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COMBUSTION CHARACTERISTICS OF FUEL STAGED COMBUSTOR FOR AEROENGINES AT LTO CYCLE CONDITIONS

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ABSTRACT

In JAXA, combustion technologies have been developed with an aggressive target that is an 80% NOx reduction of CAEP/4. For the drastic reduction of NOx emissions, a fuel nozzle was designed based on the lean staged combustion concept. This paper describes single-sector combustor tests of a fuel staged combustor at ICAO LTO cycle conditions of an assumed engine with rated output of 40 kN and overall pressure ratio of 25.8. The results showed that the combustor enables a 77% reduction of the NOx standard of CAEP/4.

NOMENCLATURE

AFR	Air/fuel ratio
AFRc	AFR based on total air mass flow rate and total fuel mass flow rate
AFRm	AFR based on air mass flow rate of main mixer and fuel mass flow rate of main injector
AFRn	AFR based on air mass flow rate of whole fuel nozzle and total fuel mass flow rate of pilot injector and main injector
AFRp	AFR based on air flow rate of pilot mixer and fuel mass flow rate of pilot injector
CAEP	Committee on Aviation Environmental Protection
CE	Combustion efficiency, %
CO	Carbon monoxide
EICO	Emission index of CO, g/kg-fuel
EIHC	Emission index of HC, g/kg-fuel
EINOx	Emission index of NOx, g/kg-fuel
FN	Fuel nozzle
HC	Hydrocarbon
ICAO	International Civil Aviation Organization
LTO	Landing and Takeoff
MCL	Maximum Climb thrust
MTO	Maximum Takeoff thrust
NOx	Nitrogen oxides
OPR	Overall pressure ratio

INTRODUCTION

NOx emissions from aeroengines cause the atmospheric pollution near airports. In addition, in the troposphere NOx reacts with hydrocarbons in the atmosphere in the presence of sunlight to form ozone, which is a powerful greenhouse gas and thus is a secondary greenhouse gas [1]. There is a trend of increasing pressure ratio in aeroengines, as this reduces the specific fuel consumption and emissions of the most important greenhouse gas CO_2. However, NOx increases with pressure ratio so that the reduction of NOx in future aeroengines is more difficult. The volume of air transportation will increase in the future. Therefore, the development of technologies for NOx emissions reduction from aeroengines is very important.

ICAO CAEP has been stepped up the NOx standard as showed in Figure 1. Engine data were referred from the ICAO Aircraft Engine Emissions Databank [2]. Engine manufacturers and national research institutes are actively working on the low-NOx technologies to meet the lower NOx emissions standard. In Japan, Research and Development for an Environment-friendly Small Aircraft Engine (Eco-Engine) [3] is in progress. The thrust range of the engine is 8,000 to 12,000 pounds and the overall pressure ratio is 17. In this project, IHI, Kawasaki Heavy Industries and Mitsubishi Heavy Industries are developing three low-NOx combustors using different combustion types that are aimed at a 50% reduction of CAEP/4 standard. Rolls-Royce Deutschland is developing a core engine with 65% NOx reduction of the CAEP/2 and proved a 70% NOx reduction in a full annular combustor in the Engine 3E (Environment, Economy and Efficiency) program [4]. ACARE

(Advisory Council for Aeronautics Research in Europe) aims at an 80% NOx reduction in Vision 2020. In the United States, NASA ERA (Environmentally Responsible Aviation) project is progressing [5]. It aims at a 75% NOx reduction of CAEP/6.

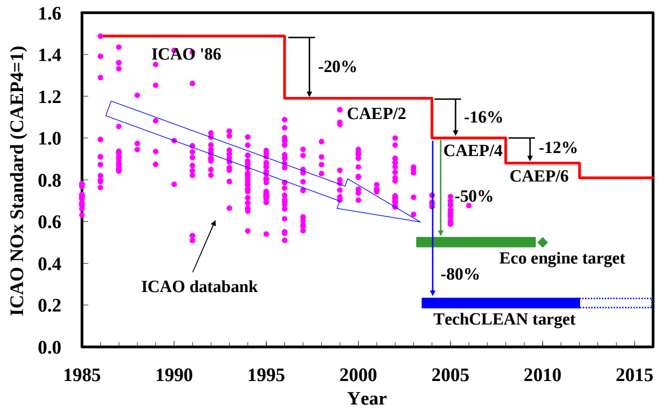

Figure 1. ICAO NOX STANDARD AND THE TARGET OF TECHCLEAN PROJECT.

JAXA started TechCLEAN project [6] in October 2003 for conducting research and development of the aeroengine technologies for environmental adaptation. In this project, technologies for reduction of noise, NOx and CO2 are being developed. Target of the NOx is an 80% reduction of ICAO CAEP/4. For the drastic reduction of NOx emissions, a fuel nozzle based on the lean staged combustion concept was designed. It has a pilot fuel injector for diffusion combustion at the center of the fuel nozzle and a main fuel-air mixer for lean premixed combustion around the pilot.

Geometric variations of the main swirler have been investigated in a single-sector combustor rig at four conditions of the LTO cycle of Eco-Engine [7]. A fuel nozzle, so-called model E, which is characterized by a triple contrary swirler showed highest low-NOx performance. The test results shows that the NOx emission of the fuel nozzle is a 72% reduction of ICAO CAEP/4 standard.

The fuel nozzle was also tested in a multi-sector combustor at the same conditions [8]. The combustor is three-sixteenth size of a small annular combustor and has three fuel nozzles. The test results showed that the combustor has combustion characteristics equivalent to a 70% NOx reduction of CAEP/4, which was almost same with the single-sector combustor. For improvement of the combustion efficiency at middle engine power conditions, the fuel staging amongst the main fuel injectors was also investigated. The results showed that the fuel staging is effective to improve the combustion efficiency of the annular combustor.

In the present work, the fuel nozzle was tested in the single-sector combustor rig at four conditions of the LTO cycle of an assumed engine. The engine has rated output of 40 kN and overall pressure ratio of 25.8.

FUEL STAGED COMBUSTOR

Figure 2 shows the cross-section of the selected lean staged fuel nozzle, model E. The specification of the fuel nozzle model is listed in Table 1. Figure 3 shows the outlet side of the fuel nozzle.

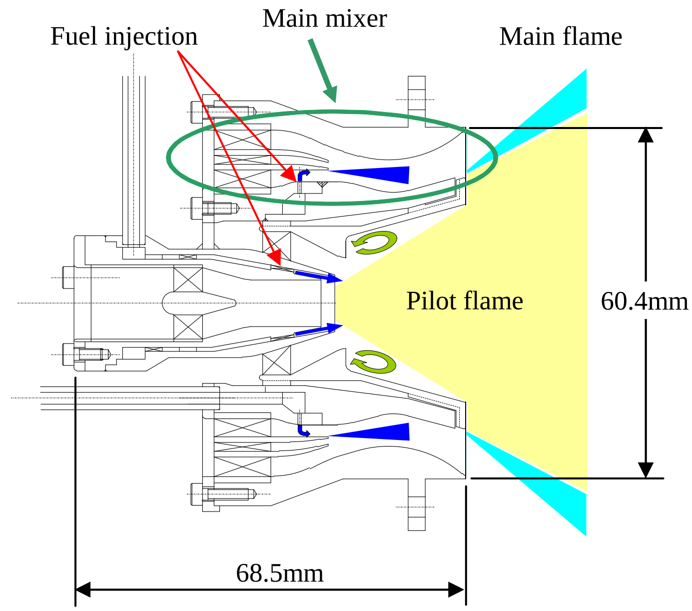

Figure 2. THE CROSS-SECTION OF THE FUEL NOZZLE MODEL E.

Table 1. THE SPECIFICATION OF THE FUEL NOZZLE MODEL E.

Item		Unit	Value
Swirler vane angles	Pilot inner	degree	+55
	Fuel grooves	degree	+50
	Pilot outer	degree	-45
	Main inner	degree	-50
	Main middle	degree	+50
	Main outer	degree	-50
Number of pilot fuel injection grooves		-	8
Width of grooves of pilot		mm	0.5
Depth of grooves of pilot		mm	0.5
Number of main fuel injection holes		-	10
Diameter of main injection holes		mm	0.5
Effective opening area		mm2	532

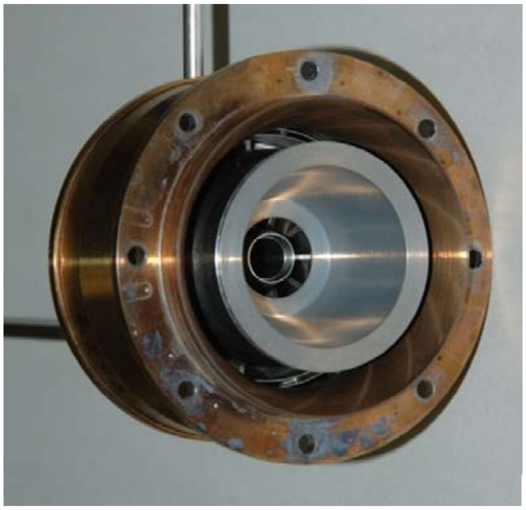

Figure 3. THE OUTLET SIDE OF THE FUEL NOZZLE MODEL E.

The fuel nozzle has a pilot fuel nozzle in the center. The pilot nozzle is a pre-filming type air blast one and uses diffusion combustion. The vortex generated on the backward-facing step prevents the fuel spray attaching the wall. The main fuel mixer using premixed combustion is set in a coaxial layout. The main fuel is injected from simple holes and penetrates the airflow and reaches a pre-filmer, a cylinder for pre-filming of fuel. The distance between the fuel injection hole and the pre-filmer is very short.

The main fuel is injected in the middle and high engine power conditions, cruise, climb and takeoff. Therefore, the main fuel can be controlled to penetrate to the pre-filmer at all times by adjusting the pilot fuel flow rate at the same time. When the engine power is increased at transition from the pilot mode to the pilot plus main mode, the pilot fuel is decreased and the main fuel is injected simultaneously. When the power is decreased through the clacking point, the main fuel is cut and the pilot fuel is increased. The fuel nozzle has ten main fuel injection holes. As injection holes increase, the fuel concentration goes to uniform, however the fuel penetration becomes weak. The number of the injection holes was selected to balance these.

The fuel nozzle has a contrary triple swirler for main airflow. The swirler forms strong shear region in the main passage and strong swirling flow in the combustion chamber. Two shear layers between three flows make intense turbulence. The turbulence promotes atomization of the fuel and mixing of fuel and air.

Figure 4 shows schematics of the single-sector combustor. It has a square cross-section 85 mm x 85 mm. Four liner walls are cooled by air running through the angled air holes and are kept from the combustion gas by air film. Each curved wall has three dilution air holes with 6.5mm of diameter in opposite each other. The exit is narrowed in one direction. A bar type gas sampling probe is placed to the downstream of the exit. The distance from the downstream edge of the fuel nozzle to sampling probe is about 190 mm.

Table 2 shows the effective opening area of the single-sector combustor.

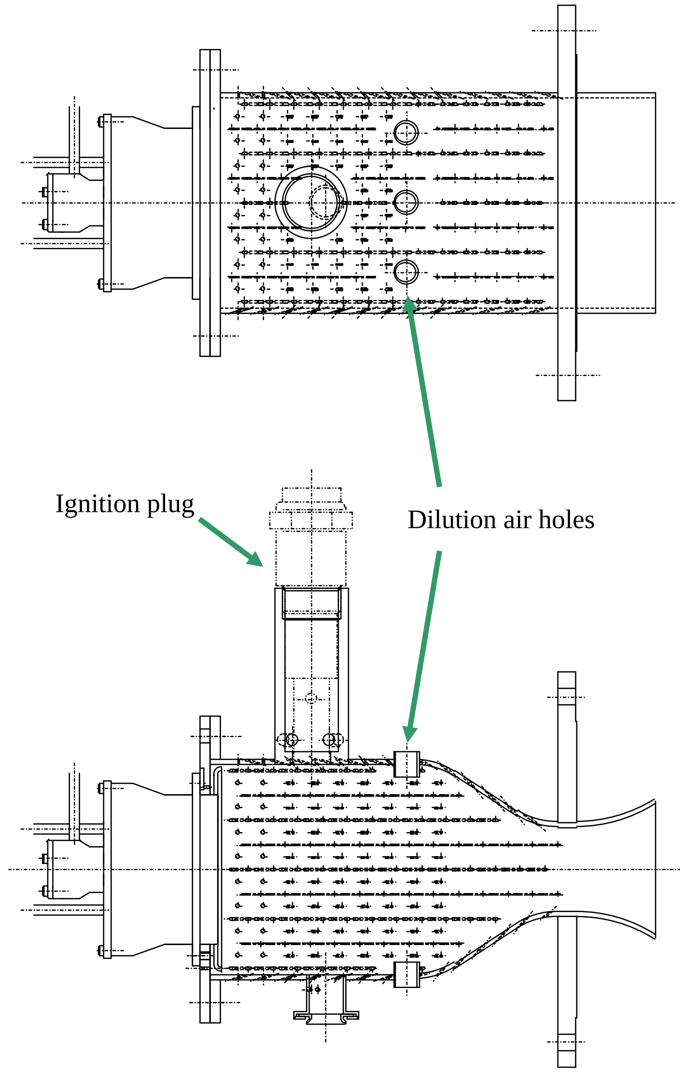

Figure 4. SCHEMATICS OF SINGLE-SECTOR COMBUSTOR

Table 2. THE EFFECTIVE OPENING AREA BREAKDOWN OF THE SINGLE-SECTOR COMBUSTOR.

Item	Opening area, mm2
Combustor total	1106
Fuel nozzle	532
Pilot mixer	110
Main mixer	422
Combustion liner	574
Dilution air holes	168
Cooling air holes, etc.	406

MEASUREMENT SYSTEMS

Exhaust gas was sampled at the exit of the combustor by the bar type water-cooled probe. It has nine sampling holes that is placed at equal intervals. The sampled gas was analyzed by using HORIBA MEXA-7100D to obtain the concentrations of CO, CO2, HC, NOx and O2.

SAE smoke number was measured by a smoke meter developed in JAXA in conformity with the SAE regulation.

TEST CONDITIONS

A fanjet engine was assumed for evaluations of the low NOx technologies. Its rated output is 40 kN and overall pressure ratio (OPR) is 25.8. The combustor conditions of the LTO cycle of the engine are shown in Table 3. Ten fuel nozzles fit the assumed engine based on the air mass flow rate. Table 4 shows ICAO standards for the assumed engine and the targets of TechCLEAN.

Table 3. THE COMBUSTOR CONDITIONS OF THE LTO CYCLE OF THE ASSUMED ENGINE.

Conditions	Unit	7%	30%	85%	100%
Pressure	kPa	487	1077	2266	2619
Temperature	K	503	609	756	787
Air flow rate	kg/s	3.96	7.91	14.24	15.82
Fuel flow rate	g/s	42.4	103.3	302.7	369.1
Air fuel ratio	-	93.2	76.5	47.0	42.9

Table 4. ICAO STANDARDS FOR THE ASSUMED ENGINE AND THE TARGETS OF TECHCLEAN.

Emission	Standard	Target	
Unit	g/kN	% of standard	g/kN
NOx	70.6	20	14.1
HC	19.6	100	19.6
CO	118.0	100	118.0
Smoke	30.4	100	30.4

Total pressure loss coefficient was kept at 4.0% in all conditions. In actual engines, the pressure loss coefficient of the combustor decreases as the engine power increases. Therefore, the air mass flow rate of the combustor is larger than one-tenth of air flow rate of the assumed engine in Table 3. It is about 107% at the 85% MTO condition and 109% at the 100% MTO condition.

The fuel was kerosene instead of jet fuel. The fuel split in each LTO cycle condition is shown in Table 5. In the 7% and 30% MTO conditions, the whole fuel was injected from the pilot fuel injector. In the 85% MTO condition, 11-18 % of the total fuel was supplied to the pilot fuel nozzle and the rest to the main one. In the 100% MTO condition, 11-19 % of total fuel was supplied to the pilot fuel nozzle.

Table 6 shows the adiabatic flame temperatures for the fuel and the air of the pilot mixer, the fuel and the air of the main mixer, the total fuel and the fuel nozzle air and the total fuel and the total air at the LTO conditions. Pilot fuel split of 16% is used at the 85% MTO condition and 12% in the 100% MTO condition.

Table 5. THE FUEL SPLIT AT EACH LTO CYCLE CONDITION.

Condition	Pilot, %	Main, %
7% MTO	100	0
30% MTO	100	0
85% MTO	11-18	82-89
100% MTO	11-19	89-81

Table 6. THE ADIABATIC FLAME TEMPERATURES OF FOUR AFRS AT THE LTO CYCLE CONDITIONS ON THE KELVIN SCALE

Condition	AFRp	AFRm	AFRn	AFRc
7% MTO	2180	503	1316	922
30% MTO	2027	609	1555	1101
85% MTO	1817	2127	2068	1458
100% MTO	1689	2286	2171	1534

TEST RESULTS AND DISCUSSIONS

Figure 5 shows the dependence of the emission indices of NOx, HC and CO on the air/fuel ratio obtained from the air flow rate of the pilot mixer and the fuel mass flow rate of the pilot injector (AFRp) at the pressure and the air temperature of the 7% MTO condition.

The green vertical line shows the AFR of the pilot mixer at the 7% MTO, when the number of the fuel nozzle of the assumed combustor is ten. The vertical red and green lines show a +-3% variation in AFR. EINOx has the maximum value at 14.7 of AFRp and decrease to both sides, rich and lean. EIHC and EICO are low in the middle region on the contrary.

The AFRp of lean blowout was 23.3. It corresponds to the combustor AFR of 233 and is high enough.

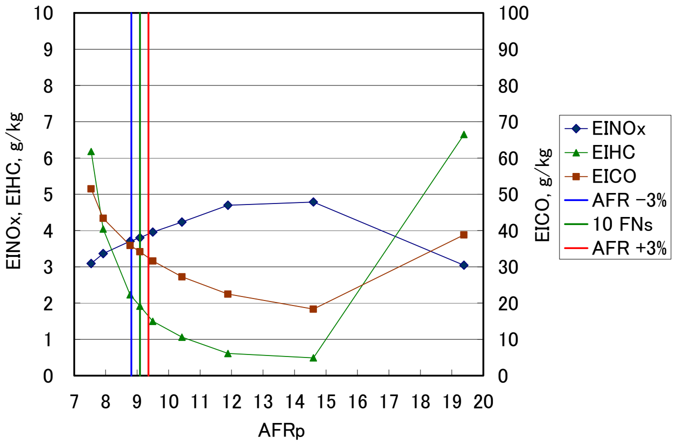

Figure 5. DEPENDENCE OF EMISSION INDICES ON AFR BASED ON THE AIR FLOW RATE OF THE PILOT AT PRESSURE AND AIR TEMPERATURE OF 7% MTO CONDITION.

Figure 6 shows the dependence of emission indices of NOx, HC and CO and the SAE smoke number on the AFRp at pressure and air temperature of the 30% MTO condition. The smoke number is almost same with the standard at +3% of the original AFR. It is smaller than the standard at the original AFR and -3% AFR. The smoke number is low enough comparing with the standard at the 7%, 85% and 100% MTO conditions.

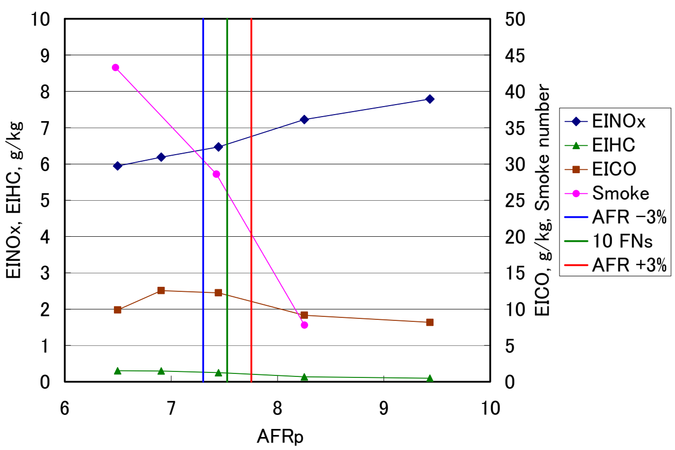

Figure 6. DEPENDENCE OF EMISSION INDICES ON THE AFR BASED ON THE AIR FLOW RATE OF THE PILOT AT PRESSURE AND TEMPERATURE OF 30% MTO CONDITION.

Figure 7 shows the dependence of emission indices of NOx, HC and CO on air/fuel ratio obtained from whole fuel nozzle and total fuel mass flow rate of pilot injector and main injector (AFRn) at pressure and air temperature of the 85% MTO condition. As AFRn increases, EINOx decreases and EIHC and EICO increase. EICO at the original AFR is low enough. For the engine with 17 of overall pressure ratio, EICO is low at the 85% MTO condition and staging of main injectors among fuel nozzles was necessary to obtain low EINOx [7, 8]. In this work, assuming engine with 25.8 of OPR, the air temperature at the combustor inlet is higher than the former, it was not necessary to assume the staging of main injectors.

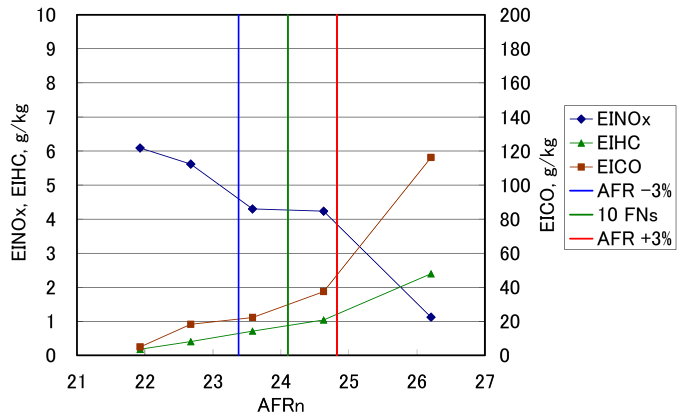

Figure 7. DEPENDENCE OF EMISSION INDICES ON THE AFR BASED ON THE AIR FLOW RATE OF THE FUEL NOZZLE AT PRESSURE AND TEMPERATURE OF 85% MTO CONDITION.

Figure 8, 9 and 10 show the dependence of emission indices of NOx, HC and CO on AFRn, respectively, at pressure and air temperature of the 100% MTO condition. Data are classified to six AFRp ranges. As AFRp increases, EINOx decreases. EINOx increases as AFRp decreases. EIHC is small in all tested AFRn. EICO is small in low AFRn region, but increases in higher AFRn than 23.5. In low AFRn region, EINOx is high and in high AFRn region, EICO is high. Therefore, it is necessary to operate the combustor in the balanced AFRn region of NOx and EICO.

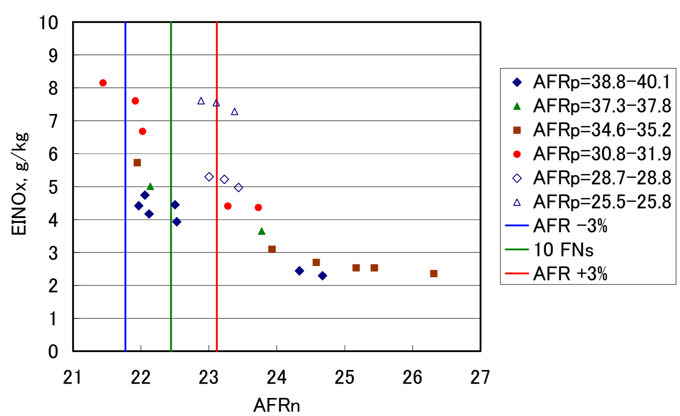

Figure 8. DEPENDENCE OF NOX EMISSION INDICES ON THE AFR BASED ON THE AIR FLOW RATE OF THE FUEL NOZZLE AT PRESSURE AND TEMPERATURE OF 100% MTO CONDITION.

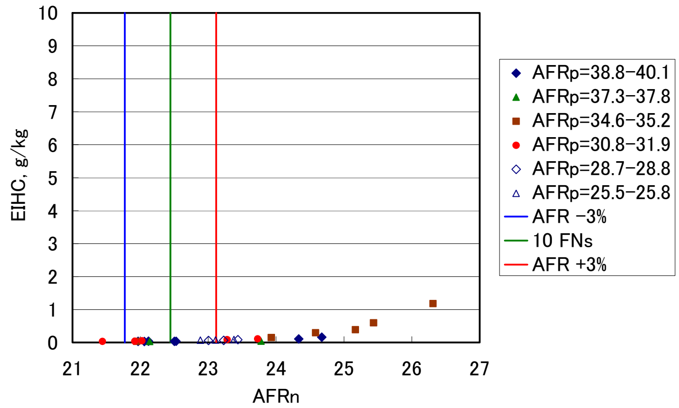

Figure 9. DEPENDENCE OF HC EMISSION INDICES ON THE AFR BASED ON THE AIR FLOW RATE OF THE FUEL NOZZLE AT PRESSURE AND TEMPERATURE OF 100% MTO CONDITION.

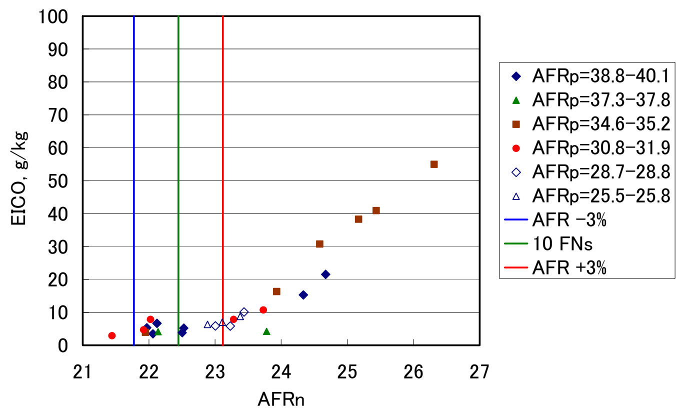

Figure 10. DEPENDENCE OF CO EMISSION INDICES ON THE AFR BASED ON THE AIR FLOW RATE OF THE FUEL NOZZLE AT PRESSURE AND TEMPERATURE OF 100% MTO CONDITION.

Figure 11 shows dependence of NOx emission index and combustion efficiency on the AFRp, when only pilot fuel is injected. Blowout limit was 33.8 of AFR. EINOx increases as AFRp decreases. EICO is high in the region where the flame exists. When the main fuel was injected, a stable pilot flame exists to 40.1 of AFRp. The hot gas that is generated by the main flame raise the gas temperature in the recirculation zone enables the combustion of the pilot fuel.

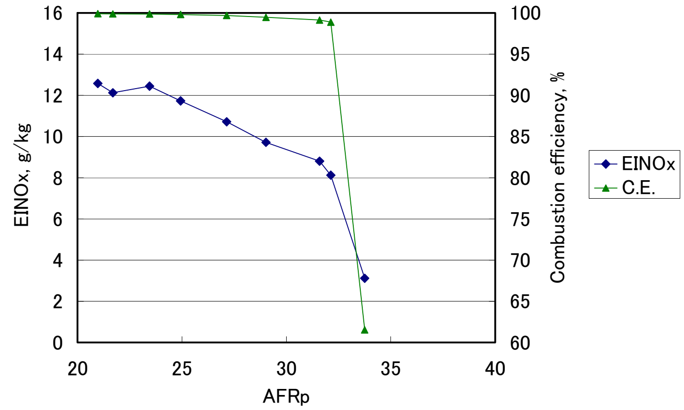

Figure 11. DEPENDENCE OF NOx EMISSION INDEX AND COMBUSTION EFFICIENCY ON THE AFR BASED ON AIR FLOW RATE OF PILOT MIXER AT PRESSURE AND TEMPERATURE OF 100% MTO CONDITION.

Table 7 shows total emissions of three AFR settings that include original AFR, -3% AFR and +3% AFR, in the LTO cycle of the assumed engine against the ICAO standards. At the 100% MTO condition, interpolations and extrapolations were conducted with data of AFRp=38.3-40.1. NOx and HC emissions have little change by three AFR settings. At original setting, CO emission and smoke are within the ICAO standards. At -3% AFR, CO emission is lower than the original one, however, smoke reaches the standard. At +3% AFR, smoke is lower than that of original AFR, however, CO emission is almost same with the standard. It means that this fuel nozzle has only 6% margin to meet the standards. Smoke at the 30% MTO and EICO at the 7% and 85% MTO have to be decreased.

Table 7. TOTAL EMISSIONS IN LTO CYCLE OF ASSUMED ENGINE AGAINST THE ICAO CAEP STANDARDS.

AFR setting	NOx	HC	CO	Smoke at 30% MTO
AFR -3%	23.4	22.7	75.8	100.3
Original AFR 10 fuel nozzles	22.9	21.5	81.3	85.6
AFR +3%	22.4	20.7	94.1	67.0

Figure 12 shows NOx emissions against the CAEP/4 standard at each LTO cycle condition in three AFR settings. The LTO NOx emission increases as the AFR decreases. NOx emissions at 85% and 100% MTO increase.

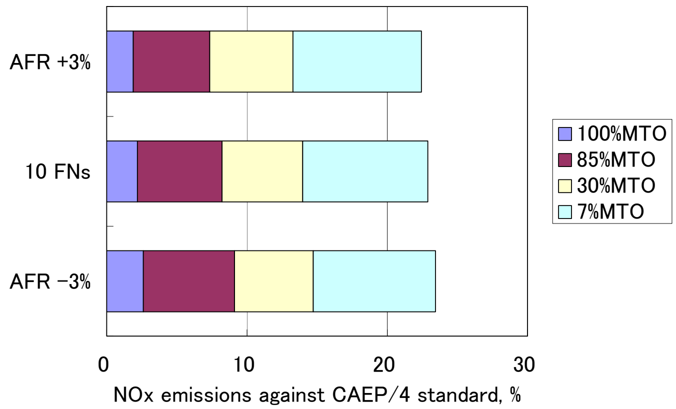

Figure 12. NOx EMISSIONS AGAINST THE CAEP/4 STANDARD AT LTO CYCLE CONDITIONS IN THREE AFR SETTINGS OF THE FUEL NOZZLE.

Figure 13 shows HC emissions against the CAEP standard at each LTO cycle condition in three AFR settings. The LTO HC emission increases as AFR grows, however, they are enough smaller than the CAEP standards. All HC emissions at the 100% MTO is very small. As AFR grows, the HC emission at the 85% MTO increases, however, HC emission at the 7% MTO decreases. All HC emissions at the 30% MTO is small.

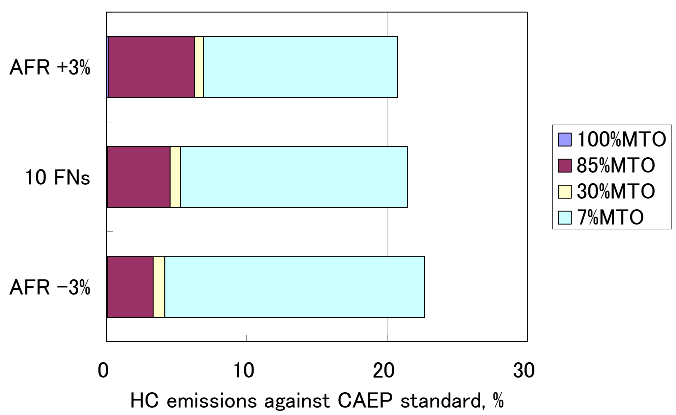

Figure 13. HC EMISSIONS AGAINST THE CAEP STANDARD AT LTO CYCLE CONDITIONS IN THREE AFR SETTINGS OF THE FUEL NOZZLE.

Figure 14 shows the CO emissions against the CAEP standard at each LTO cycle condition in three AFR settings. CO emissions of 7% and 30% do not change, however, those of 85% and 100% increase as AFR grows.

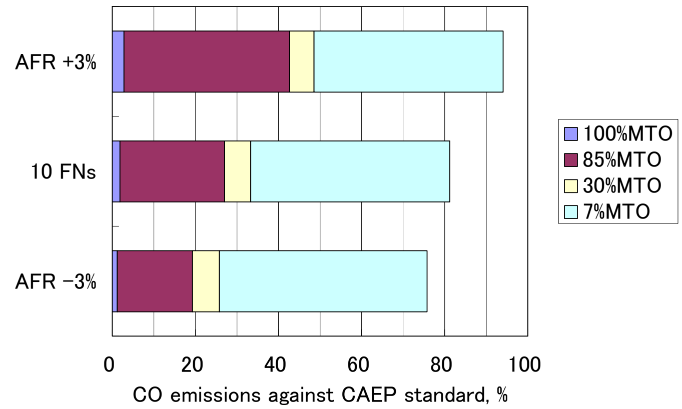

Figure 14. CO EMISSIONS AGAINST THE CAEP STANDARD AT LTO CYCLE CONDITIONS IN THREE AFR SETTINGS OF THE FUEL NOZZLE.

CONCLUSIONS

A fuel staged single-sector combustor was tested in the ICAO LTO cycle conditions of the assumed engine. Test results showed that the combustor has NOx characteristic of 77% reduction of CAEP/4. At +3% AFR condition, the CO emission is almost same with the CAEP standard. At -3% AFR condition, SAE smoke number reached the standard at the 30% MTO condition. Reduction of the smoke at higher thrust condition than the 30% MTO and reduction of the CO emission at lower thrust condition than the 85% MTO condition is necessary.

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