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Emission Reduction of Fuel-Staged Aircraft Engine Combustor Using an Additional Premixed Fuel Nozzle

The Japan Aerospace Exploration Agency (JAXA) is conducting research and development on aircraft engine technologies to reduce environmental impact for the Technology Development Project for Clean Engines (TechCLEAN). As a part of the project, combustion technologies have been developed with an aggressive target that is an 80% reduction over the NO_x threshold of the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP)/4 standard. A staged fuel nozzle with a pilot mixer and a main mixer was developed and tested using a single-sector combustor under the target engine's landing and takeoff (LTO) cycle conditions with a rated output of 40 kN and an overall pressure ratio of 25.8. The test results showed a 77% reduction over the CAEP/4 NO_x standard. However, the reduction in smoke at thrust conditions higher than the 30% MTO condition and of CO emission at thrust conditions lower than the 85% MTO condition are necessary. In the present study, an additional fuel burner was designed and tested with the staged fuel nozzle in a single-sector combustor to control emissions. The test results show that the combustor enables an 82% reduction in NO_x emissions relative to the ICAO CAEP/4 standard and a drastic reduction in smoke and CO emissions. [DOI: 10.1115/1.4007868]

Introduction

NO_x emissions from aircraft engines cause atmospheric pollution near airports. In addition, in the troposphere, NO_x reacts with hydrocarbons in the presence of sunlight to form ozone, which is a powerful greenhouse gas, and thus NO_x is a secondary greenhouse gas [1]. There is a trend of increasing the pressure ratio in aircraft engines, since this trend reduces the fuel consumption and emission of the most important greenhouse gas, CO_2 . However, NO_x increases with pressure ratio, thereby making the reduction in NO_x in future aircraft engines more difficult. Air transportation volume will increase in the future. Therefore, the development of technologies to reduce NO_x emissions from aircraft engines is very important.

ICAO CAEP has tightened the NO_x emission standard, as shown in Fig. 1. Engine data were taken from the ICAO Aircraft Engine Emissions Databank [2]. Engine manufacturers and national research institutes are actively working on low- NO_x technologies to meet lower NO_x emission standards. In Japan, research and development of environmentally compatible engines for small aircraft (ECO engine project) [3] is being conducted. The thrust range of the engine is 8000–12,000 pounds. For this project, IHI, Kawasaki Heavy Industries, and Mitsubishi Heavy Industries developed three low- NO_x combustors using different combustion types that were aimed at a 50% reduction over the CAEP/4 standard.

Rolls-Royce Deutschland is developing a core engine with a 65% reduction over the CAEP/2 NO_x standard and proved a 70% reduction in a full annular combustor in the Engine 3E (Environment, Economy, and Efficiency) program [4]. Advisory Council for Aeronautics Research in Europe (ACARE) aims at an 80% reduction in NO_x emission in its vision for aeronautics in the year 2020, Vision 2020. In the United States, the NASA Environmentally Responsible Aviation (ERA) project is also underway [5]. It

aims at a 75% reduction over the CAEP/6 NO_x standard. General Electric developed a lean-staged combustor, namely twin annular premixing swirler (TAPS) combustor, and applied it to a new practical engine, GENx.

The Japan Aerospace Exploration Agency (JAXA) started TechCLEAN [6] in October 2003 for conducting research and development of aircraft engine technologies to reduce environmental impact. In this project, technologies for noise, NO_x and CO_2 reduction are being developed. The target for NO_x emissions is an 80% reduction over the ICAO CAEP/4 standard. For this drastic reduction in NO_x 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 were investigated in a single-sector combustor rig under four conditions of the LTO cycle of ECO engine [7]. A fuel nozzle, so-called model E, which was characterized by a triple contrary swirler, showed the best low- NO_x performance. The test results showed that the NO_x

Fig. 1 ICAO NO_x standard and target of TechCLEAN

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Fig. 2 Cross-section of LSF

emission of the fuel nozzle was a 72% reduction over the ICAO CAEP/4 standard.

This fuel nozzle was also tested in a multisector combustor under the same conditions [8]. The combustor is 3/16th the size of a small annular combustor and has three fuel nozzles. The test results showed that the combustor had combustion characteristics equivalent to a 70% reduction over the CAEP/4 NO_x standard, which was almost the same as that of the single-sector combustor. For improvement of combustion efficiency (CE) under the middle power conditions of the engine, fuel staging among the main fuel mixers was investigated. The results showed that fuel staging was effective in improving the CE of the annular combustor.

As a next step, the fuel nozzle was tested in the single-sector combustor rig under the four conditions of the LTO cycle of an assumed engine [9]. The engine has a rated output of 40 kN and an overall pressure ratio (OPR) of 25.8. Test results showed that the combustor has a NO_x emission, which is a 77% reduction over CAEP/4. However, a reduction in smoke emissions under thrust conditions higher than the 30% MTO condition and a reduction in CO emissions under thrust conditions lower than the 85% MTO condition are necessary.

In this study, an additional fuel nozzle, called the emissions control fuel nozzle (ECF), was designed to reduce NO_x, smoke, and CO emissions. The single-sector combustor with the lean-staged fuel nozzle (LSF) and the additional fuel nozzle was tested.

Lean-Staged Fuel Nozzle

Figure 2 shows the cross-section of LSF. Specifications for the fuel nozzle model are listed in Table 1. Figure 3 shows the outlet side of the fuel nozzle. The fuel nozzle has a pilot mixer in the center. The pilot mixer is a prefilming-type air blast one and forms a diffusion flame. The vortex generated on the backward-facing step prevents the fuel spray attaching onto the wall. The main fuel mixer using premixed combustion is set in a coaxial layout. The main fuel is injected from round holes, and it penetrates the air-flow and reaches a prefilmer that is a cylinder for prefilming of the fuel. The distance between the fuel injection hole and the prefilmer is very short.

The main fuel is injected under the middle and high engine power conditions of cruise, climb, and takeoff. Therefore, the main fuel can be controlled to penetrate into the prefilmer at all times by adjusting the pilot fuel flow rate. When the engine power is increased at the 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

Table 1 Specifications of LSF

Item	Unit	Value
Swirler vane angles		
Pilot inner		+55
Fuel injection grooves		+50
Pilot outer	Degree	-45
Main inner		-50
Main middle		+50
Main outer		-50
Number of pilot fuel injection grooves	—	8
Width of pilot grooves	mm	0.5
Depth of pilot grooves	mm	0.5
Number of main fuel injection holes	—	10
Diameter of main injection holes	mm	0.5
Effective opening area	mm ²	532

Fig. 3 Outlet side of LSF

clacking point, the main fuel is cut and the pilot fuel is increased. The fuel nozzle has 10 main fuel injection holes. As the number of injection holes increases, the fuel concentration becomes more uniform; however, the fuel penetration becomes weaker. The number of injection holes was selected to balance these effects. The fuel nozzle has a contrary triple swirler for the main airflow. This swirler forms a strong shear region in the air passage of the main mixer and a strong swirling flow in the combustion chamber. Two shear layers between three flows create an intense turbulence. The turbulence promotes atomization of the fuel as well as mixing of fuel and air. The residence time of the fuel-air mixture in the main mixer is much shorter than the autoignition time of the mixture at the combustor inlet air temperature of the 100% MTO of the assumed engine. However, air temperature of higher pressure ratio engines exceeds 900 K and autoignition time becomes exponentially shorter. The passage of the main mixer has to be redesigned to fit higher pressure ratio engines.

Summary of the Single-Sector Combustor Test of LSF

Before conducting this study, LSF was tested in the single-sector combustor rig under four conditions of LTO cycle of an assumed engine [9]. Figure 4 shows the original single-sector combustor, C1. It has a square cross-section 85 mm × 85 mm. Four liner walls are cooled by air running through the angled air holes, and the liner walls are kept away from the combustion gas

Fig. 4 Original single-sector combustor, C1

Table 2 Effective opening area breakdown of C1

Item	Opening area, mm ²
Combustor total	1106
Fuel nozzle	532
Pilot mixer	110
Main mixer	422
Combustion liner	574
Dilution air holes	168
Cooling air holes, etc.	406

Table 3 Total emissions in LTO cycle of assumed engine against the ICAO CAEP/4 standard

NO _x	HC	CO	Maximum SN
22.9	21.5	81.3	85.6 at 30% MTO

by the air film. Each curved wall has three dilution air holes with a diameter of 6.5 mm located opposite each other. The exit is narrowed in one direction. A bar-type gas sampling probe was placed downstream of the exit. The distance from the downstream edge of the fuel nozzle to the sampling probe is about 190 mm. Table 2 shows the effective opening area of the single-sector combustor.

Table 3 shows the total emissions of C1 in the LTO cycle of the assumed engine against the ICAO CAEP standard. Test results showed that the combustor enables a 77% reduction in LTO NO_x emission relative to the ICAO CAEP/4 standard. However, the reduction in smoke at thrust conditions higher than the 30% MTO condition and of CO emission at thrust conditions lower than the 85% MTO condition are necessary.

Fig. 5 Fuel scheduling

Fig. 6 Cross-section of ECF

Test of the Single-Sector Combustor With the Additional Fuel Nozzle

Under the 30% MTO condition, it is necessary to increase the air/fuel ratio (AFR)_p in order to reduce the smoke and burn the rest of the fuel after premixing with air, which in turns helps in reducing the NO_x emissions. However, the air temperature at the combustor inlet is too low to burn the fuel with low HC and CO emissions. Therefore, an axial-staged combustion is used. First, the pilot flame is used to burn a part of the fuel and the rest of the fuel and air mixture is burned using the hot-burned gas of the pilot flame, yielding low emissions. For the second combustion, an additional fuel nozzle, ECF, was designed. A main mixer designed to obtain enough combustion efficiency under the 85% MTO condition generates a higher emission index of NO_x (EINO_x) under 100% MTO condition. ECF is also used to reduce NO_x emissions under high engine thrust conditions. Figure 5 shows a schematic of the fuel scheduling.

Details of ECF and the Single-Sector Combustor

Figure 6 shows the cross-section of ECF. Specifications for the fuel nozzle are listed in Table 4. The fuel nozzle is a prefilming-type air blast one and similar to the pilot mixer of LSF. However, it has three swirlers, and the swirler vane angles are small to prevent the formation of a recirculation flow in the mixing zone of the fuel nozzle. A flame held in the recirculation flow may generate high NO_x emissions. The fuel is injected at the upper stream comparing to the pilot fuel injector. The modification has an effect that makes the fuel film more uniform and the

Table 4 Specifications of ECF

Item	Unit	Value
Swirl angles		
Inner swirler		+20
Fuel injection grooves	Degree	+20
Middle swirler		-20
Outer swirler		+5
Number of fuel injection grooves	—	8
Width of fuel injection grooves	mm	0.5
Depth of fuel injection grooves	mm	0.5
Effective opening area	mm ²	140

Table 5 Effective opening area breakdown of C2

Item	Opening area, mm ²
Combustor total	1053
Fuel nozzle	532
Pilot mixer	110
Main mixer	422
Additional fuel nozzle	140
Combustion liner	381

Table 6 Combustor conditions of the LTO cycle of 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

Fig. 7 Single-sector combustor with ECF, C2; (a) front view; (b) side view

air-fuel mixture becomes more uniform. The airflow from the outer swirler keeps the fuel away from the fuel nozzle wall.

The single-sector combustor with ECF is tested under the LTO cycle of the assumed engine. Figure 7 shows the single-sector combustor, C2. The inner surfaces of the sidewalls are made with heat-resistant concrete. The top and bottom walls are cooled by air running through the angled air holes and are kept away from the combustion gas by the air film. The pitch of the air holes is 4 mm × 4 mm. C2 has no dilution air holes. The size and shape of the combustion chamber are the same as those of C1. The distance from the downstream edge of LSF to the center axis of ECF is 50 mm. Table 5 shows the effective opening area breakdown of C2. The effective opening area is 99% of 1/10th of the combustor for the assumed engine.

Measurement Systems

Exhaust gas was sampled at the combustor exit by a bar-type water-cooled probe. It has nine sampling holes that are placed at equal intervals. The sampled gas was analyzed using HORIBA MEXA-7100D to achieve the concentration of CO, CO₂, HC, NO_x, and O₂. The Society of Automotive Engineers (SAE) smoke number was measured by a smoke meter developed by JAXA in conformity with SAE regulations.

Test Conditions

A fanjet engine was assumed for evaluating low NO_x combustion technologies. Its rated output is 40 kN and OPR is 25.8. The combustor conditions of the LTO cycle of the engine are shown in Table 6. Ten single-sector combustors are equivalent to the annular combustor of the assumed engine in terms of the air mass flow rate. Table 7 shows the ICAO standard for the assumed engine and the TechCLEAN targets. The airflow rate of the combustor was adjusted to maintain the total pressure loss coefficient between the combustor upstream and the combustor exit at 4.0% under all conditions.

The fuel used was kerosene, not jet fuel. The fuel split in each LTO cycle condition is shown in Table 8. In the 7% MTO condition, the total fuel was injected from the pilot fuel injector. In the 30% MTO condition, the fuel was spitted between the pilot mixer and ECF. In the 85% MTO condition, 12% of the total fuel was supplied to the pilot fuel mixer and the rest to the main mixer. In the 100% MTO condition, a percentage of the pilot fuel was fixed to 11% and the rest was spitted between ECF and main mixer.

Table 7 ICAO standard for the assumed engine and the Tech-CLEAN targets

Emission	Standard	Target
Unit	g/kN	% of standard
NO _x	70.6	20
HC	19.6	100
CO	118.0	100
Smoke	30.4	100
		g/kN

Table 8 Fuel split at each LTO cycle condition

Condition	Pilot, %	ECF, %	Main, %
7% MTO	100	0	0
30% MTO	100	0	0
		100	0
85% MTO	12	0	88
100% MTO	11	0	89
	11	89

Fig. 8 Comparison of EINO_x and EIHC of C1 and C2 at pressure and air temperature of the 7% MTO condition

Test Results and Discussions

Figures 8 and 9 show the dependence of EINO_x, emission index of HC (EIHC), and emission index of CO (EICO) on the AFRp at the pressure and air temperature of the 7% MTO condition. The red vertical line shows the AFRp under the 7% MTO condition when the number of LSFs for the assumed combustor is 10. The EIHC and EICO of C2 are low in the wider AFRp region than those in C1. The improvement was achieved by removing the dilution air holes. The EINO_x under the 7% MTO condition of C1 and C2 are almost the same. The AFRp of lean blowout was 28.3. It corresponds to the combustor AFR of 272 and is sufficiently high.

Figure 10 shows the EINO_x, EIHC, EICO, and SN under the pressure and air temperature of the 30% MTO condition when only pilot fuel is injected. The red vertical line shows the AFRp under the 30% MTO condition when the number of LSFs for the assumed combustor is 10. The EINO_x has a peak around AFRp of 15; however, it is at a minimum near the 30% MTO condition. The EIHC and EICO are low and flat around the same condition. The SN under the 30% MTO condition is 20, which is smaller than the standard value; however, the slope of the curve is steep. It means that the SN increases and exceeds the standard value under a little higher thrust condition.

Figure 11 compares the EINO_x, EIHC, EICO, and SN of C1 and C2. The trends of the EINO_x curves of C1 and C2 are different. However, the values under the 30% MTO condition are close.

Fig. 9 Comparison of EICO of C1 and C2 at pressure and air temperature of the 7% MTO condition

Fig. 10 EINO_x, EIHC, EICO, and SN of C2 at pressure and air temperature of the 30% MTO condition when only pilot fuel is injected

Fig. 11 Comparisons of EINO_x, EIHC, EICO, and SN of C1 and C2 at pressure and air temperature under the 30% MTO condition when only pilot fuel is injected

The curves of the EIHC and EICO of C1 and C2 are similar. The slope of the SN curve of C1 is steeper than that of C2.

Figure 12 shows variations in the EINO_x, EIHC, EICO, and SN under the 30% MTO condition with an ECF fuel percentage from 43% to 65% when both the pilot fuel and the ECF fuel are injected. When only the pilot fuel is injected, the EINO_x is 6.6 g/kg. When both the pilot fuel and ECF fuel are injected, the

Fig. 12 Dependence of $EINO_x$, $EIHC$, $EICO$, and SN at the 30% MTO condition on ECF fuel percentage when both fuel and ECF fuel are injected

Fig. 13 Comparisons of $EINO_x$, $EIHC$, and $EICO$ of C1 and C2 at pressure and air temperature under the 85% MTO condition

$EINO_x$ is almost flat and slightly lower than the pilot only case. As the ECF fuel percentage increases from 43.0% to 65.2%, the AFR_p increases from 14.4 to 22.6 and the $EINO_x$ of pilot flame decreases from 9.9 to 5.9, as shown in Fig. 10. Considering the difference of the NO_x emissions between the pilot only case and the pilot plus ECF case is NO_x formed by ECF, the $EINO_x$ of ECF increases from 0.7 to 4.0, except for the data at 62%. However, the $EINO_x$ of ECF is smaller than the NO_x of the pilot only case in this range. There is only one SN datum. However, it is obvious that the SN is low enough in the high AFR_p range.

Figure 13 shows comparisons of the $EINO_x$, $EIHC$, and $EICO$ of C1 and C2 at the pressure and air temperature of the 85% MTO condition. The $EINO_x$ of C2 is lower than that of C1, because the pilot fuel percentage of C1 is 17%, which is higher than that of C2. The $EIHC$ and $EICO$ are lower than those of C1, which is caused by the quenching of the main flame by the cooling and dilution air.

Figure 14 shows comparisons of the $EINO_x$, $EIHC$, and $EICO$ of C1 and C2 at the pressure and air temperature of the 100% MTO condition. The $EINO_x$ of C1 and C2 agree. The $EIHC$ and $EICO$ of C2 are much lower than those of C1.

Figure 15 shows the dependence of $EINO_x$, $EIHC$, and $EICO$ on the AFR_b under the 100% MTO condition. The AFR_p was maintained at 39 and fuel flow rates of the main mixer and ECF were changed. The equation “P + M” indicates the injection of the pilot and main fuel. The equation “P + M + E” indicates the injection of the pilot, main, and ECF fuel. The red vertical line shows the AFR_b under the 100% MTO condition. From an extrapolation of the “P + M” data, the $EINO_x$ is around six under the 100%

Fig. 14 Comparisons of $EINO_x$, $EIHC$, and $EICO$ of C1 and C2 at pressure and air temperature under the 100% MTO condition

Fig. 15 Dependence of $EINO_x$, $EIHC$, and $EICO$ on AFR_b under the 100% MTO condition; E indicates ECF

Fig. 16 Dependence of $EINO_x$, $EIHC$, $EICO$, and CE at 100% MTO condition on ECF fuel percentage

MTO condition. However, the $EINO_x$ can be controlled to be less than four by ECF.

Figure 16 shows the dependence of $EINO_x$, $EIHC$, $EICO$, and CE under 100% MTO condition on the ECF fuel percentage. The CE is more than 99.9% of ECF fuel percentage that ranges from 10% to 30%. The $EINO_x$ has a minimum value of 1.75 g/kg at the 21% ECF fuel. The $EIHC$ is almost zero in the indicated range. The $EICO$ increases when the ECF fuel percentage is less than 10% and more than 30%.

Table 9 Total emissions in LTO cycle of assumed engine of combustor model C1 and C2 against the ICAO CAEP standards

Combustor	NO _x	HC	CO	Maximum SN
C1	22.9	21.5	81.3	85.6 at 30% MTO
C2 pilot + ECF at 30% MTO	17.8	15.6	55.9	Less than 5
C2 pilot only at 30% MTO	19.5	6.6	42.7	69.0

Table 10 Fuel splits at LTO cycle conditions of C1

Condition	Pilot, %	Main, %
7% MTO	100	0
30% MTO	100	0
85% MTO	17	83
100% MTO	11	89

Table 11 Fuel splits at LTO cycle conditions of C2

Condition	Pilot, %	Main, %	ECF, %
7% MTO	100	0	0
30% MTO pilot + ECF	35	0	65
30% MTO pilot only	100	0	0
85% MTO	12	88	0
100% MTO	11	68	21

Table 12 AFR and adiabatic flame temperature of each mixture at LTO cycle conditions: upper: AFR; lower: temperature on the Kelvin scale

Condition	Pilot	Main	LSF	ECF	LSF + ECF
7% MTO	9.6 2101	Inf. 503	46.6 1288	Inf. 503	58.9 1140
30% MTO	22.8 2015	Inf. 609	110.3 958	15.4 2451	48.4 1354
85% MTO	40.5 1605	21.2 2211	23.5 2098	Inf. 756	29.7 1864
100% MTO	39.2 1657	25.1 2054	27.1 1976	26.8 1988	27.1 1979

Table 9 shows the total NO_x, HC, and CO emissions and the maximum SN of C1 and C2 in the LTO cycle of the assumed engine, relative to the ICAO CAEP standard at the fuel split shown in Tables 10 and 11. All emissions of C2 are reduced compared with C1. HC and CO emissions of C2 without ECF fuel injection are lower than the case of C2 with ECF fuel injection at the 30% MTO condition. The NO_x emission of C2 with ECF satisfies the target of TechCLEAN. Even though NO_x emission of C2 without ECF is higher than that of C2 with ECF, it satisfies the TechCLEAN NO_x target. However, SN of C2 without ECF is much higher than that of C2 with ECF. The clacking point of the fuel split from the pilot only mode to pilot plus ECF mode must be decided by the balance of CO emission and SN.

Table 12 shows the adiabatic flame temperatures for the AFR_p, AFR_m, AFR_n, AFR_e, and AFR_b of C2 under the LTO cycle conditions. At the 100% MTO condition, AFR_n and AFR_e are almost the same and the minimum EINO_x is obtained.

Figure 17 shows the NO_x emissions of C1 and C2 with ECF fuel injection relative to the CAEP/4 standard under each LTO cycle condition. The NO_x emissions under the 30%, 85%, and 100% MTO conditions decreased.

Figure 18 shows the HC emissions of C1 and C2 with ECF fuel injection relative to the CAEP standard under each LTO cycle

Fig. 17 Comparisons of NO_x emissions of C1 and C2 with ECF fuel injection relative to the CAEP/4 standard at each LTO cycle condition

Fig. 18 Comparisons of HC emissions of C1 and C2 with ECF fuel injection relative to the CAEP standard at each LTO cycle condition

Fig. 19 Comparisons of CO emissions of C1 and C2 with ECF fuel injection relative to the CAEP standard at each LTO cycle condition

condition. The HC emissions under the 7% and 85% MTO conditions are reduced by removing the dilution and cooling air holes. The HC emissions under the 30% MTO condition are increased.

Figure 19 shows the CO emissions of C1 and C2 with ECF fuel injection relative to the CAEP standard under each LTO cycle condition. The CO emissions under the 85% MTO condition are drastically reduced by decreasing the number of cooling air holes. The CO emissions under the 30% MTO condition are increased.

Conclusions

In this study, an additional fuel burner was designed to control the emissions and was tested with the staged fuel nozzle in a single-sector combustor. The test results show that the combustor enables a reduction of 82% in LTO NO_x emissions relative to the ICAO CAEP/4 standard and drastic reductions in smoke and CO emissions. The NO_x emission target of TechCLEAN is achieved at the single-sector combustor level. The next step is multisector combustor tests of LSF and ECF. Influences by interference between flows of adjacent fuel nozzles and temperature distributions in the combustor exit will be evaluated.

Nomenclature

AFR = air/fuel ratio
 AFRb = AFR based on total air mass flow rate and total fuel mass flow rate of LSF and ECF
 AFR_e = AFR based on air mass flow rate and fuel mass flow rate of ECF
 AFR_m = AFR based on air mass flow rate of main mixer and fuel mass flow rate of main injector
 AFR_n = AFR based on air mass flow rate of LSF and total fuel mass flow rate of pilot injector and main injector
 AFR_p = AFR based on air mass 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
 ECF = emissions control fuel nozzle

EICO = emission index of CO, g/kg-fuel
 EIHC = emission index of HC, g/kg-fuel
 EINO_x = emission index of NO_x, g/kg-fuel
 FN = fuel nozzle
 HC = hydrocarbon
 ICAO = International Civil Aviation Organization
 LSF = lean-staged fuel nozzle
 LTO = landing and takeoff
 MTO = maximum takeoff thrust
 NO_x = nitrogen oxides
 OPR = overall pressure ratio
 SN = smoke number of the Society of Automotive Engineers

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