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SUPPRESSION OF NOX EMISSION OF A LEAN STAGED COMBUSTOR FOR AN AIRCRAFT ENGINE

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ABSTRACT

Due to the increasing demands for environment protection, the regulation of NOx emissions from aircraft engines specified by ICAO have become more stringent year by year. A combustor with lean staged fuel injectors is one of the effective methods to reduce NOx emissions. Kawasaki heavy industries Ltd GTBC and Japan Aerospace Exploration Agency (JAXA) have been conducting joint research on a lean staged concentric fuel nozzle for a high pressure ratio aero engine. High pressure combustion tests were performed to clarify the effect of the contour of the air flow passage of the main premix duct, the arrangement of the swilers and the fuel injection position on the NOx emission especially at high power. Visualization of the fuel spray at elevated pressure inside of the premix duct using a model with transparent walls and a laser diagnostics technique showed clear relationship between the distribution of the fuel spray and the NOx emission.

INTRODUCTION

Reduction of NOx emission from aircraft engines is important to keep the clean atmosphere around the airports and at altitude. For aircraft engines NOx emission is the most critical at the maximum take-off condition because NOx emission exponentially increases with the temperature of the flame. The recent demand for fuel efficient engines, aiming at reducing both CO_2 and fuel cost, has pushed up the turbine inlet temperature, causing NOx emission to increase due to high temperature combustion. Research for low NOx combustion at high temperature has been conducted in recent years to pursue low CO and low NOx simultaneously. NOTE You cannot do combustion research to reduce CO2. That is determined only by the engine cycle. Two categories of research have been performed to reduce NOx, one of which is based on the lean burn concept and the other based on the so-called rich burn quick quench lean burn [1-2], both of which avoid the stoichiometric condition where the formation of NOx is the most critical. Though the lean burn concept with premix combustion seems to have greater potential for reducing NOx, it has fundamental disadvantages such as the tendency to cause combustion instability, auto-ignition and flashback in the premixing duct and the degradation of relight performance at altitude. Basic research for understanding fundamental processes of atomizing fuel in turbulent flows and combustion of lean premixed fuel and air has been performed. The double annular combustor for aircraft engines based on the lean premix concept has been studied, where there are two rows of burners, one of which is for pilot combustion which operates at any engine power condition to keep the flame stable and the other for main combustion operating only at high power[3]. The combustor of this type was successfully developed and is being used for large aircraft engines. Recently, a combustor with both of pilot and main burners installed in one fuel nozzle has been devised to simplify combustor cooling, the fuel nozzle of which is of a so-called concentric lean burn type[4-7]. The concentric lean burn fuel nozzle normally consists of an inner pilot burner operating at all times to keep the flame stable and a main burner of premix type operating only at high power to burn most of the fuel producing less NOx. Kawasaki Heavy Industries GTBC (KHI) and Japan Aerospace Exploration Agency (JAXA) have been jointly conducting research for concentric lean burn fuel nozzles both for aircraft and industrial gas turbines for many years. Design and high pressure combustion test routines have been repeated many times together with supporting CFD and spray visualization. In this paper, the results of the spray visualization test at elevated pressure inside of the main premix duct of a concentric burner developed in the joint research will be introduced and the relationship between the distribution of the spray and the NOx emission index will be explained.

DESIGN OF THE CONCENTRIC FUEL NOZZLE

Figure 1 shows the cross-sectional view of the concentric fuel nozzle, which consists of an inner pilot burner surrounded by an outer main burner. A photograph of the concentric fuel nozzle taken from downstream after a high pressure combustion test is shown in Figure 2. The total effective area of the fuel nozzle is around 1400mm^2, around 25 percents of which is for pilot and 75% for main.

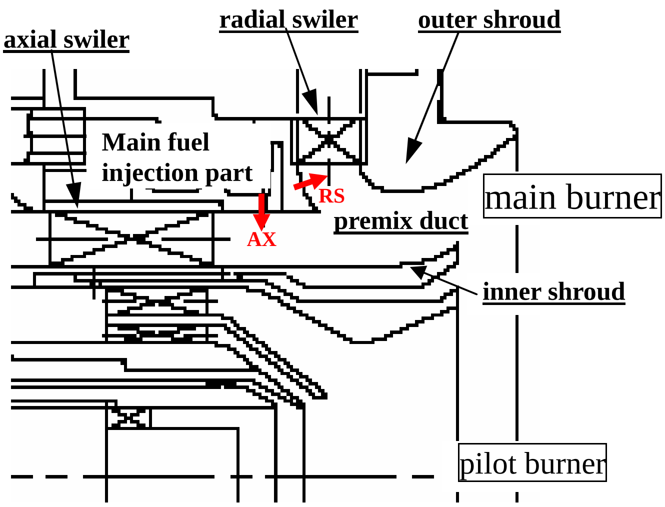


Figure 1: Cross sectional view of the concentric fuel nozzle

The main burner consists of co-rotating radial and axial swilers, the main fuel injection part located between the two swirling air flow passages and the premix duct formed by the outer and inner shrouds. Co-rotating main swiler arrangement is preferable from the view point of ignition and efficiency at low power because the strong swirl of the main air flow which diffuses rapidly downstream of the main burner in the combustion chamber induces a steep adverse pressure gradient which is essential for the formation of the recirculation zone keeping steady combustion of the pilot flame. Triple swirler arrangement with a small reverse rotating swirler between two large co-rotating swilers promotes mixing of fuel and air without decreasing the total swirl number.

The swirl angle of the axial and radial swilers is around 40 degrees and the effective areas of the radial and axial swilers are in the ratio of around 60:40. The fuel for the main burner is injected in either the AX or RS direction as shown in figure 1 through twenty circumferentially uniformly distributed 0.6 mm diameter holes (Figure 3). In Type AX fuel nozzle, all the main fuel is injected through the twenty holes as is shown by the arrow AX in figure 1, while in the case of Type RS fuel nozzle, it is injected as is shown by the arrow RS. There could be other options with the main fuel injected to both of axial and radial flows, or selectively injected to either flows depending on the engine power. These design options may be considered to improve part load efficiency with the disadvantage of the complicated cooling structure inside of the main fuel injection part. In this paper, these options will not be discussed and attention is focused on the spray distribution and NOx emission of Type AX and RS. The design of the pilot burner is presented in the paper GT2011-46187.

Figure 2: photograph of the concentric fuel nozzle (viewing from downstream after an HP combustion test)

Figure 3: main fuel holes for RS direction (viewing from downstream after a HP combustion test)

The concentric fuel nozzle developed was designed so that only the pilot burner operates at low power, while both pilot and main burners operate at intermediate to high power. Two design points for the combustor, IP and HP, are shown in table 1, each of which corresponds to the lowest and highest power conditions in the range where both pilot and main burners are used. The combustor was designed so that around 70% of the total air flow enters through the fuel nozzle into the combustion chamber while 30% enters through the cooling holes on the liner. Around 85% of the total fuel flow goes to main burner, while 15% fuel goes to pilot in both cases. The pressure loss at the combustor was assumed to be 4% of the inlet pressure.

	Inlet pressure	Inlet temperature	combustor total air fuel ratio (AFR)
IP	14 bar	800K	41
HP	30 bar	900K	32

Table 1: combustor design points

VISUALIZATION OF THE MAIN FUEL SPRAY

The visualization of the main fuel spray was conducted in the high pressure spray test facility [8], shown in Figure 4. Main fuel was injected through the spray test model of the concentric fuel nozzle and atomized through the pressurized air blowing downward in the chamber. A laser sheet was injected through one of the optical windows into the fuel spray and the Mie scattering image of the spray was captured through the other optical window. The fuel was injected through only one fuel hole out of the total twenty fuel holes of the main burner making it possible to see clearly the trajectory of the main fuel. The spray test conditions were listed in table 2, which were determined so that the penetration length of the spray is equal to that of the corresponding IP and HP conditions.

	q	z	Weber	Ta	Pa	PLR	fuel	AFR
		mm		K	bar	%	cc/s	
IP combustion	0.46	2.7	2688	800	14	4.0	2.3	41
IP spray test	0.46	2.7	3120	293	5	13.0	2.5	38
HP combustion	1.42	4.4	5760	900	30	4.0	5.9	32
HP spray test	1.42	4.4	3120	293	5	13.0	4.4	22

Table 2: spray test conditions

The penetration length z was estimated based on the equation shown below at the distance X twenty times as large as the diameter of the fuel hole D, while q stands for the momentum ratio of fuel to the air [9]. The penetration length at HP condition is about 60% larger than that at IP condition.

$$\frac{z}{D} = 1.48 \cdot q^{0.42} \cdot \ln\left(1 + 3.56 \cdot \frac{x}{D}\right)$$

The spray test model of the concentric fuel nozzle is shown in figure 5 where the outer shroud of the main premix duct is made of transparent acrylic so that the laser sheet passes through the outer shroud and the image of the spray distribution inside of the main premix duct can be captured. The spray test model rotated around its axis for 180 degrees during the test so that Mie scattering images at different circumferential cross sections were obtained without moving the optical instruments. The Mie scattering image was captured every 4 degrees, totally 45(=180/4) images being obtained which were merged into the 3D image of the spray. Spray tests of Type AX and RS fuel nozzles were performed for IP and HP conditions, thus total four spray tests were performed, the results of which are shown in Figures 7 to 16.

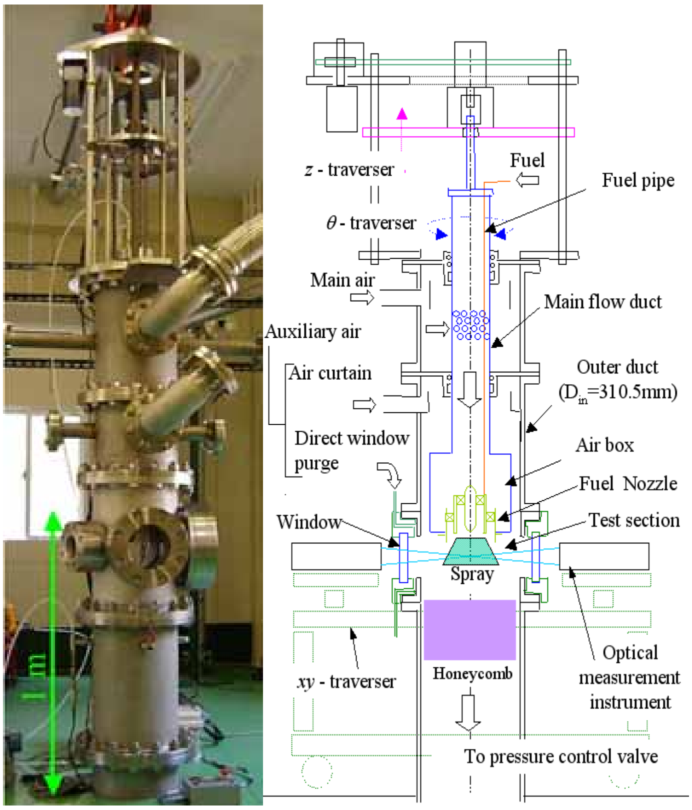


Figure 4: High pressure spray test facility

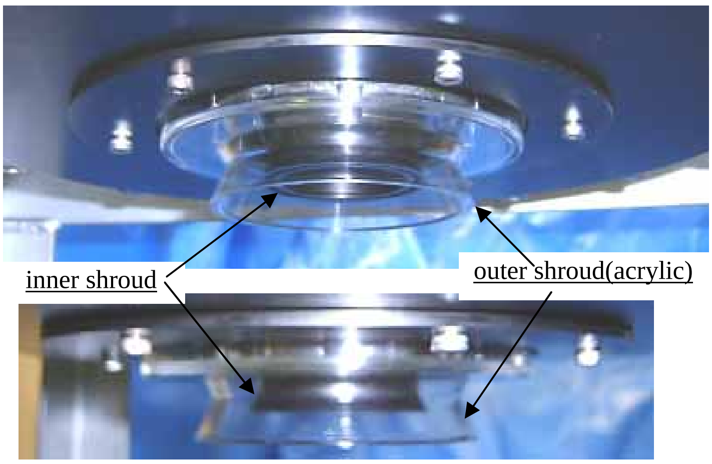


Figure 5: spray test model of the concentric fuel nozzle

Figures 7 to 10 show the spray distributions at the cross sections perpendicular to the nozzle axis Z, the axial positions of which are illustrated in figure 6, while those on the circumferential cross sections are shown in figures 11 to 14. The color is normalized so that red corresponds to the maximum laser reflection intensity while blue corresponds to the minimum in each test. It should be noted that different color mapping between color and reflection intensity was applied to each test so that the distribution of any spray can be seen clearly.

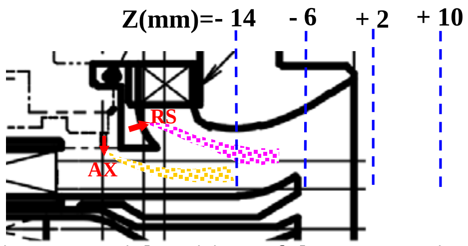


Figure 6: Axial positions of the cross sections

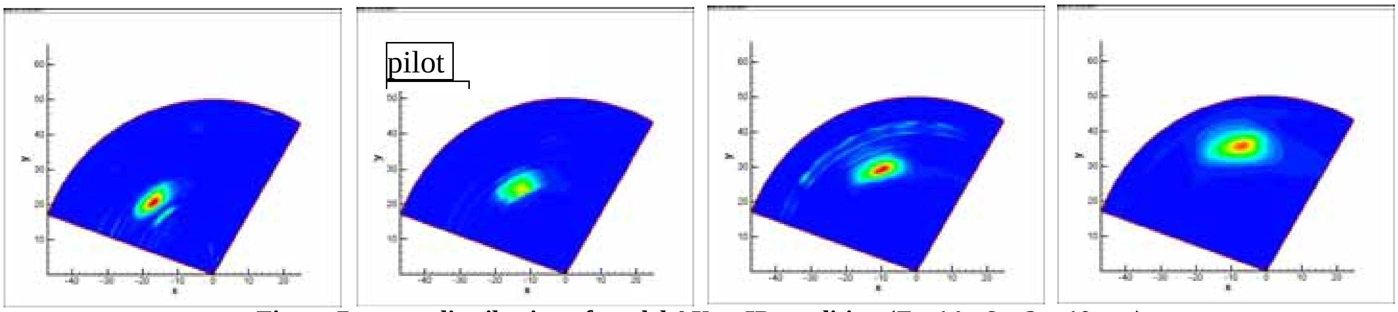


Figure 7: spray distribution of model AX at IP condition (Z=-14, -6, +2, +10mm)

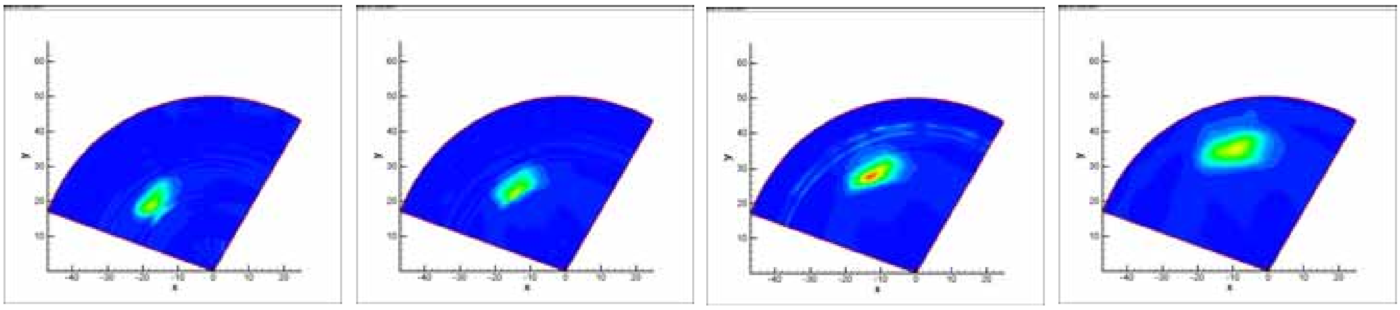


Figure 8: spray distribution of model AX at HP condition (Z=-14, -6, +2, +10mm)

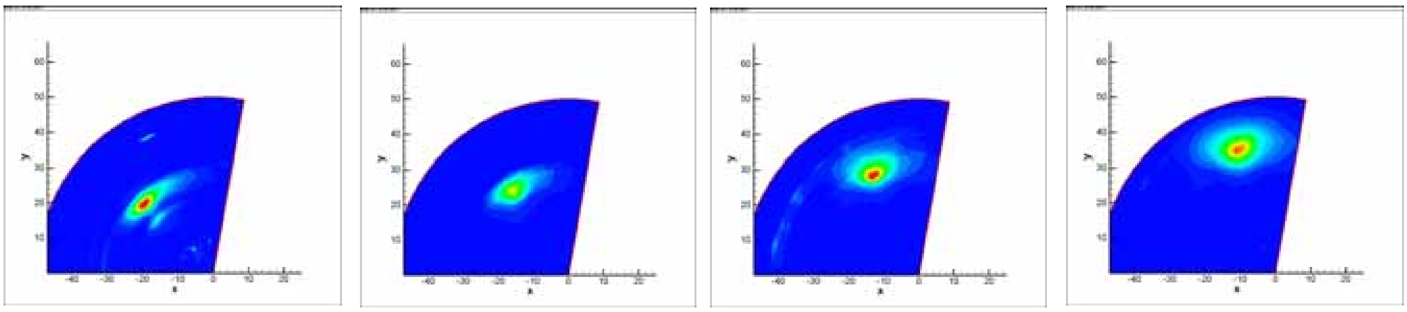


Figure 9: spray distribution of model RS at IP condition (Z=-14, -6, +2, +10mm)

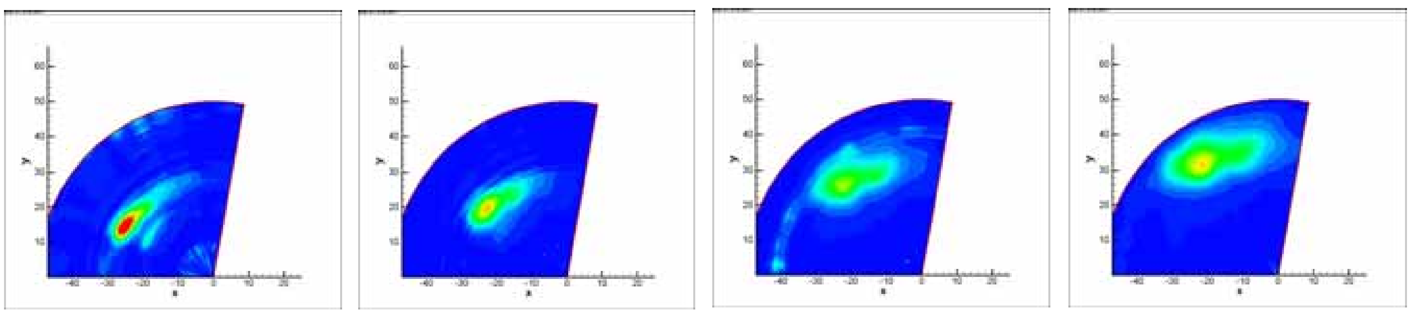


Figure 10: spray distribution of model RS at HP condition (Z=-14, -6, +2, +10mm)

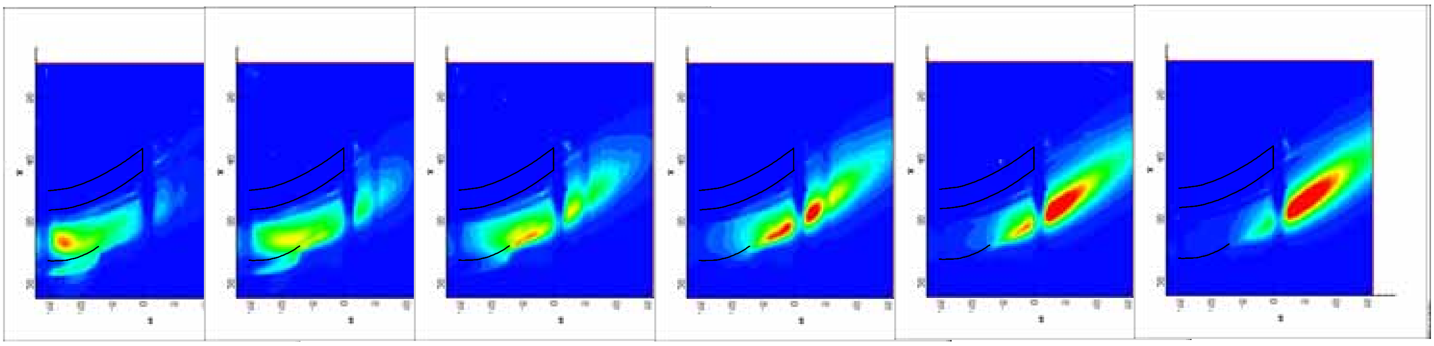


Figure 11: spray distribution of model AX at IP condition

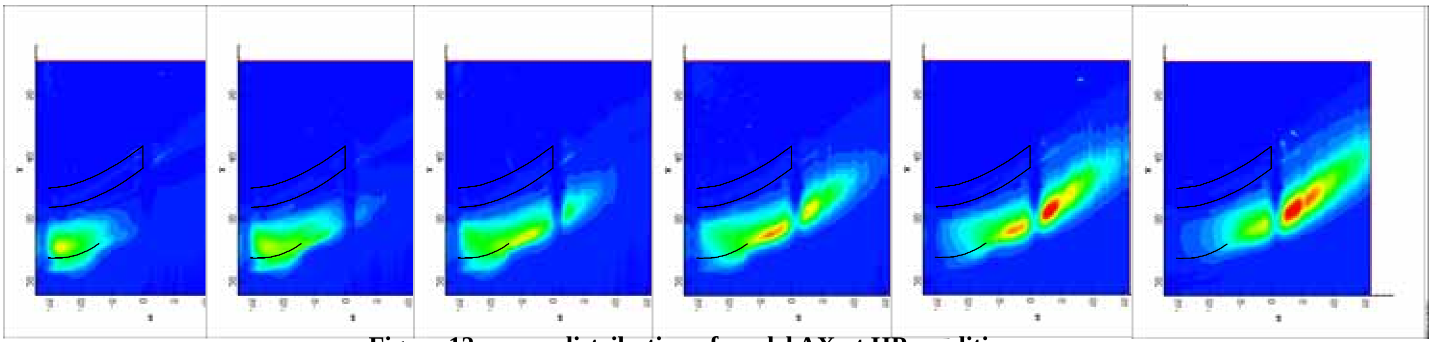


Figure 12: spray distribution of model AX at HP condition

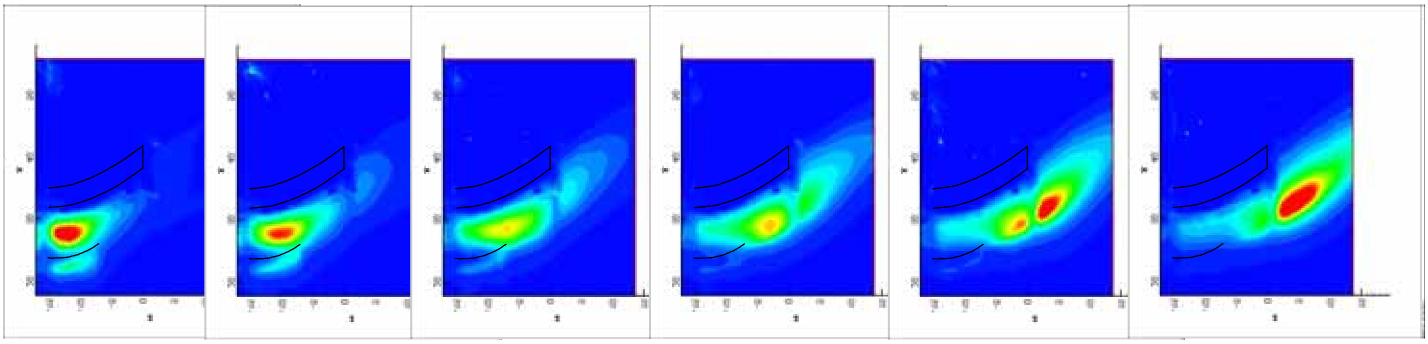


Figure 13: spray distribution of model RS at IP condition

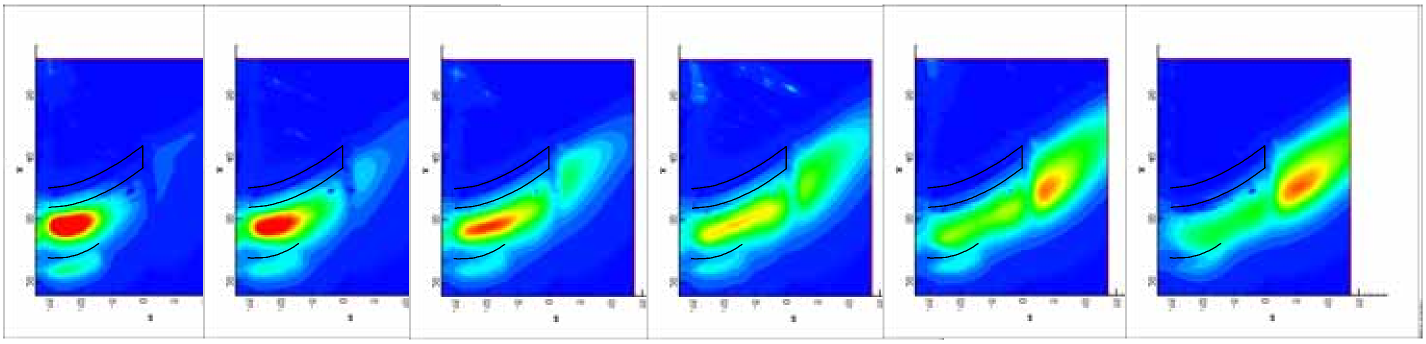


Figure 14: spray distribution of model RS at HP condition

Figure 11 shows the spray of the Type AX fuel nozzle under IP condition. The spray distribution is biased to the inner side of the main premix duct, some of which attaches to the inner shroud and spreads out from its edge. The spray of Type AX under HP condition shown in figure 12 is similar to figure 11, indicating that the effect of the enhanced penetration on the spray distribution is unclear in the case of Type AX. On the other hand, figure 13 shows that the spray of the Type RS fuel nozzle under IP condition is located near the core of the main premix duct though it is slightly biased to the inner side without attaching to the inner shroud. The spray of Type RS under HP condition is located at the center of the main premix duct which is not biased either to the inner or outer shroud. The difference of the spray distributions of Type RS between under IP and HP conditions is due to the difference in penetration length. Figures 15 and 16 are the supporting photographs taken through the optical window during the spray tests, also showing that the spray was biased to the inner side for Type AX while it was located near the core for Type RS.

Circumferential spray distributions in figures 7 to 10 show that the spray rotates clockwise as it moves outward and flows downstream in any test. The trajectories of the core of the spray in figures 7-9 are similar to each other, while that in figure 10 differs slightly from the others, which needs some explanation. Figure 17 illustrates the radial swirl flow field just downstream of the radial swiler. The air entering through the radial swiler is turned strongly in the axial direction by the walls of the main fuel injection part and the outer shroud. As is always true in any curving flow, the flow near the concave or pressure surface tends to lose its speed with the increase in static pressure, while the flow near the convex or suction surface tends to be accelerated. On the other hand, the circumferential component of the air velocity is not so different throughout the radial swirl flow region between the convex and concave surfaces because of the preservation of the angular momentum generated through the radial swiler. The swirl angle, which is defined by the ratio of the circumferential to the axial component of air velocity, of the inner air flow near the main fuel injection part is relatively high because of the lower air velocity with the same circumferential velocity compared to the outer air flow near the outer shroud. The spray penetration of Type RS at HP condition is strong enough to make most of the fuel reach the outer high speed and low swirl flow region causing less rotation of the spray as is shown in figure 10, while the less penetrating spray is conveyed through the low speed and high swirl flow at IP condition shown in figure 9. Careful observation of figure 10 shows that the spray distribution is elongated circumferentially because part of the spray moves in the same manner to that shown in figure 9 indicating that part of the spray is trapped in the inner high swirl flow even though most of it reached the outer low swirl flow region under HP condition. The steep curvature of the radial swirl flow passage thus has a favorable effect on the circumferential distribution of the spray.

Figure 15: Spray of Type AX under IP condition

Figure 16: Spray of Type RS under IP condition

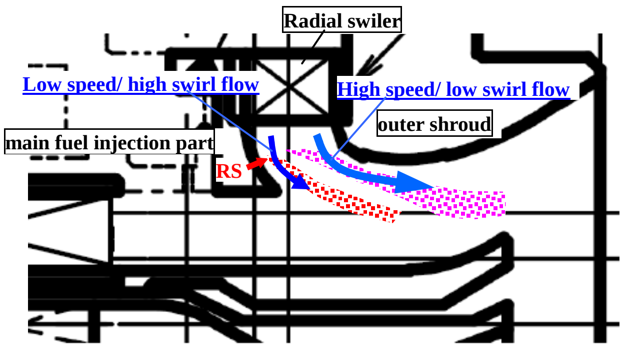


Figure 17: Flow field in the radial swirl flow

NOX EMISSION AT COMBUSTION TEST

Combustion tests of the fuel nozzles type AX and RS were performed under the HP condition in the combustion test rig (Figure 18). A 125mm diameter circular cross section liner with around one thousand effusion cooling holes was used, downstream of which exhaust gas was gathered through a water-cooled sampling probe with 9 sampling holes (Figure 19). The flame of the main and pilot burners was observed through a camera installed downstream of the liner. The air mass flow was controlled so that the pressure loss for the combustor was 4% of the inlet pressure. Vibro-meter CP211 high temperature oscillation pressure sensor was installed on the liner to monitor the pressure oscillation inside of the liner.

Figure 20 shows the NOx emission index against the adiabatic flame temperature based on the fuel nozzle local air fuel ratio. NOx emission index of Type RS fuel nozzle was smaller than that of Type AX. The NOx emission index of Type RS was around 8 at the HP design point where the adiabatic flame temperature was around 2175K, while it was around 15 for Type AX fuel nozzle.

Figure 18: JAXA AP7 combustion test rig

Figure 19 : the fuel nozzle, the liner and a gas sampling probe (viewing from downstream)

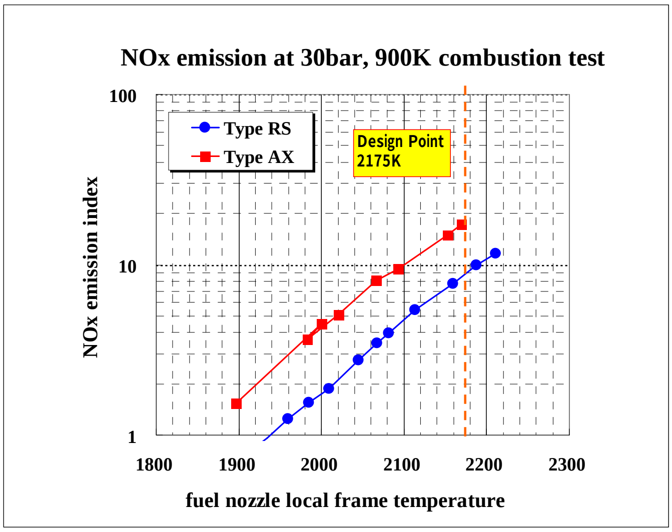


Figure 20 : NOx emission index obtained at 30bar, 900K Combustion test

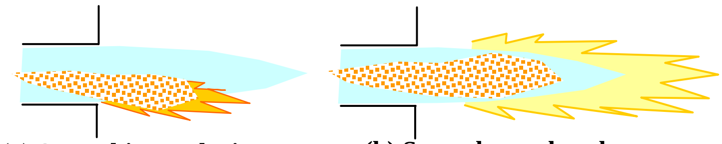
DISCUSSION AND CONCLUSION

Additional spray and combustion tests were performed after the tests shown above and it was found that the NOx emission of the fuel nozzle having a spray biased to either side of the premix flow, like Type AX, cannot be suppressed even with the swilers of counter rotating arrangement. On the other hand, the Type RS fuel nozzles combined with the swilers of counter rotation or the triple swiler arrangement did not show much improvement in NOx emission. It was also found that injecting fuel from either inner or outer shroud of the premix duct to make it reach to the core of the premix flow was not successful due to the limited penetration length, or in other words, the diameter of the fuel hole becomes too small to be mechanically drilled to make the penetration strong enough.

It was deduced from the joint research so far that it is the most essential for suppression of NOx emission of the main premix burner that the fuel injection holes are properly located so that the spray is mainly distributed in the core of the premix flow and that promotion of the mixing through counter rotating swirling flows has a secondary effect. The limited effect of the counter swirl on the spray distribution may be due to the fact that the length of the premix duct is so short that the turbulent mixing does not have much chance to mix fuel and air. A long premix duct may change the situation though it is not realistic for aero-engine combustors because of the increased risk of flashback and auto-ignition inside of the premix duct and the weight problem. Moreover, it should be noted that it is extremely difficult to move the spray from the edge of the premix flow to the core region even with a long premix duct though it should have some effect on improving circumferential distribution of the spray.

The way in which the position of the spray in the main premix flow affects NOx emission can be explained as illustrated in figure 21. The edge of an annular jet always loses its speed quickly after it blows out into a chamber due to the mixing with the surrounding still air, while the core of a jet maintains its speed for a relatively a long time. The spray located at the edge of the premix flow, therefore, begins to burn within a short distance from the exit of the main burner indicating that burning of the spray occurs in a narrow region before fuel and air are fully mixed, which produces high NOx due to combustion in local fuel-rich regions. On the other hand, the spray located at the core of the premix flow tends to maintain its speed for a long distance making the spray burn little by little as it gradually loses its speed. Moreover the air and fuel in the spray have more chance to be uniformly mixed before they burn. This eliminates the local high temperature combustion where the formation of NOx is critical.

In conclusion, it is essential to locate the fuel injection holes so that the spray is properly distributed in the core of the main premix flow which results in gradual combustion producing less NOx.



(a) Spray bias to the inner **(b) Spray located at the core**

Figure 21 : illustration of the premix flame

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