 3MPa.

In this report, we review our previous report before introducing our experiments of three single-sector combustors, and then present parametric emission and performance data obtained for these combustor models.



Schematic cross-sectional drawing and design concept of target combustor.

Trend of NOx emissions and achieved level of NOx reduction with ICAO standards.

Fig.1 Overview of development process of aircraft combustor shown with TRL (Technology Readiness Level).

DEVELOPMENT PROCESS OF COMBUSTOR

Preliminary Design of Combustor

The development process of our combustor shown in Fig.1 was already discussed in previous reports [2-4]. But to make smooth introduction to this report, some discussions related to the design concept of the combustor, and brief review of each development stage are presented here. The upper left figure of Fig.1 shows a cross-sectional drawing of our combustor with descriptions 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 required to be simple. At the same time, the reduction of NOx emissions is also required, sustaining 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 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 through the fuel nozzle should be about 10% of the total air flow. This means that the summation of combustion, dilution and cooling air flow should be 90% of the total air flow. Yet under 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 require. To satisfy these requirements simultaneously, the Rich-Lean combustion approach [6] was utilized for this combustor. As we should choose a simple and cost effective fuel nozzle for this combustor, we applied the concept of single fuel supplied air blast type nozzle proposed by Parker-Hannifin [7]. The fuel nozzle is shown in Fig.1a, and for reference, the correlation between the pressure drop through the fuel nozzle and the SMD (Sauter Mean Diameter) at three different fuel mass flow rate from 1 to 3 g/sec is shown in Fig.2.

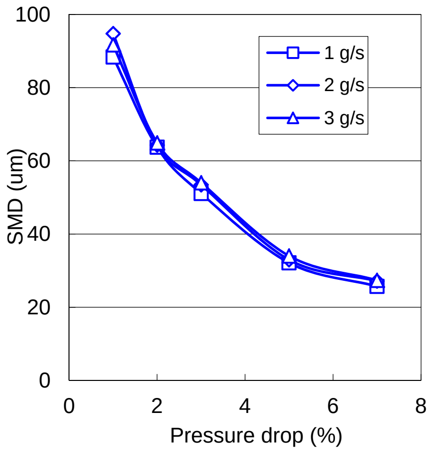


Fig.2 Correlation of pressure drop and SMD (Sauter mean diameter) of fuel nozzle under atmospheric pressure.

Table 1. Comparison of emission summation in ICAO LTO cycle among combustor models and target level in percentage figures of ICAO CAEP4 standard.

	NOx	THC	CO
Development target	50.0%	90.0%	90.0%
Single-sector (Fig.1c)	44.3%	92.9%	37.8%
Multi-sector (Fig.1d)	40.9%	3.5%	54.6%
Full annular (Fig.1e)	38.1%	16.3%	60.1%

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.

Review of Combustor Development Process

In the preliminary emission tests with tubular combustors (Fig.1b) under atmospheric pressure, the air mass flow ratio was tuned to show the Rich-Lean combustion behavior, that is, reducing NOx emissions at low AFR (Air to Fuel Ratio) condition, also sustaining high combustion efficiency. The emission tests were conducted for more than 20 combustor models with different air hole locations and sizes.

Based on the designed air mass flow ratio, rectangular single-sector combustors were designed (Fig.1c), simulating 1/16 region of the target combustor. To compare emission results with the ICAO CAEP4 standard, combustion tests were conducted under inlet air temperature, pressure and mass flow rate which were set to simulate the operating conditions corresponding to the ICAO LTO cycle; 7%, 30%, 85% and 100% thrust of MTO (Max Take-Off) design points of the target engine. As shown in Table 1, the level of NOx emissions was reduced to 44.3% of the ICAO CAEP4 standard and achieved the emission target, while THC emission exceeded the target slightly.

Following the results of the tubular and rectangular single-sector combustor tests, multi-sector combustors with three fuel nozzles (Fig.1d) were designed, simulating 3/16 region of the target combustor. Through combustion tests under the ICAO LTO cycle conditions, air mass flow ratio was modified, and staggered allocation was selected for combustion air holes. Finally, NOx emissions were reduced by almost 40% of the ICAO CAEP4 standard as shown in Table 1, and THC and CO emissions were also reduced much lower than the standard.

Then based on the design of the multi-sector combustor, full annular combustors were designed. Figure 1e shows a photograph of the full annular combustor liner, equipped with 16 fuel nozzles. Through combustion tests under the ICAO LTO cycle conditions, the combustion characteristics were tried to be adjusted to those of the multi-sector combustor, by tuning the size of the combustion and dilution air holes. This modification successfully adjusted the mass flow ratio to that of the multi-sector combustor, and the emission plots also became closer. And for the summation over the ICAO LTO cycle, which is shown in Table 1, NOx emissions were successfully reduced to 38.1% of the ICAO CAEP4 standard.

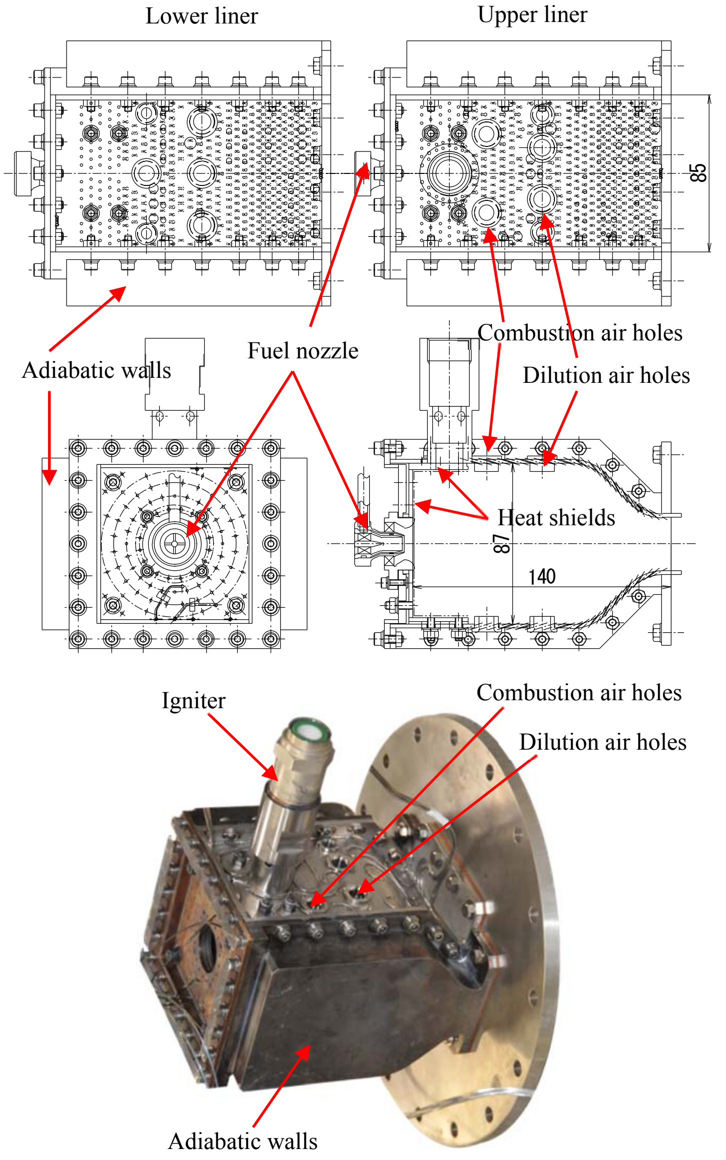


Fig.3 Schematic drawings (upper) and photograph (lower) of rectangular single-sector combustor.

PARAMETRIC COMBUSTION TESTS OF SINGLE SECTOR COMBUSTORS

Setup of Single-Sector Combustor Tests

In the combustor development process mentioned above, rectangular single-sector combustors (Fig.1c) were tested under the ICAO LTO cycle conditions of the target engine up to 100%MTO, with inlet air temperature up to 700K and with inlet pressure up to 1.65MPa. In order to conduct combustion tests under higher temperature and pressure conditions, the single-sector combustor was modified to the heat-resisting configuration as shown in Fig.3. Upper and lower liner walls and heat shields were made of hastelloy, and two side walls with effusion cooling air holes were replaced with adiabatic walls stuffed with heat insulating material. The cooling air holes which had been on the side walls were moved to combustor liners keeping the total effective area of cooling air holes. This means that the cooling of combustor liners was also enhanced. Additionally, for combustion tests with different configuration parameters, three single-sector

Table 2 Configuration parameters of single-sector combustor models. (FNAR: Mass air flow ratio through fuel nozzle, DCAR: Ratio of mass air flow between dilution and combustion air holes)

Combustor model	Air hole size		FNAR	DCAR
	Combustion	Dilution		
SSC1	ϕ 10.20	ϕ 11.50	6.85%	1.907
SSC2	ϕ 10.20	ϕ 10.90	7.09%	1.713
SSC3	ϕ 8.22	ϕ 9.12	9.12%	1.846

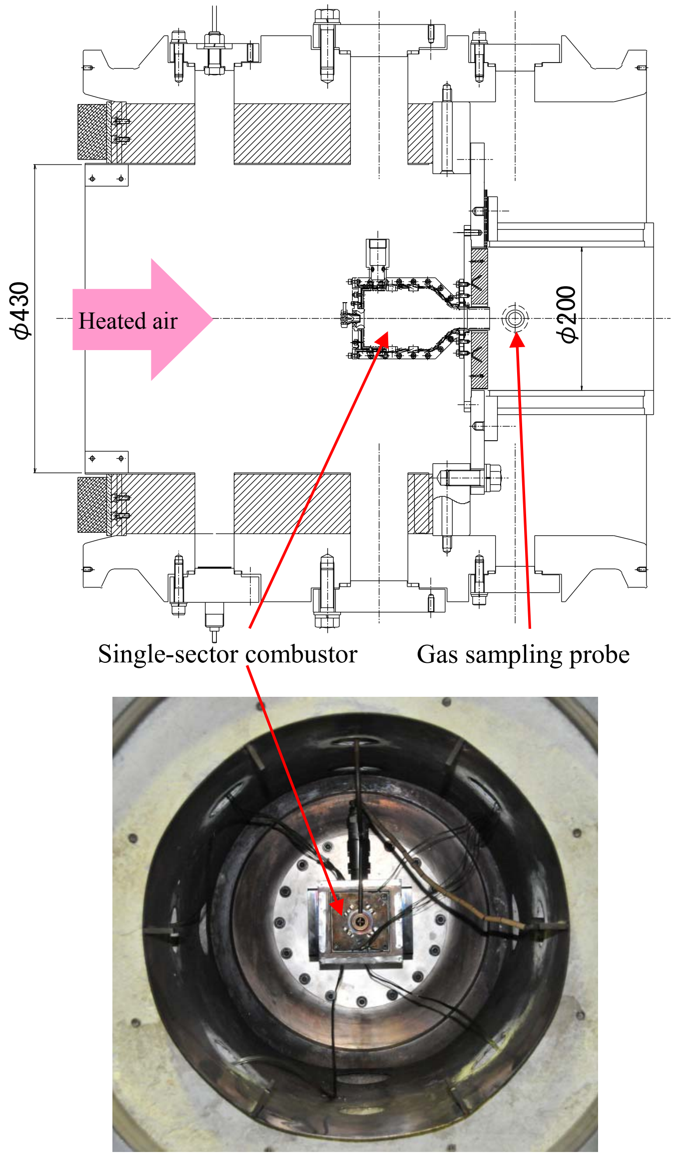


Fig.4 Schematic drawings (upper) and photo (lower) of setup of rectangular single-sector combustor inside high-pressure combustion test casing.

combustor models SSC1, SSC2 and SSC3 were tested modifying the size of combustion and dilution air holes on the liners as shown in Table 2. By this modification, two configuration parameters; mass air flow ratio through the fuel nozzle (FNAR), and ratio of mass air flow between dilution and combustion air holes (DCAR) varied accordingly as shown in Table 2.

These single-sector combustors were set into a high pressure combustion test casing as shown in Fig.4, and embedded in the "High-Temperature and Pressure Combustion Test Facility" in JAXA, which is shown in Fig. 5 with the testing setup. In this facility, inlet air was compressed by one 1900kW and two 720kW compressors and was heated through a 2MW electric heater, then continuously supplied to the combustion test casing. For combustion tests, kerosene was used for fuel. Test conditions were set as shown in Table 3; the inlet air temperature increased from 450K to 825K, and also the inlet pressure and air mass flow rate were accordingly changed along the design line of ordinary small aircraft engines. SSC1 and SSC2 models were tested up to 800K with 50K intervals, except for 600K of the SSC2 model (limited by experimental duration). The SSC3 model was also tested up to 800K, and was additionally tested at 825K which approached to 3MPa for inlet pressure. Under these inlet air conditions, pressure drops through combustors were also measured between a pressure probe upstream of the test casing and a sampling probe downstream of the combustor exit.

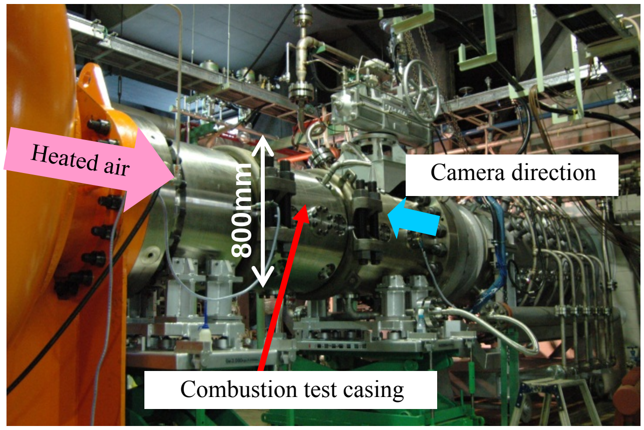


Fig.5 Photograph of "High-Temperature and Pressure Combustion Test Facility."

Table 3. High temperature and high pressure inlet air conditions of parametric combustion tests of single-sector combustors.

Temperature (K)	Pressure (MPa)	Mass flow rate (kg/s)	AFR
450	0.315	0.260	95.3
500	0.504	0.402	84.3
550	0.738	0.554	73.2
600	1,018	0.715	62.1
650	1,345	0.886	51.0
700	1,757	1.067	48.8
750	2,220	1.257	40.8
800	2,738	1.456	32.8
825	3,015	1.560	28.9

Exhaust gas composition and pressure at the combustor exit were measured by a nine point collective hot-water-cooled sampling probe, located just below the combustor exit as shown in Fig.4. The sampled gas was led through the heated sampling line to the gas-analyzer HORIBA MEXA-7100D which measured the concentrations of CO, CO2, THC (as CH4), NO, and NOx by standard gas analysis procedures: chemiluminescence for NO, nondispersive infrared

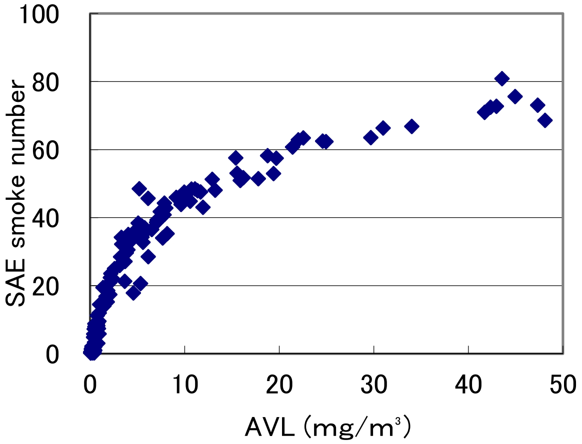


Fig.6 Correlation of soot measurement value between AVL smoke meter (mg/m^3) and SAE smoke number.

absorption for CO and CO2, flame ionization for THC, and paramagnetic analysis for O2. These gas sampling procedures were based on the standard of the ICAO [15]. Meanwhile, soot emission was mainly measured by the “AVL 415S” variable sampling smoke meter, and for calibration, soot was also measured by the smoke meter which was developed in JAXA in accordance with the SAE standard [16]. The soot emissions measured by the "AVL 415S"in the unit of mg/m^3, and can be converted to SAE smoke number through the plots shown in Fig.6, which have been measured in other combustion tests under high temperature and pressure conditions.

Furthermore, combustion behavior was observed by a direct monitoring system consisting of a CCD camera through a periscope downstream of the combustor.

RESULTS AND DISCUSSIONS

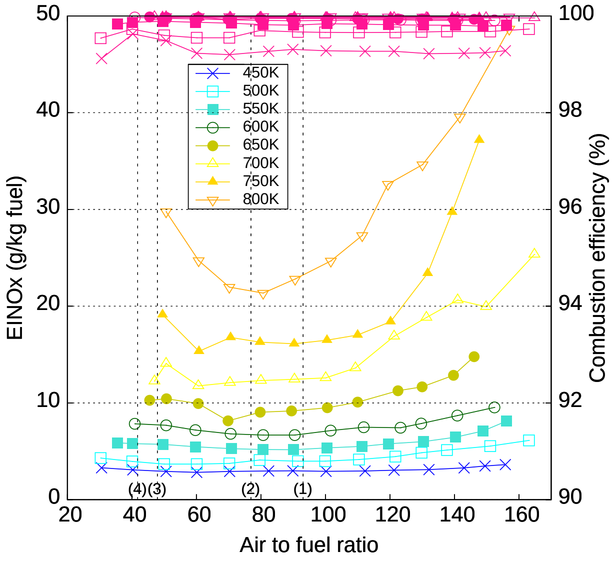
Emission results of single-sector combustors SSC1, SSC2 and SSC3 are shown in Fig.7 to Fig.12. NOx, CO and soot emissions are plotted versus AFR (Air to fuel ratio) in Fig.7, 9 and 10 respectively, shown with combustion efficiencies. Correlations of CO emission with NOx emissions and soot emission with NOx emissions are also shown in Fig.11 and Fig.12. In these graphs, emissions of NOx and CO are expressed by EI (Emission Index), that is, grams of emitted matter per 1kg fuel. The combustion efficiency is calculated from the analyzed gas concentration. In Fig.7, 9 and 10, the designed AFR at each condition of the ICAO LTO cycle of the target engine; 7%, 30%, 85% and 100%MTO are shown for references by vertical dotted line noted from (1) to (4). For other information, pressure drop through the combustor was observed between 3 and 4.5%. For this pressure drop, Sauter mean diameter of the fuel spray under atmospheric pressure is about 40μm from Fig.2, while the diameter is expected to be smaller under high pressure conditions.

From Fig.7 and Fig.9, we can see Rich-Lean combustion behavior, that is, reduces NOx emissions at low AFR range, also sustaining high combustion efficiency. Also we can see that EINOx plots of three combustor models have common tendency. By decreasing AFR from higher range, plots of EINOx have maximum values, then decrease, have minimum values and increase again in low AFR range. But AFR values of peak EINOx and maximum and minimum value of EINOx are different among three combustor models. In addition, in lower AFR range under 40, some disturbance can be seen, with rapid change in both NOx and CO emissions. Besides, from emission correlations of CO with NOx shown in Fig.11, we can see that for all combustor models, CO and NOx emissions have strong inverse correlation, and there is no stray point. This means that oxidant and evaporated fuel was sufficiently mixed and reacted for whole AFR range tested in this report.

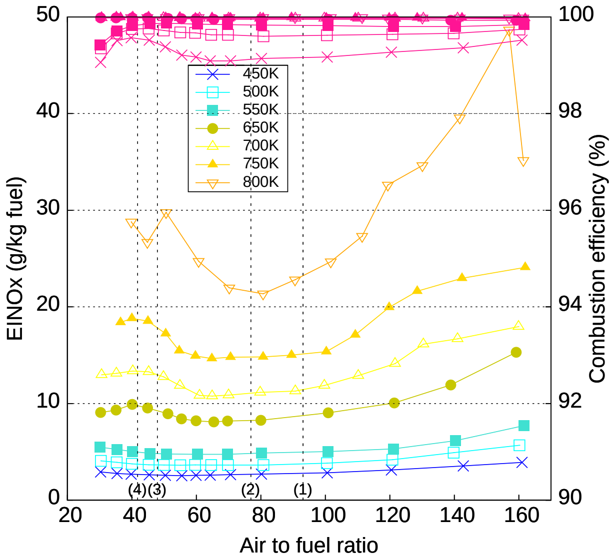
For soot emission, plots in Fig.10 have peak values in low AFR range and decrease again in higher AFR range. For inlet air conditions, as inlet temperature (and also pressure) increases, soot emissions get higher, have maximum values under high inlet temperature conditions between 650K and 700K, and decrease again. Their numerical values decreases from SSC1 to SSC3 models, but with 850K inlet temperature, soot emission of SSC3 model rapidly increases in the low AFR range. Emission correlations of soot with NOx are also shown in Fig.12. These plots are somewhat dispersed and we can see almost no correlation between them. We expected some correlation between soot and NOx emissions, but there should be some controlling factors other than NOx formations.

Furthermore, to see the dependency of NOx emissions on inlet air temperature Tin, and the difference among combustor models, EINOx is plotted versus AFR and Tin in Fig.8 for each combustor model, using same data plotted in Fig.7. For each data, a curved surface mesh is also plotted. These surfaces are expressed by third-order polynomial approximations of AFR and Tin, which are fitted to measured EINOx plots by linear least-square fitting method. From these surface equations, NOx emissions can be estimated approximately at a certain set of AFR and Tin for each combustor model. Here, as mentioned before, inlet air temperature Tin is not an independent parameter, that is, inlet air pressure and mass flow rate are also accordingly changed along the design line of ordinary engines.

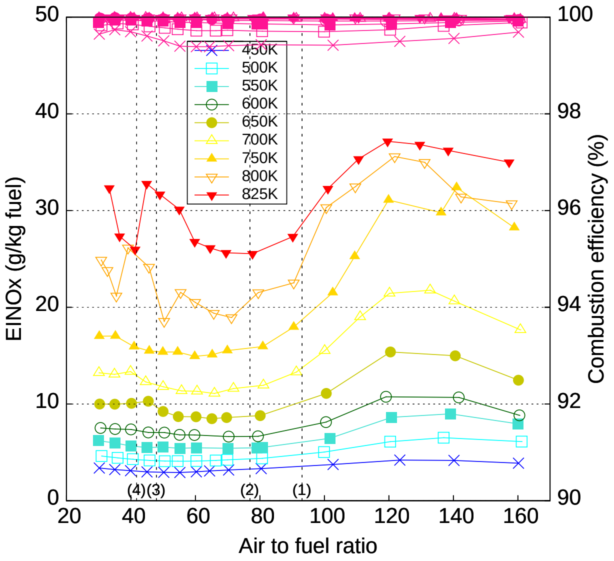
From EINOx plots and fitted surfaces shown in Fig.7 and Fig.8, we can see that NOx emission tendency with AFR and Tin changes in accordance with the change of combustor models from SSC1 to SSC3. As shown in Table 2, we chose two configuration parameter for the combustor models; the mass air flow ratio through the fuel nozzle (FNAR), and the ratio of mass air flow between dilution and combustion air holes (DCAR). FNAR monotonously increases from SSC1 to SSC3, and DCAR decreases from SSC1 to SSC2 and increases from SSC2 to SSC3. So considering with the tendency of EINOx shown before, FNAR can be one of the controlling configuration parameter for NOx emission characteristics of our combustor. Similar analysis can be conducted for CO and soot emissions, versus other configuration parameters. Then by tuning these configuration parameters, the emission characteristics of single-sector combustors, which are similar to our combustors, can be modified to desired mode.



(a) SSC1

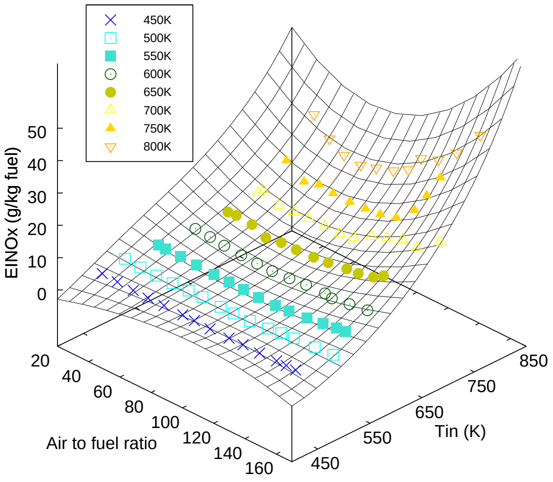


(b) SSC2

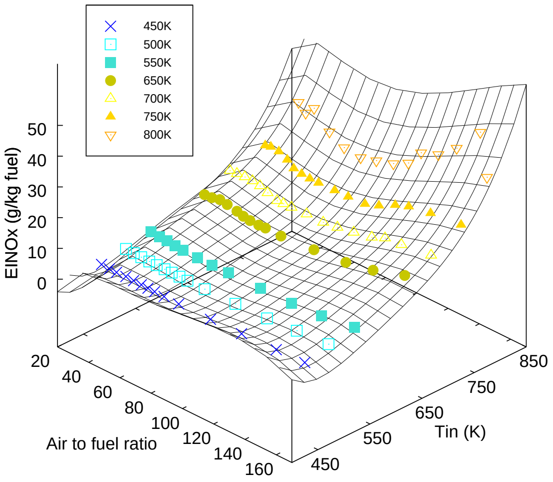


(c) SSC3

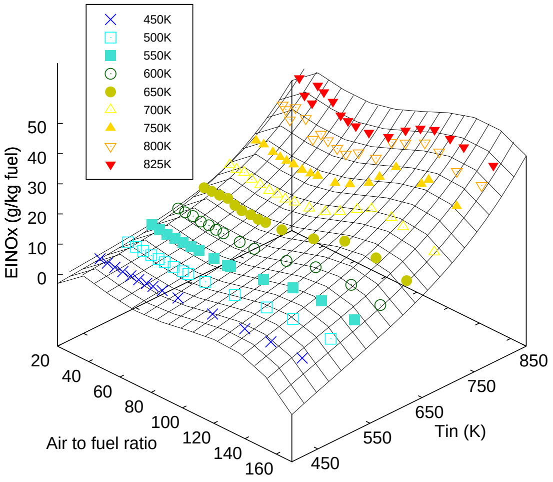
Fig.7 NOx emissions and combustion efficiency under parametric test conditions. (Varied color lines: EINOx, pink lines: combustion efficiency.)



(a) SSC1

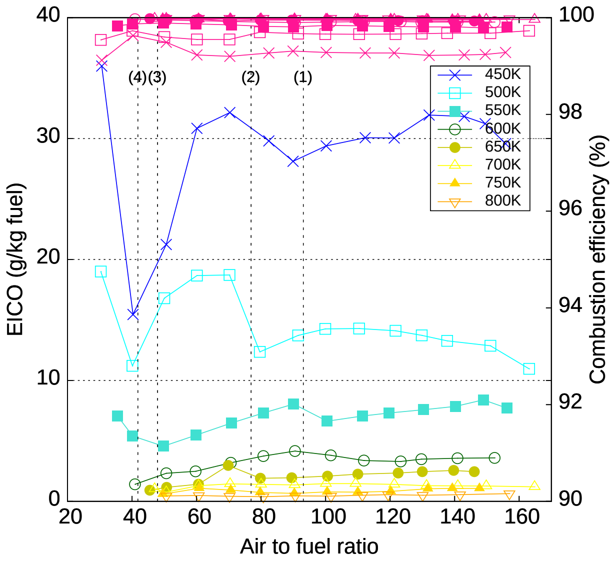


(b) SSC2

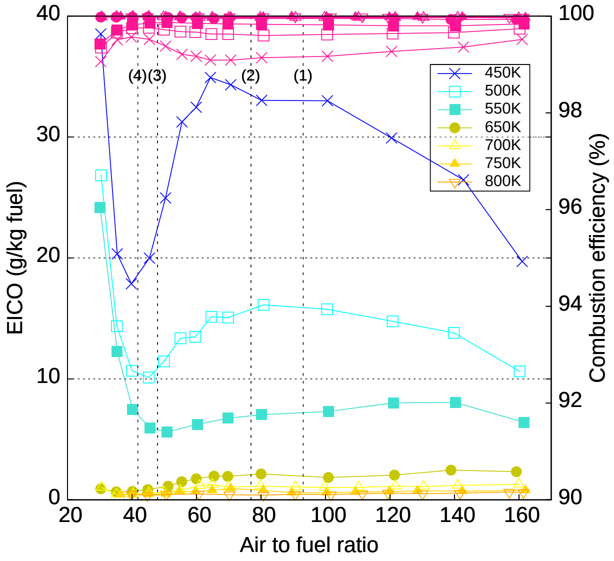


(c) SSC3

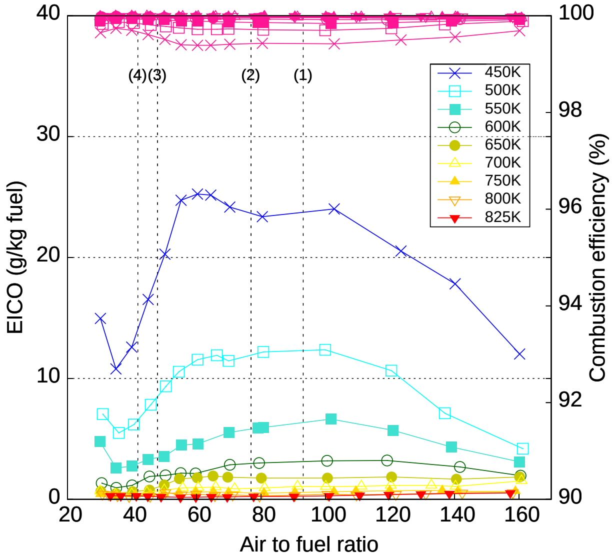
Fig.8 Plots of NOx emissions versus air to fuel ratio and inlet temperature with fitted surface mesh.



(a) SSC1

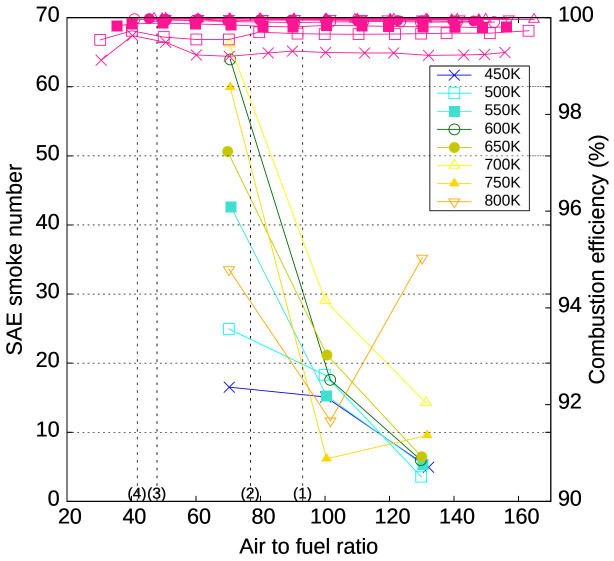


(b) SSC2

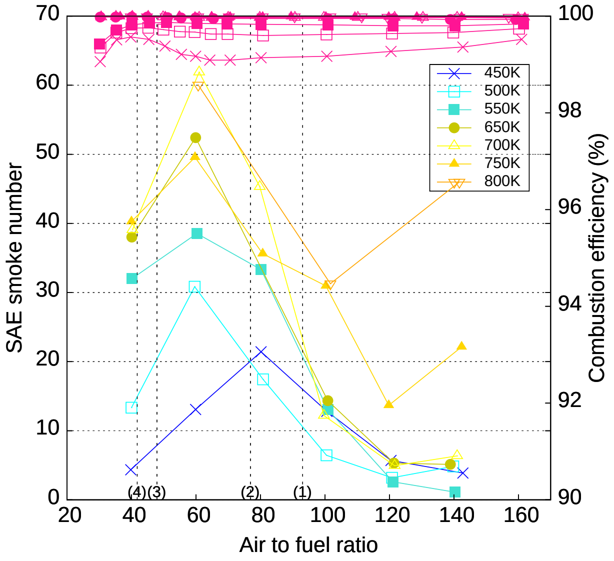


(c) SSC3

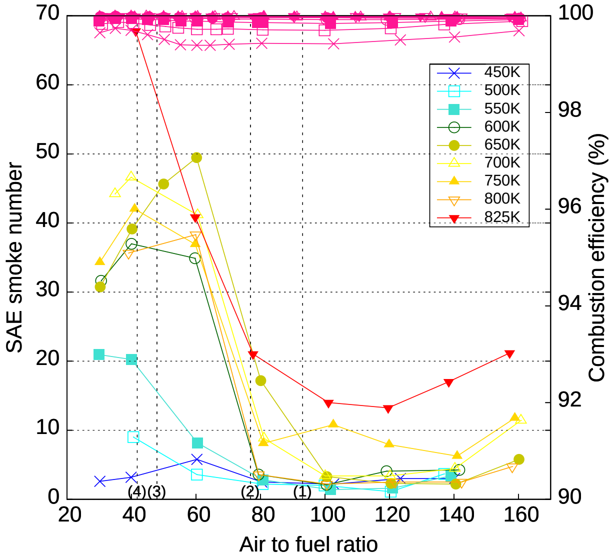
Fig.9 CO emission and combustion efficiency under parametric test conditions. (Varied color lines: EINOx, pink lines: combustion efficiency.)



(a) SSC1

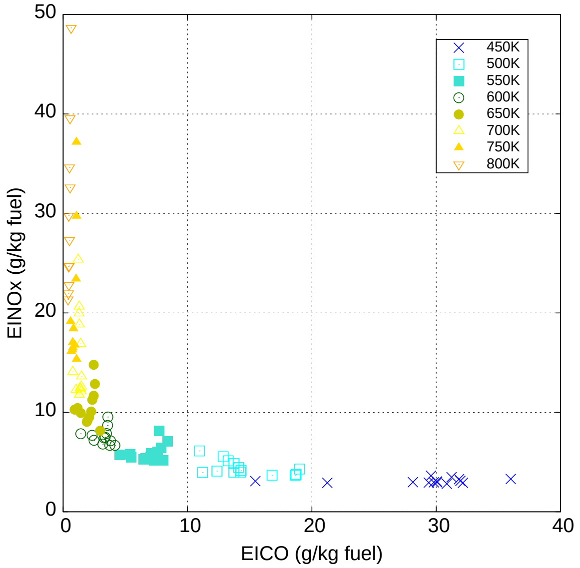


(b) SSC2

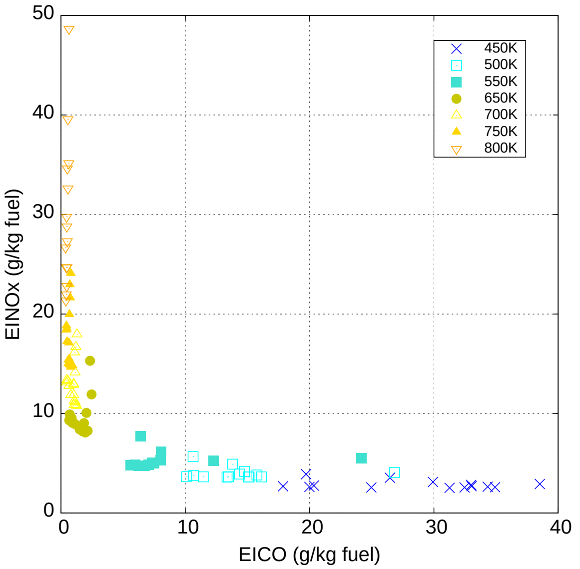


(c) SSC3

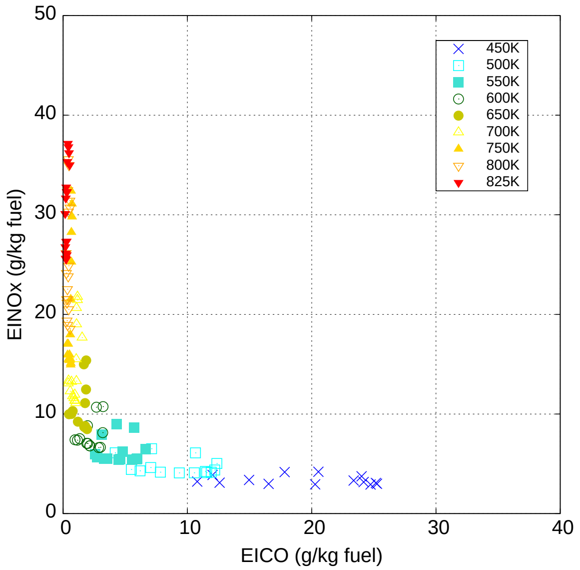
Fig.10 Soot emission and combustion efficiency under parametric test conditions. (Varied color lines: EINOx, pink lines: combustion efficiency.)



(a) SSC1

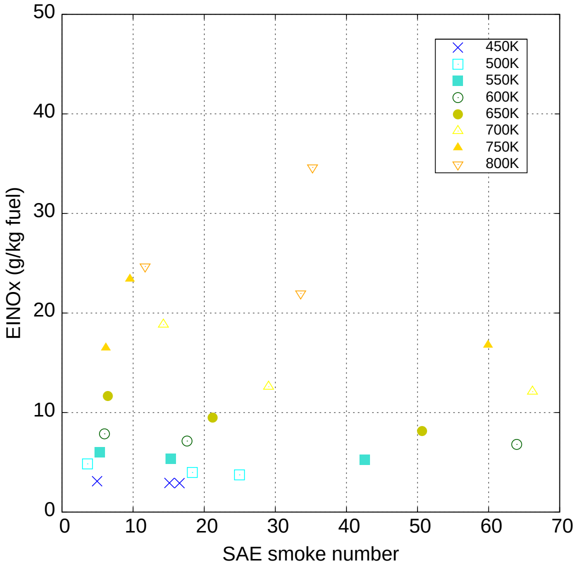


(b) SSC2

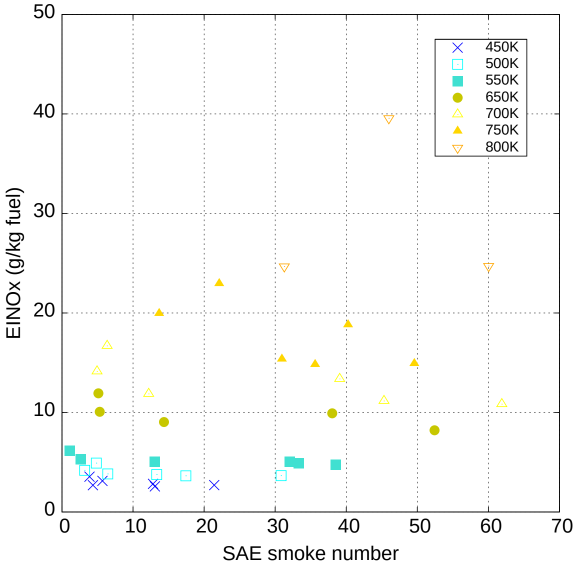


(c) SSC3

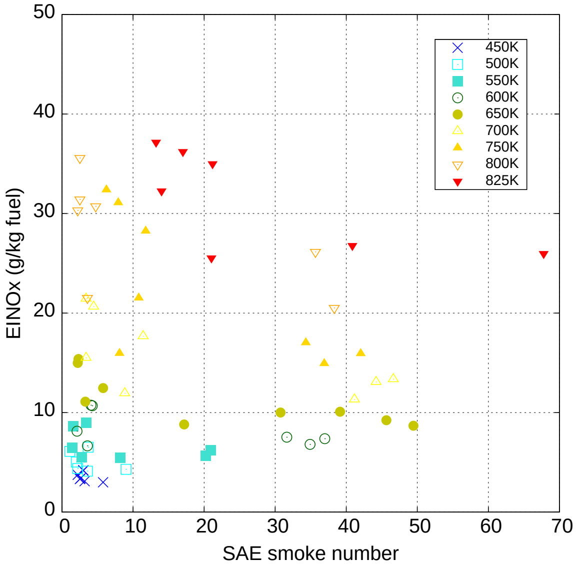
Fig.11 Correlation of CO and NOx emissions under parametric test conditions.



(a) SSC1



(b) SSC2



(c) SSC3

Fig.12 Correlation of soot and NOx emissions under parametric test conditions.

SUMMARY AND FUTURE WORK

In the TechCLEAN project of JAXA, experimental research has been conducted to develop a combustor for a small aircraft engine. Parametric experimental research was conducted with Rich-Lean type single-sector combustors. By combustion tests with inlet gas temperature increasing from 450K to 825K, emission characteristics of the combustor were investigated. Furthermore, configuration of the combustors was also changed parametrically, and the mass air flow ratio through the fuel nozzle was estimated as one of the major parameters.

We are now preparing to investigate the emission characteristics of the combustor by analytical tools including chemical reactions, which lead to analysis of the impact of the design parameters on the combustor performance. Furthermore, we will apply the operating condition of more efficient aircraft engine and estimate the emission performance using the data obtained in this research.

NOMENCLATURE

AFR	Air to Fuel Ratio
CAEP	Committee on Aviation Environmental Protection
DCAR	Ratio of mass air flow between dilution and combustion air holes
DOC	Direct Operating Cost
EICO	Emission Index of CO
EINOx	Emission Index of NOx
FNAR	Mass air flow ratio through fuel nozzle
ICAO	International Civil Aviation Organization
LBO	Lean Blowout
LTO	Landing and Take-Off
MTO	Max Take-Off
SMD	Sauter Mean Diameter
SSC	Single-Sector Combustor
THC	Total Hydrocarbon
Tin	Inlet air temperature
TRL	Technology Readiness Level

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