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IMPROVEMENT ON IGNITION PERFORMANCE FOR A LEAN STAGED LOW NOX COMBUSTOR

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ABSTRACT

KHI (Kawasaki heavy industries Ltd, Japan) and JAXA (Japan Aerospace Exploration Agency) have been working together since 2004 to improve lean staged concentric fuel injector technologies. One of the weak points of a lean staged fuel injector is said to be ignition / light around performance. Ignition characteristics were assessed on several fuel injector configurations in burner tests. Laser diagnosis, CFD analysis and high-speed video camera recording were used to understand the effect of fuel injector geometry on fuel spray distribution and ignition characteristics. They showed a clear relationship between the burner geometry and ignition characteristics. Light around characteristics was evaluated with the burner configuration optimized in burner tests. Light around performance deteriorated in multi sector unit compared to that in burner test. CFD analysis and some ignition tests with different configuration of combustor gave a clue to restore the light around characteristics deteriorated in multi sector unit.

INTRODUCTION

Due to the increasing demands for environment protection, the regulation specified by ICAO (International Civil Aviation Organization) on NOx emissions from aircraft engines have been becoming stringent[1]. In the circumstances, engine manufactures and research institutes are making a lot of efforts to develop competitive low emission combustor technologies for the future environmental friendly engines [2-8].

KHI and JAXA collaborate to improve lean staged concentric fuel injector technologies aiming at 20% CAEP2 NOx emissions. Through out the efforts the team has accomplished the target NOx emissions level without deterioration of other required performances for airworthiness such as altitude relight, start ignition, and emissions characteristics at typical engine operating conditions including cruise combustion efficiency. The team has also studied mechanical design aspects of the injector required to install into engines such as thermal stress, vibration stress, and anti-coking structure. In staged fuel injectors, the main fuel passage should be effectively cooled with pilot fuel when pilot only fuelled. Moreover, when main fuel is shut down, main fuel shouldn't dribble inside the injector. In this joint research activity, the team has tried to tackle all necessary aspects to install engines. This report focuses on the improvement of ignition performance of the injector.

Although lean staged fuel injectors have a great potential for NOx reduction, one of the weaknesses may be poor ignition performance because the large amount of air flows into combustor across fuel injector. T. Bosbach investigated experimentally altitude relight under realistic condition using laser and high speed video technique [9].

The fuel injector technology to improve ignition performance has been developed in single burner unit at the first stage. The effects on ignition performance were assessed with various pilot fuel spray distributions formed by different swirler angles and swirler lip configurations. CFD analysis on flow field, laser diagnosis on spray tests and high-speed video camera recording at ignition tests were used to understand how ignition was taken place.

The fuel injector with the optimized pilot spray distribution in term of ignition performance was installed into multi sector combustor unit to evaluate light around performance. The results showed that ignition (light around) performance at multi sector unit was considerably deteriorated compared to ignition performance obtained at single burner unit. CFD analysis and laser diagnosis were used in order to understand the reason why ignition performance was deteriorated in multi sector unit. Throughout these activities, there found the reason for the deterioration and an effective way to restore ignition performance.

This paper reports the above research works to improve ignition performance performed in single burner unit and in multi sector unit.

TECHNICAL ISSUES OF LEAN STAGED INJECTOR

Figure 1 shows schematic view of the lean staged burner developed by KHI and JAXA team. The burner has pilot burner at the centre and main burner radially outside of the pilot. 25% percent of air passing through the burner is for pilot and the remaining 75% is for main. The pilot burner consists of triple swirlers with pre-filming fuel injection system. The burner diameter is around 80mm. The design of the main burner is presented in the paper GT2011- 46256.

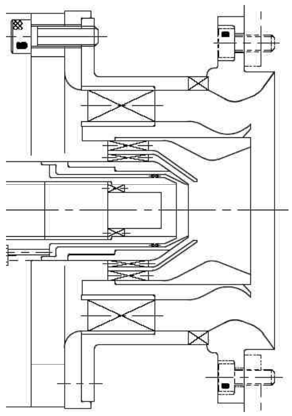


Figure 1 Schematic view of lean staged fuel injector

At the low power settings such as idle and approach conditions, pilot burner is only fuelled to have a locally rich mixture for stable combustion. At high power settings such as climb and take-off conditions, main burner is also fuelled to have lean mixture to suppress thermal NOx formation. Somewhere between approach and climb conditions, burner is fuel-staged pilot only mode from/to pilot and main mode. Depending on the engine operating points, there may be the case that all pilots and selectively several mains are fuelled to meet targets of combustion efficiency, smoke and so on.

Low NOx emissions can be achieved by forming uniform lean mixture in main mixer. And at the same time auto-ignition or flashback in the main mixer must be avoided. Therefore the mixer should be as short as possible to reduce residence time and also long enough to accomplish the acceptable mixing for NOx target. Combustion instability which may result in damage of engine parts or flashback at the main mixer, should be suppressed.

At middle power settings such as cruise, high combustion efficiency is the most important for fuel consumption because engines are normally operated at cruise condition at the most of the time during the flight mission.

At low power settings, combustion takes place only by pilot burner. A large amount of air passes through the main air passage, which may quench pilot flame and may cause poor ignition, lean blow out and combustion efficiency. Thus the key to resolve the low performance at the low power settings is to suppress the interaction of pilot flame and the main air stream.

IGNITION / LIGHT AROUND PROCESS

Successful ignition at annular type combustor may be divided into several processes shown below.

1. At a fuel injector adjacent to an igniter, an initial flame (kernel) should be formed by electric spark around igniter tip. Fuel droplets should be allocated around igniter tip.
2. The kernel should be successfully carried upstream to the burner exit and the flame should be formed at the burner exit.
3. Once the flame can be maintained at the igniter fuel injector, the flame should propagate to the adjacent fuel injectors (light around).

Due to the concentrically inside arrangement of the pilot burner, a large amount of main air may prevent the processes described above. Pilot spray displacement is thought to be the key issue for the above processes to improve ignition performance. For the first step, single burner ignition tests and fuel spray displacement and flow field measurement by laser diagnosis have been performed to find solutions for successful light at the igniter fuel injector. For the next step, a fuel injector, which shows the best ignition and lean blow out capability, has been installed into a multi burner test unit to assess the light around performance.

SINGLE BURNER TEST RESULTS

Outer swirler lip length and inner swirler angle have been applied as design parameters to vary pilot fuel spray distribution (Table1 and Figure 2).

The effective area of the each inner swirler was arranged the same by changing the centre body diameter during the investigation of the inner swirl angle effects.

Table 1 Design Parameters

No.	Lip length	Inner swirler angle
1	L	-45 degree
2	L2	-45 degree
3	L3	-45 degree
4	L4	-45 degree
5	L	-45 degree
6	L	-20 degree
7	L	0 degree

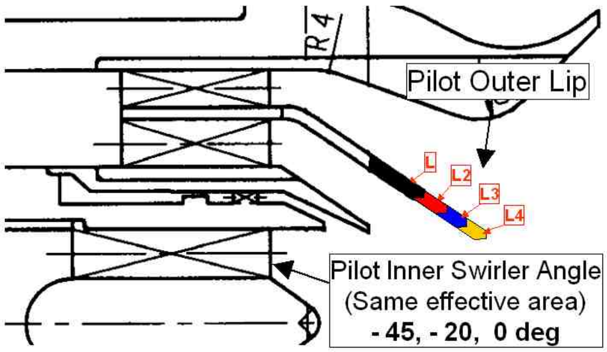


Figure 2 Design parameters

Figure 3 shows single burner ignition and lean blow out test unit. The ignition tests were performed at atmospheric pressure and temperature conditions. Pressure loss across the fuel injector has been varied from 1% to 6%. A cylindrical crystal quarts liner (the diameter is around 125mm, the length is around 300mm) is used for an optical access for flame observation. Igniter is located at 55mm downstream from the burner exit surface.

Fig. 3 Single burner ignition / lean blow out test unit

Figure 4 shows the ignition and lean blow out results for each fuel injector. To avoid scattering of the ignition data, the data is plotted when 3 consecutive lights within 10 seconds after igniter spark are obtained. The data points of AFR Ignition=0 mean that 3 consecutive lights were not obtained. Lean blow out data was obtained when flame went off during gradually reducing the fuel flow rate.

The test results show that ignition and lean blow out capability becomes better as the lip length becomes long. Although the capability becomes better, observed flame in the test becomes unstable when the lip length is long and it has been observed that a very small amount change in fuel flow rate often leads to flame extinction in lean blow out test.

Figure 5 shows the effect of inner swirler angle on ignition and lean blow out capability. The capability improves when the angle of inner swirler reduces. As for the flame stability, it becomes stable when inner swirler angle reduces. Especially, the performance has greatly improved in the case that the inner swirler angle is 0 degree.

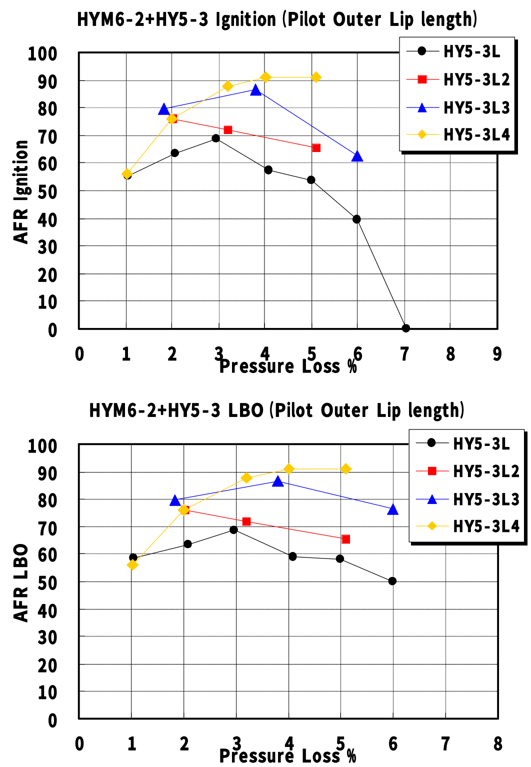


Figure 4 Single burner ignition / lean blow out result (Effect of pilot outer lip length)

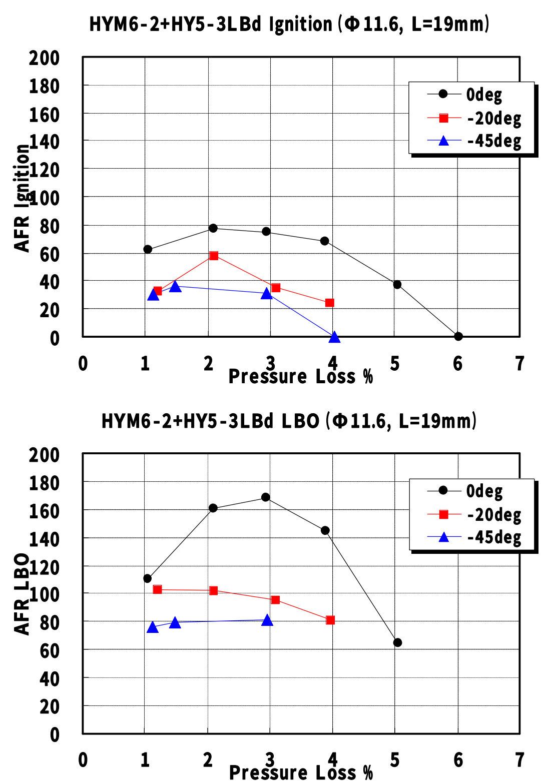
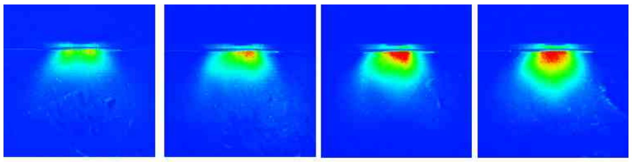


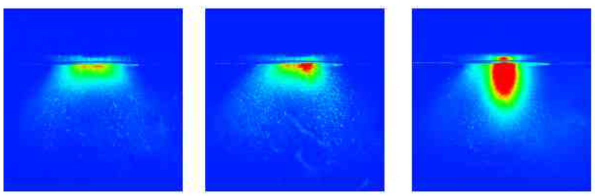
Figure 5 Single burner ignition / lean blow out result (Effect of inner swirler angle)

To understand the above ignition and lean blow out test results, pilot spray distribution was measured for each burner by using Mie scattering of laser sheet technique. Figure 6 and Figure 7 show the effect of pilot outer lip length and inner swirler angle on the fuel spray distribution. The spray tests were performed at 4% pressure loss across the fuel injector at the atmospheric pressure and temperature conditions. The test AFR is 40 to 1.



HY5-3L HY5-3L2 HY5-3L3 HY5-3L4

Figure 6 Single burner pilot spray distribution (Effect of pilot outer lip length)

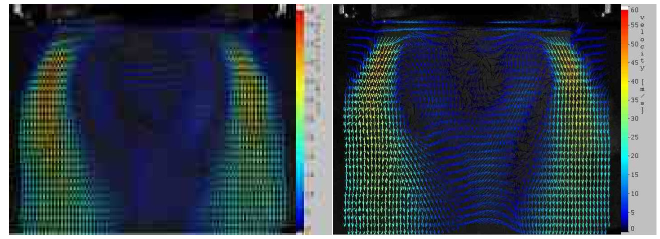


HY5-3LBd –45deg HY5-3LBd –20deg HY5-3LBd 0deg

Figure 7 Single burner pilot spray distribution (Effect of inner swirler angle)

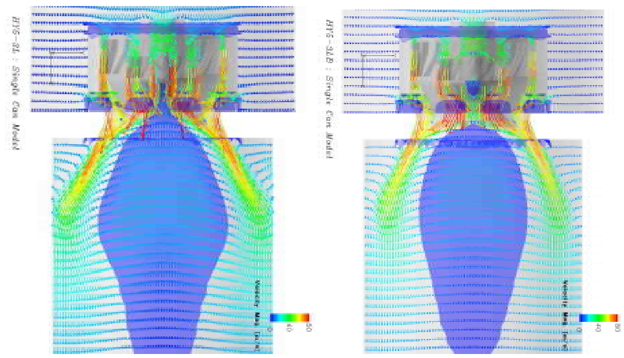
The fuel spray tends to locate at the burner centre as the lip length becomes long and as the angle of inner swirler reduces. Especially when the inner swirler angle is 0 degree, fuel spray is located at the most centre position compared to other fuel injectors. Based on the above results, it can be said that the more fuel spray is located at the centre, the better ignition and lean blow out capability is obtained.

To investigate further to get relationship between fuel injector flow field and pilot fuel distribution, airflow filed downstream of the injector with inner swirler –45 degree and 0 degree was measured by PIV (Figure 8) and was analyzed by CFD (Figure 9). Each flow field downstream of the fuel injectors seem similar each other. A small amount of inner swirler air doesn't affect the whole flow field pattern. At the centre, there is a low speed or recirculation region formed by main fuel injector swirling flow. Although the flow fields are similar each other, observed flame (Figure 10) in the burner tests are quite different. In the case of –45 degree inner swirler angle, the flame spreads widely with blue flame periphery. Whereas in the case of 0 degree inner swirler, the flame is luminous and seems to be confined in the recirculation zone predicted by CFD or measured by PIV. As a reference, pilot fuel distribution results for – 45 and 0 degree inner swirler measured by Mie scattering system are shown again in Figure 11.



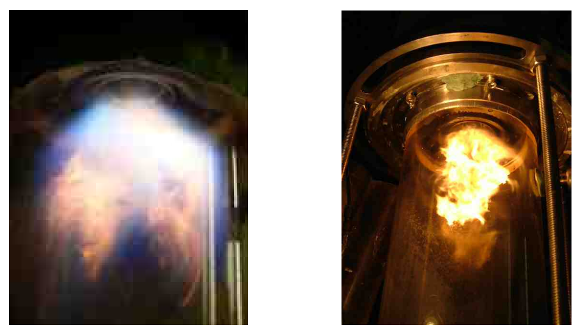
(-45 degree) (0 degree)

Figure 8 Flow field by PIV measurement



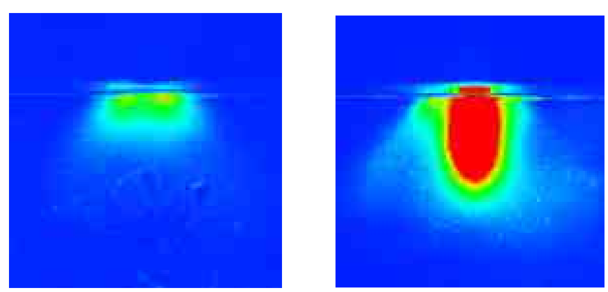
(-45 degree) (0 degree)

Figure 9 CFD analisys



(-45 degree) (0 degree)

Figure 10 Flame in burner tests



(-45 degree) (0 degree)

Fig.11 Pilot fuel distribution

Combining all the results in Figures 8 - 11, it may be said that in the case of –45 degree inner swirler angle the most of fuel droplets disperse outward into main cold air therefore the pilot flame is being quenched, which leads to poor lean blow out capability. On the other hand, in the case of 0 degree inner swirler angle, it may be said that the most of fuel is confined in the recirculation region, which gives less quenching by cold main air and a better lean blow out capability. Although the lean blow out capability can be explained in that way described above, as for the ignition by igniter spark, the reason for 0 degree inner swirler to show a better ignition capability can not be explained.

To understand how the ignition process is taken place, a high-speed video is used for the above 2 fuel injectors. In the case of 0 degree inner swirler, the high-speed video recording showed that even though igniter tip was located at the surface of the quarts liner, the igniter sparks penetrated into some distance enough to reach recirculation region, where the most of fuel droplets were located. Therefore a kernel managed to be generated at the edge of recirculation region. Once it is generated, the kernel propagates to the upstream toward the fuel injector via fuel droplets located in the recirculation region. And once the kernel reaches to the fuel injector exit, flame is developed and stabilized. On the other hand, in the case of - 45 degree inner swirler, the high speed video recording showed that a kernel could be generated around an igniter tip but there were less chances for the kernels to travel upstream. This assumption may explain the difference in ignition performance between 0 degree and –45 degree inner swirler angle.

MULTI BURNER TEST RESULTS

The fuel injectors shown the best ignition and lean blow out capability (inner swirler angle 0 degree) were installed into a multi sector unit shown in Figure 12 to assess light around performance. An igniter is located at 55mm downstream of the middle fuel injector and rectangle quarts liner (125mm height by 360mm width by about 300mm length) is used for an optical access. The ignition tests were performed at atmospheric pressure and temperature conditions. Pressure loss across the fuel injector was varied from 1% to 6%. The photograph of the flame and the ignition and lean blow out test results are shown in Figure 13 and Figure 14. For comparison, the result in cylinder liner is also shown in Figure 14.

The light around was possible but the flame observed in the multi sector unit is unstable and quite different from that observed in the single cylinder liner. The ignition and lean blow out characteristics are much poorer than those in the single cylinder liner.

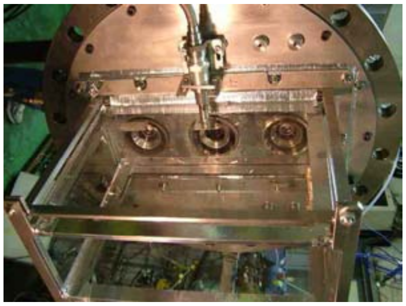
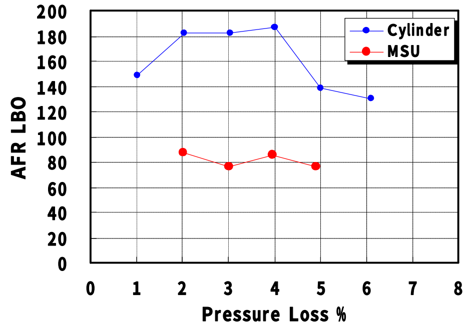


Fig. 12 Multi sector unit (3 sectors)

Figure 13 Observed flame in multi sector unit



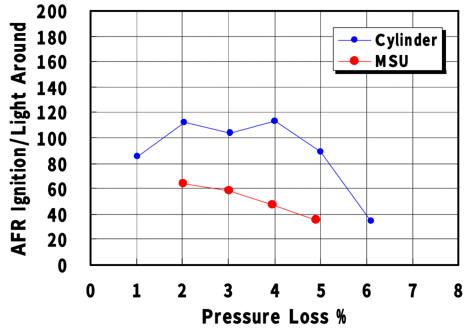


Fig. 14 Light around and lean blow out result in multi sector unit

In order to understand the deterioration in light around and lean blow out characteristics in multi sector unit, a diagnosis test was performed with single rectangle liner. The results are shown in Figure 15. The characteristics in single rectangle liner and multi sector show similar results, which is much poorer than that in single cylinder liner.

CFD analysis was applied to understand the difference in flow field of recirculation region and in the flow field around igniter tip. Figure 16 shows only recirculation region at two downstream sections from the fuel injector exit (50mm and 75mm downstream from the injector exit), where the velocity in the axial direction is below zero. In cylinder liner, the recirculation region is only formed in the centre and the shape is circle. On the other hand, the recirculation regions in single rectangle liner and multi sector are distorted and there are some reverse regions outside of main flow. Figure 17 shows the flow field around igniter tip. Some particles were put at the several positions in the direction to the fuel injector centre from igniter tip, where ignition spark is likely to be generated, to assess the likelihood to swallow into the recirculation regions. The particles have no mass therefore they just follow the streamlines. In cylinder liner, there seems to be more chance for successful light than those in single rectangle and multi sector once the kernel flame is formed by igniter spark.

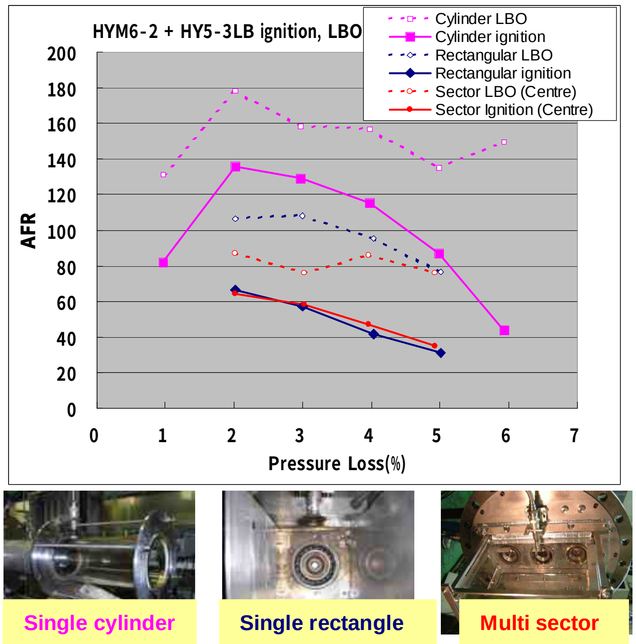


Fig.15 Comparison of ignition and lean blow out characteristics in single cylindrical, single rectangle and multi sector unit.

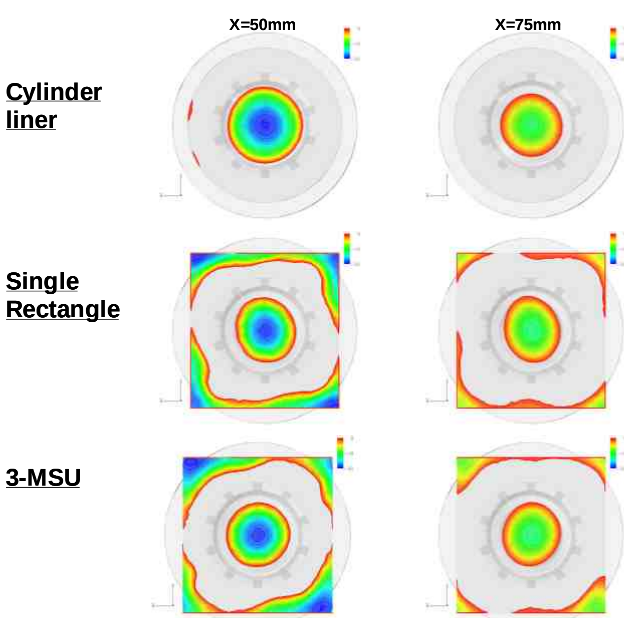


Fig.16 Comparison of recirculation region

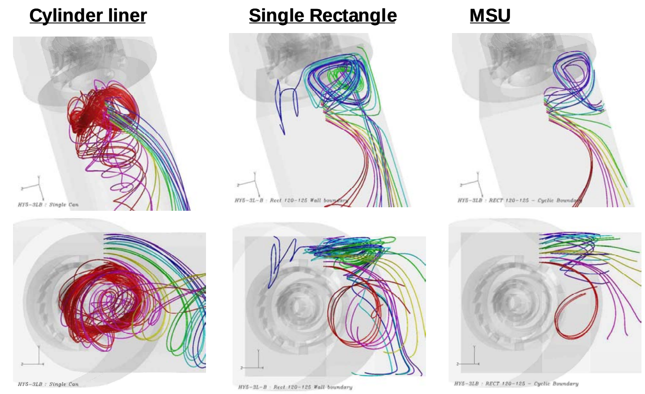


Fig. 17 Flow field around igniter tip

Based on the CFD analysis results, the shape of the section seems to have a great effect on flow field and the reason for the deterioration in the characteristics seems to be due to the deterioration in recirculation region caused by the section shape.

One of the options to restore the ignition and lean blow out performance in multi sector is to have a cylindrical shape at the burner exit to eliminate corner flow (extended heat shield shown in Figure 18 and 19). CFD analysis is applied to predict the flow field. Figure 20 shows the flow field around igniter using particle tracking method in the same manner explained the above. When the extended heat shield is attached at the exit of fuel injectors, the number of particles swallowed into the recirculation zone is increased and the flow field around igniter in multi sector unit becomes similar to that in cylinder liner.

Figure 21 shows the difference in the volume of the recirculation region between with and without the extended heat shield in multi sector. The corner flow seems to be eliminated and the volume of recirculation region becomes larger than that in multi sector without the extended heat shield.

Figure 22 shows the ignition and lean blow out results with and without the extended heat shield in multi sector. As predicted in the CFD results shown above, the ignition and lean blow out performance are improved with the extended heat shield. Because the ignition tests were performed in atmospheric temperature and pressure conditions, the extended heat shield was no cooling system. When this heat shield is applied to actual combustor, it will need some cooling structure to avoid overheating from the flame. Figure 23 shows one of the options for the extended heat shield that has backside cooling system.

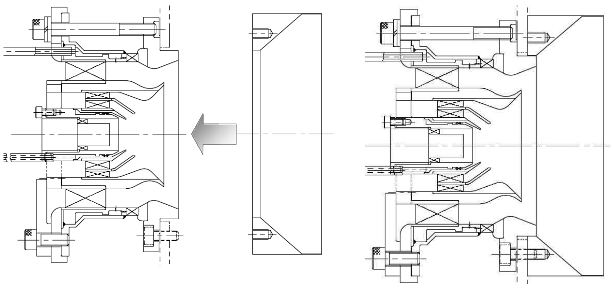


Figure 18 Fuel injector with the extended heat shield

Figure 19 Fuel injector with the extended heat shield

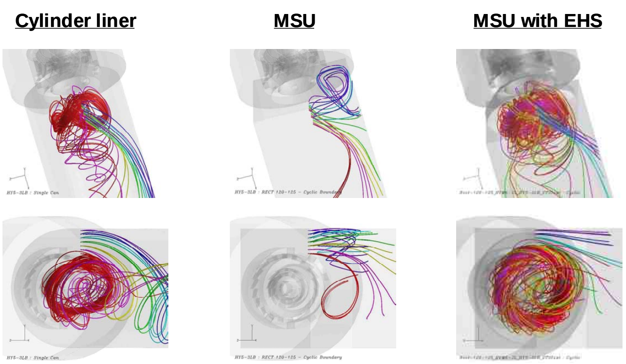
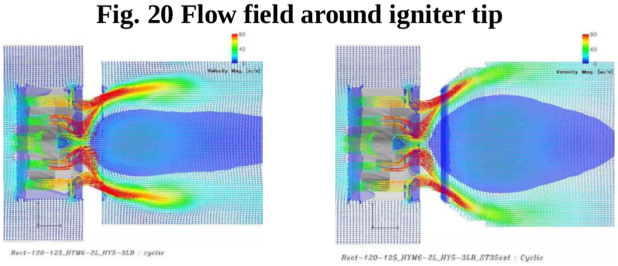


Fig. 20 Flow field around igniter tip



Without EHS With EHS

Fig.21 Comparison of recirculation region

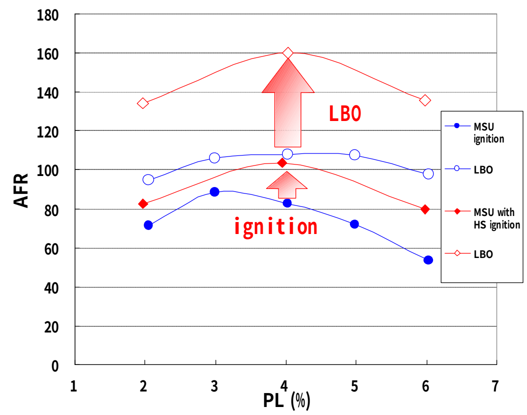


Fig.22 Improvement in performance with extended heat shield

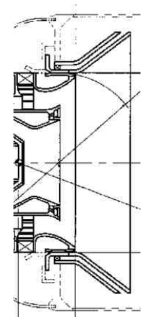


Figure 23 Extended heat shield with back side cooling system

SUMMARY

Ignition and lean blow out performance of a lean staged fuel injector have been assessed with the design parameters of pilot outer lip length and inner swirler angle. With the use of CFD, laser diagnosis and high-speed video camera, the relationship between pilot spray distribution and flow field have been worked out in single burner test. The fuel injector, which shows the best performance, has been installed into multi sector unit to assess the light around performance. The cause for the deterioration in ignition and lean blow out performance was tried to find out by using diagnosis and CFD analysis. One of the methods to improve ignition performance (Extend heat shield) was proposed and the fuel injectors with the extended heat shield showed the improvement in ignition and lean blow out. This paper only focused on how to improve ignition and lean blow out capability ignoring other important performances. For example, the installation of the extended heat shield at combustor actually leads to reduction of combustor volume. This may result in the deterioration of combustion efficiency when main burners are lit. A fuel injector should be developed looking at all necessary aspects.

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