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ADVANCED DRY LOW NOX COMBUSTOR FOR MITSUBISHI G CLASS GAS TURBINES

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ABSTRACT

Design features and verification results for Mitsubishi Heavy Industries' (MHI) latest gas Dry Low NOx (DLN) combustor technology for 1500ºC G-class gas turbines is presented. Key design improvements include: A) Inlet aerodynamics: CFD based design air inlet for improved flow uniformity into the pre-mixers. B) Fuel/air mixing: integrated fuel injector and swirler to decrease local flame hot-spots and reduce NOx while preventing flashback. C) Combustor aerodynamics: redesigned flame holding baffle and combustor outer wall to achieve better flame stability and NOx reduction. D) Acoustic resonator: two acoustic resonators, one in the liner to prevent high frequency combustion dynamics and the other in the by-pass valve for low frequency dynamics. Tests were conducted to verify the new DLN combustor by installing it in a M501G1 gas turbine at MHI's T-Point combined cycle power plant, with more than 1500 special measurements. Following the preliminary verification period the combustor was installed at the same plant for long-term operation. The results demonstrate the following capabilities: A) Less than 15ppm NOx operation with turn down to 60% load. B) Stable combustion dynamics at all load levels. C) High combustor ignition reliability. D) Suitable for daily start and stop (DSS) operation. E) Good reliability and durability. F) Retrofitable to existing 501G and 701G gas turbines.

1 INTRODUCTION

The development of DLN combustors at MHI has a long history for both gas and oil operation ([1] - [9]). The culmination of such a long history is the very successful Mk7-4 design [10]. The Mk7-4 NOx emission level operating with gas is 25 ppm, therefore a more advanced design seeking lower NOx has been developed and is presented herein. The basic design of the Mk7-4 is can annular with a center pilot nozzle and 8 main fuel nozzles in each combustor can, see Figure 1. The pilot nozzle has a stable diffusion flame that can maintain the flammability of the pre-mixed flame.

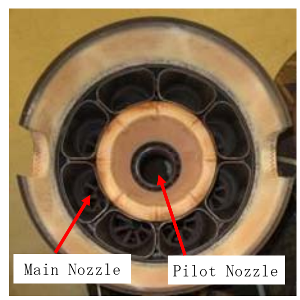


Figure 1. Combustor showing diffusion pilot in the center and 8 main nozzles (pre-mixers)

In order to maintain proper fuel / air ratio during ignition, acceleration, and partial load operation, an air bypass valve is installed at the combustion liner. This valve modulates the amount of air introduced into the combustor by by-passing a percentage of the entire air mass flow directly into the combustion liner (Fig. 2).

The G gas turbine achieves high power density and increased combined cycle efficiency by raising Turbine Inlet Temperature (TIT) to 1500 ºC. Steam is used to cool the combustor liners, which are exposed to high temperature combustion gas. Steam cooling is very effective to maintain the hardware metal temperature within the allowable range at high firing temperature while achieving low NOx.

MHI DLN combustor uses lean pre-mix combustion to reduce NOx. The lean pre-mix combustion is unstable by its nature.

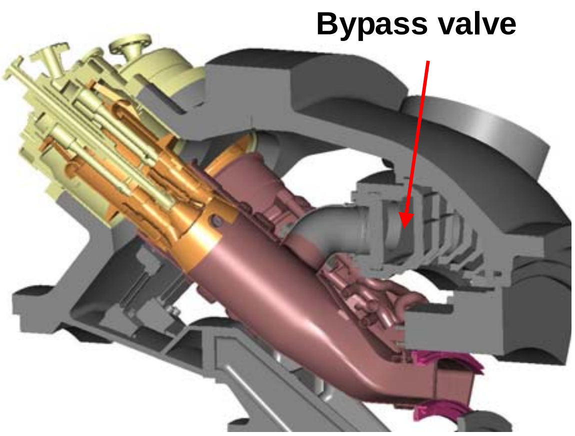


Figure 2. Mk7-4 combustor system showing the by-pass valve

Therefore, designer of DLN should balance 4 major lean pre-mix issues: NOx, Dynamics, Flashback, Carbon Monoxide/Unburned Hydro-Carbon (CO/UHC), with 4 practical commercialization issues: Life, Cost, Operability and Maintainability (Fig.3). The advanced DLN Mk8-4 combustor is the result of a compromise of these 8 conflicting issues.

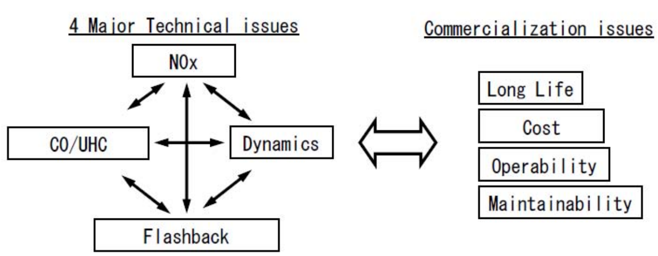


Figure 3. DLN development conflicting technical vs. commercial issues

In section 2, we present the advanced design features of the Mk8-4 combustion system, in Section 3 we present the test results followed by some concluding remarks in Section 4.

2. ADVANCED DESIGN FEATURES

Compared to the Mk7-4, there are key advanced design features that make the Mk8-4 a superior DLN combustor in terms of performance and cost (Fig. 4). The following areas are improved:

- Inlet Aerodynamics
- Fuel/Air Mixing
- Combustor Aerodynamics
- Combustor Acoustic Attenuation

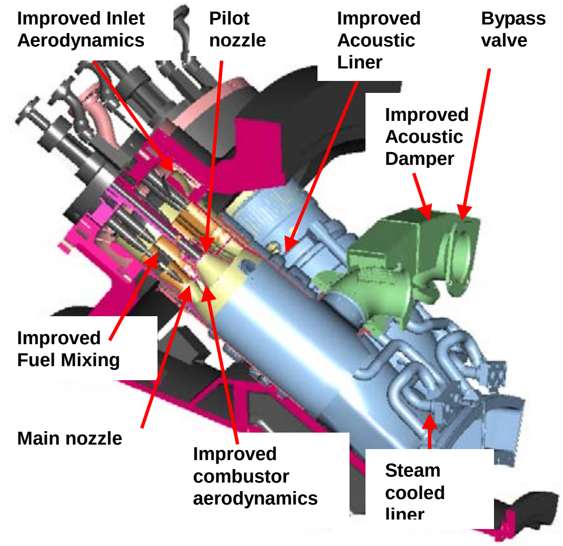


Figure 4. Mk8-4 combustion system showing some of the major improvements

2.1 Inlet Aerodynamics:

A complete redesign of the Mk7-4 inlet air system was performed for the Mk8-4 using advanced proprietary CAD to MESH methodology [11] combined with 3D CFD [12]. This lead to improved flow uniformity at the pre-mixer inlet while reducing the size, number of parts, weight and cost. Figure 5 compares the Mk7-4 and Mk8-4 cross-sections showing a length decrease close to half of the inlet section. With the reduced length of inlet section, the additional support is no longer required and manufacturing cost for the fuel supply is reduced.

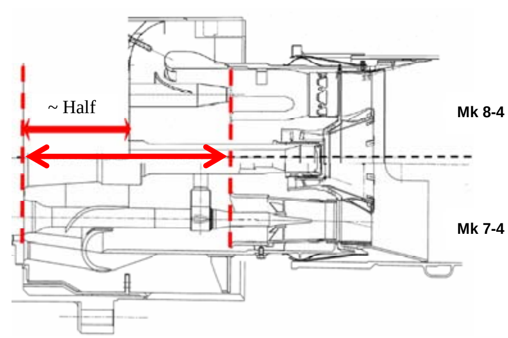


Figure 5. Comparison of Mk7-4 and Mk8-4 inlet flow systems

Figure 6 shows the improved features of the MK8-4, compared to the Mk7-4. The supports for the perforated plate (1), which is used to enforce uniform flow from the combustor casing into the combustor, are combined with the support ribs for the entire assembly to decrease the aerodynamic wakes and reduce cost and complexity. Following the perforated plate, a contraction (2) based on wind tunnel inlet design methodology [13], accelerates the flow before the turn. The back wall (3) of the turn channel is curved to reduce losses and produce a cleaner flow. The curved back wall enables a simplified top hat fuel injection (4) arrangement compared to the MK7-4. The large radius inner turn, fairing (5), is designed to minimize the turning losses [14]. In order to prepare the flow to split into 8 pre-mixers, 8 tangential cuts (6) are included in the large radius turn. The improved large radius inlet allowed for a single vane (7) and reduced pressure drop in the turn by 70%. Overall length was reduced by approximately half (8).

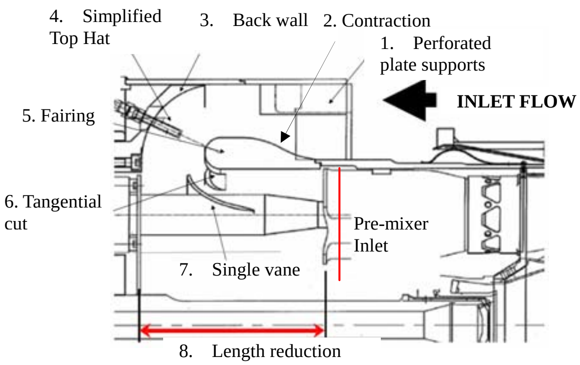


Figure 6. Improved features of the Mk8-4 inlet flow system

Using the advanced CAD to MESH methodology, a total of 20 3D geometric variations, including one and two vane configurations, were evaluated to optimize the design. Figure 7, shows CFD results in a plane in-between two pre-mixers, the single vane and tangential cuts are enough to guide the flow into the circular pre-mixers. The inlet boundary condition is assumed to be uniform for the CFD model.

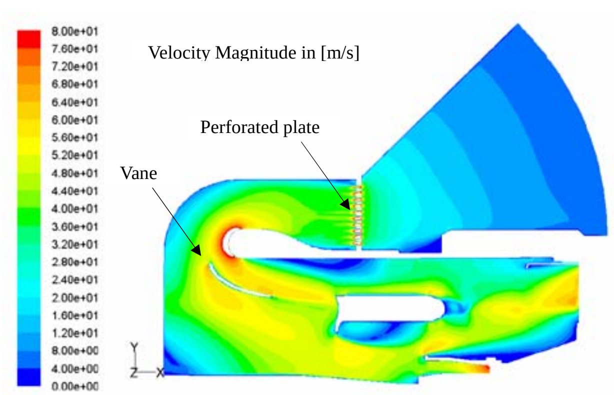


Figure 7. Contours of velocity magnitude in a plane between two pre-mixers

Figure 8 shows the velocity contours at the pre-mixer inlet for the MK7-4 and Mk8-4 (Note: scales are different). Regions of high and low speed still remain in the MK8-4, but overall uniformity level is better than the very successful Mk7-4 design and therefore are deemed acceptable.

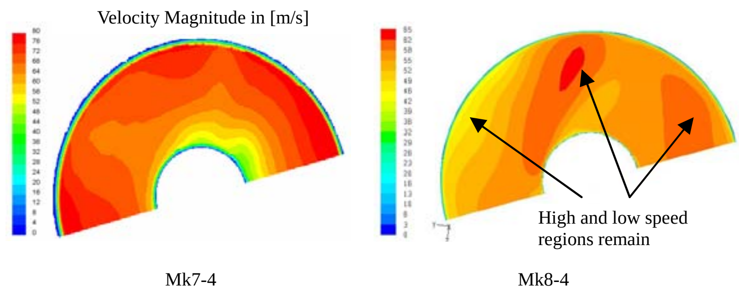


Figure 8. Velocity contours at the Pre-mixer inlet for Mk7-4 and Mk8-4 (See Fig. 6)

A Probability Density Function (PDF) is used to evaluate flow uniformity at the pre-mixer inlet. The PDF is defined by (1), where ν is the velocity magnitude and $area_k$ represents the area of a mesh cell containing ν_k. The bin_width is equal to ν_2 - ν_1.

$$PDF = \frac{\sum_{k}^{v1 \le v < v2} area_k}{\sum_{i}^{all} area_i} \Big/ bin\_width \quad (1)$$

Figure 9 compares the Mk7-4 and Mk8-4 uniformity levels. Ideal uniformity is a delta function at zero. The Velocity [%] is defined by (2), where (3) defines the area average of the velocity magnitude.

$$\tilde{\nu} = \frac{\nu - \bar{\nu}}{\bar{\nu}} \times 100 \quad (2)$$

$$\bar{\nu} \equiv \frac{\sum_{k}^{all} \nu_k \cdot area_k}{\sum_{i}^{all} area_i} \quad (3)$$

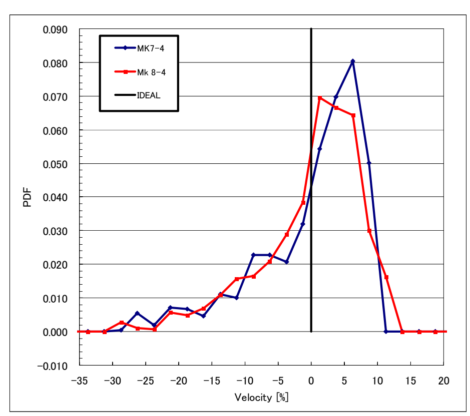


Figure 9. PDF for velocity magnitude distribution at pre-mixer inlet

In addition, the Standard Deviation (4) of the PDF function provides a single number to compare uniformity. X1 is the center of the best Gaussian fit to the PDF and A is the area of the mesh cell of velocity v.

$$\sigma = \sqrt{\sum (v - X1)^2 * A / \sum A} \qquad (4)$$

Table 1, compares the MK7-4 with single and two vane Mk8-4 designs. Even though the two vane design has slightly better flow uniformity at the pre-mixer inlet, it is not selected due to the additional cost and complexity.

Table 1. Standard Deviation of PDF to compare flow uniformity

	Center for best Gaussian fit to PDF data	Sigma based on raw data using best Gaussian fit **center**
MK7	4.22	9.13
two vane	2.04	7.80
one vane	2.84	8.22

In order to validate the CFD based design (design conditions) of the inlet system, atmospheric (rig conditions) tests are conducted. Flow visualization of the tangential cuts at rig conditions compare well with CFD at rig conditions in Figure 10. The size of the vortical structures created by the cuts is smaller at design conditions. This comparison demonstrates that the tangential cut design works and that the CFD is able to simulate it.

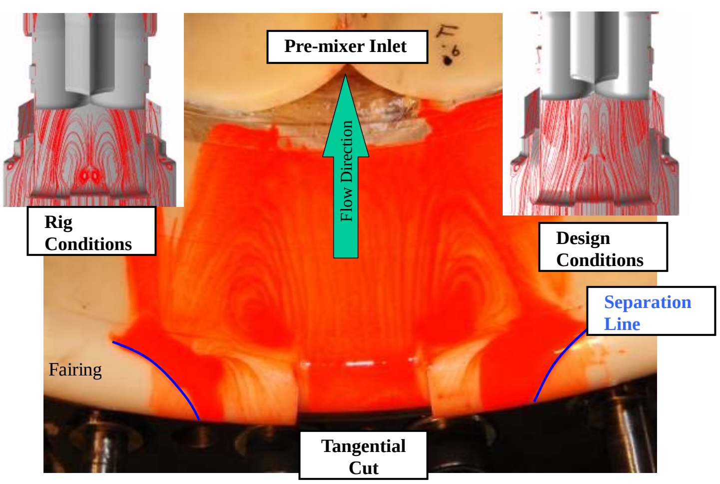


Figure 10. Comparison of oil visualization with CFD at rig conditions

The comparison of rig test measured circumferential axial velocity deviation from mean between MK7-4 and MK8-4 at the pre-mixer inlet are shown in Figure 11. The solid lines are for the Mk8-4 and dash lines for the MK7-4. This confirms that the MK8-4 has better uniformity.

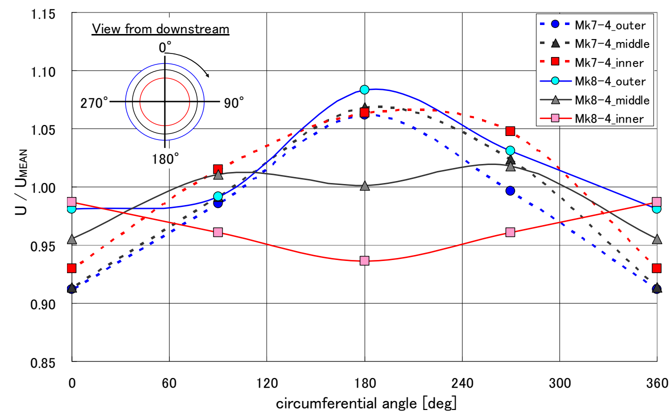


Figure 11. Circumferential axial velocity deviation versus circumferential angle

Finally, Figure 12 compares the uniformity levels between the CFD of the Mk8-4 at design conditions (Red line) and rig conditions (Green line). It is clear that the design does not perform as well at rig conditions and that better uniformity than shown in Fig. 11 can be expected at design conditions. This is due to the very low Reynolds number in some regions of the flow at atmospheric (rig) conditions causing limited laminar flow separation.

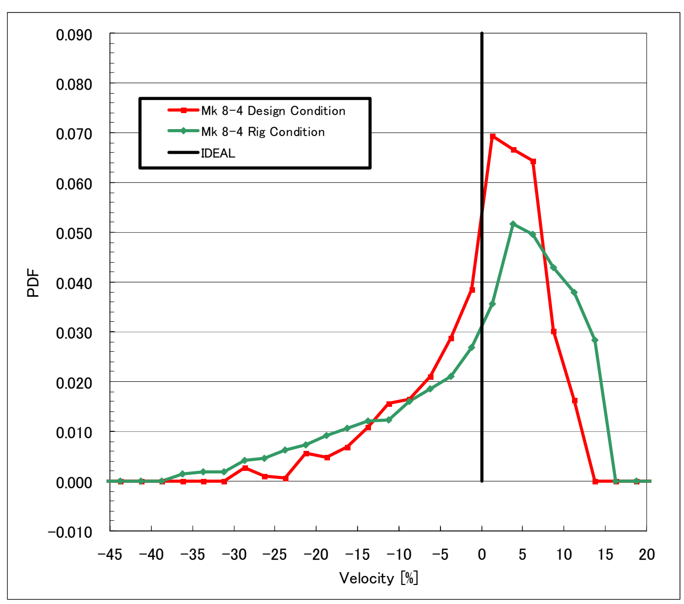


Figure 12. Comparison of uniformity for design and test conditions

2.2 Fuel / Air Mixing:

High flame temperature and hot spots have a negative impact on the amount of NOx produced in the combustion process. Therefore, it is important to achieve uniform mixing of air and fuel in order to minimize localized high temperature spots and NOx. Stagnation points and low velocity regions may lead to flash back conditions.

In the Mk8-4 DLN combustor, the fuel nozzles and swirlers were redesigned using turbine aerodynamic tools [15] in order to decrease the above mentioned localized high temperature spots in the flame and to minimize stagnation and low velocity regions. The result of the redesign is the V-nozzle which integrates the swirler with the fuel injection nozzle.

The main target of applying turbine aerodynamics design tools and computational tools is to achieve increased fuel air mixture uniformity while avoiding flash back. Figure 13 shows Planar Laser Induced Fluorescence (PLIF) results of fuel/air mixing uniformity for the Mk7-4 and Mk8-4 at the exit of the main pre-mixers. The fuel/air uniformity is better for the Mk8-4. The PLIF results are presented in the form of a PDF (similar to the CFD results in Fig. 9).

Three dimensional CFD analysis of the fuel (red) injection for the 3 hole MK7-4 and the multiple hole Mk8-4 are compared in Figure 14. The MK8-4 distributes the fuel better than the Mk7-4 leading to better fuel/air mixture uniformity.

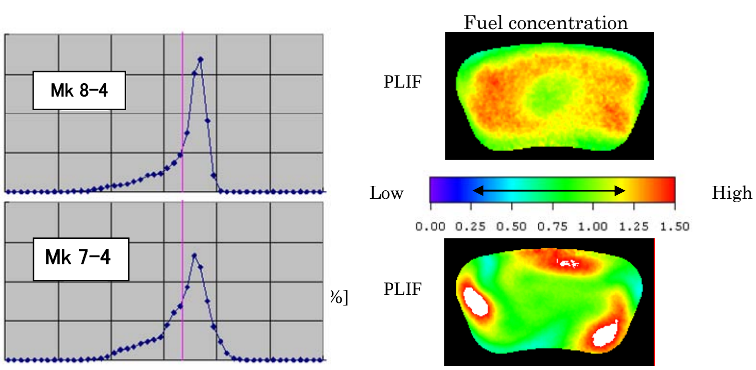


Figure 13. PLIF MK7-4 and 8-4 comparison of fuel/air uniformity at the pre-mixer exit

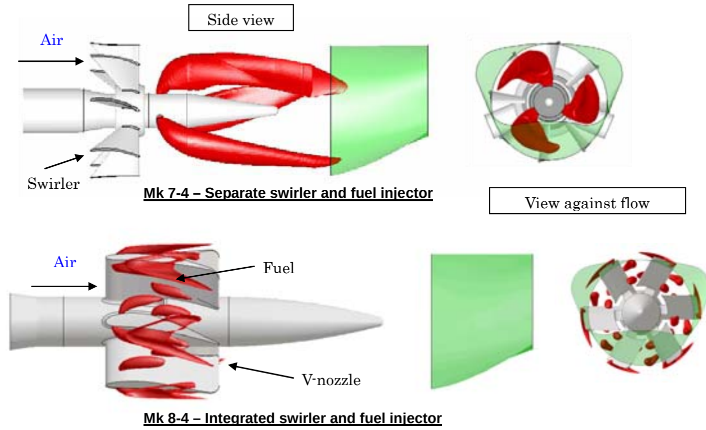


Figure 14. CFD analysis of injector and swirl vanes for Mk7-4 and 8-4

2.3 Combustor Aerodynamics:

Two improvements to the combustor aerodynamics are included: Increased flame holder size to improve flame stability and combustor outer wall shape to improve main flame shape and reduce recirculation zone temperature to reduce the NOx.

The Pilot nozzle diffusion flame is effective to prevent flame-out; however, its intensity is progressively reduced in order to minimize NOx emissions. Reductions in the Pilot to Main fuel ratio induce higher tendency for flame-out and increases combustion instability. Therefore, it is important to improve flame anchoring by increasing the pilot cone exit base area to maintain stable combustion under reduced diffusion flame conditions. Verification tests confirmed that this modification enhances combustion stability, even with Pilot ratio below 1%.

The issue of flame shape and reduced NOx is more complicated. Figure 15 shows fuel concentration CFD results of mixing (using a proprietary calibrated version of FLUENT [12]) for several wall shapes in search for the optimum design of the outer wall at the exit of the main pre-mixers. The CFD compares well with equivalent PLIF shown in the far right. A small recirculation zone on the top left corner of the exit of the pre-mixer (black circle at x=100 mm for case 1) is correlated to high temperatures. The final wall shape minimizes the size of this recirculation zone. From equivalent combustion CFD, the average temperature in the main flame recirculation zone is related to the NOx measured in experimental tests. Figure 16 shows that the average temperature from the CFD correlates well to the experimental NOx. Case 3 incorporated other changes in addition to the wall and therefore it does not have a good correlation.

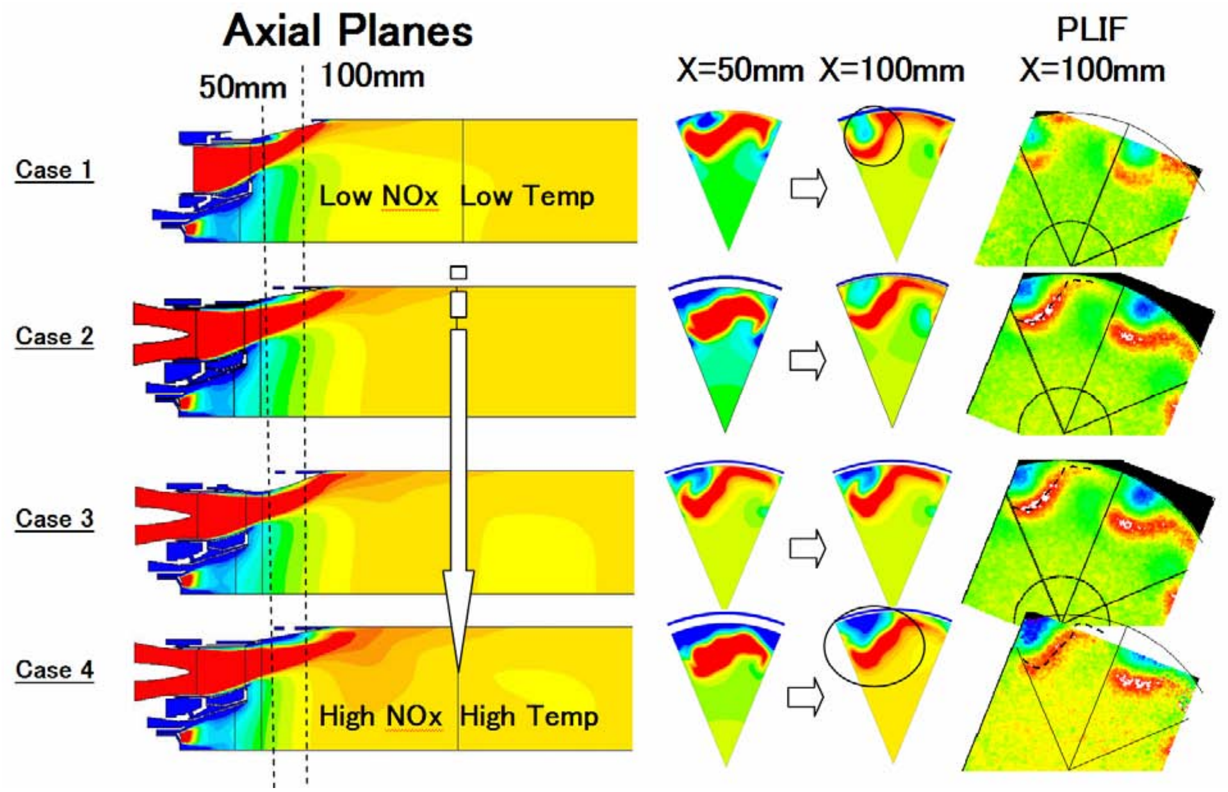


Figure 15. Fuel concentration CFD and PLIF

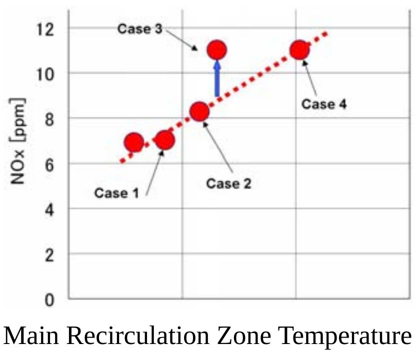


Figure 16. Relation between Temperature and NOx

Figure 17 shows CFD velocity vectors color coded by temperature for the final Mk8-4. The fuel from the main pre-mixers feeds the main flame which has a very robust recirculation zone and is well anchored.

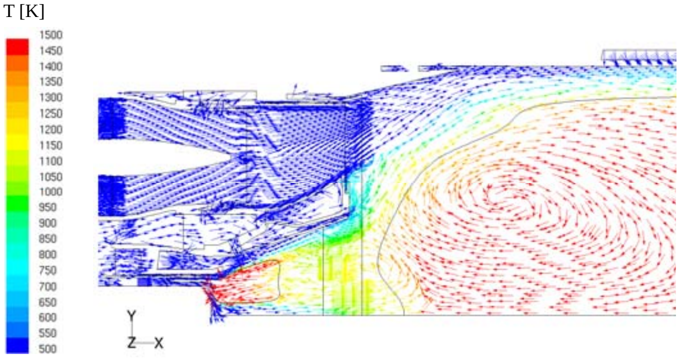
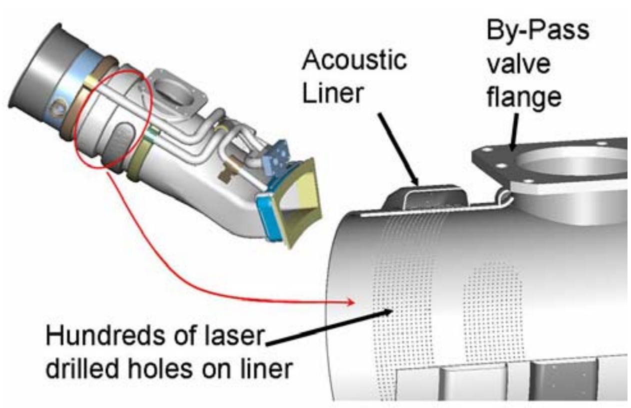


Figure 17. Velocity vectors colored by Temperature

2.4 Combustor Acoustic Attenuation:

Dynamics is the most difficult issue in DLN combustor. The Mk8-4 combustor uses improved acoustic devices to absorb dynamics. An acoustic liner is located on the combustor liner wall as shown in Fig. 18. It absorbs 1000-5000Hz dynamics.



The acoustic liner dissipates acoustic energy into heat by action of the viscosity as shown in Fig. 19. The heat is removed by the steam cooling system.

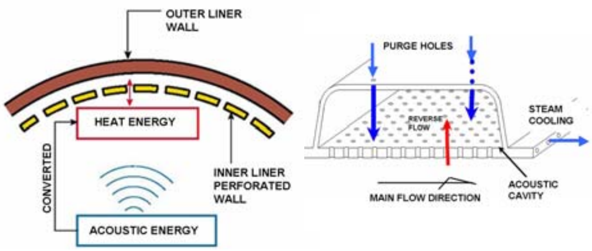


Figure 19. Acoustic liner operation

In addition, an acoustic damper is located in the duct between the combustor liner and the bypass valve. The damper absorbs 70-100 Hz dynamics. Figure 20, shows the location of the damper with respect to the by-pass valve.

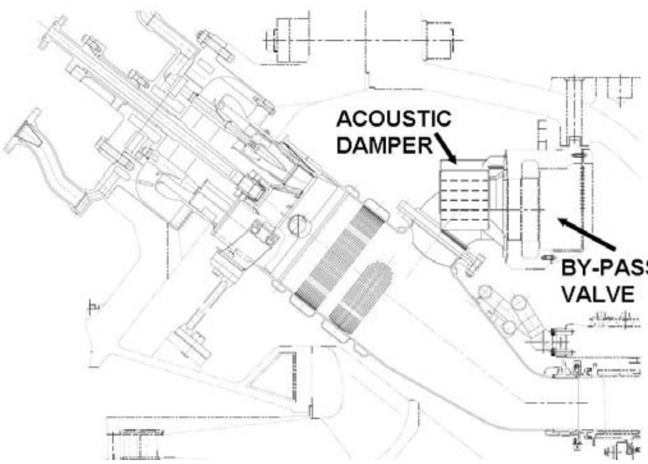


Figure 20. Acoustic damper location

The acoustic damper is slightly different in design than the liner. At the entrance there is a set of large perforated holes on the by-pass valve elbow that lead to high density metal foam damper from where the waves move into the acoustic cavity where they are converted into heat. The foam acts as a acoustic wall so that the waves remain in the cavity. Figure 21, shows a generic damper and a picture of the actual metal foam.

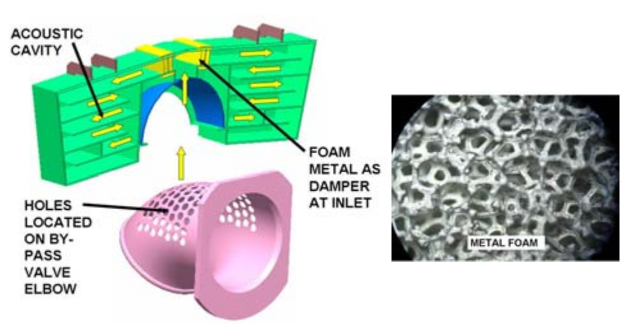


Figure 21. Acoustic damper parts

3. VALIDATION TESTS AT TAKASAGO VERIFICATION PLANT

The new DLN combustor was installed in a M501G1 gas turbine at MHI's T-Point Combined Cycle Power Plant. More than 1,500 special measurements were collected during the rigorous tests that were conducted for verification of the new design. Long-term verification was also conducted.

The results demonstrated the following capabilities:

- ✓ Less than 15ppm NOx operation with turn down to 60% load (Fig.22).
- ✓ Stable combustor dynamics at all load levels (Fig.23).
- ✓ High start-up reliability (combustor ignition)
- ✓ Suitable for daily start and stop (DSS) operation
- ✓ Confirmed reliability and durability of hot parts (Fig.24).

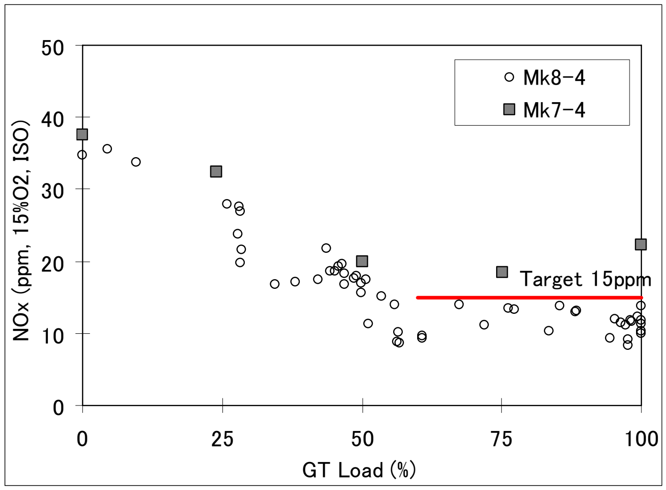


Figure 22. Engine NOx at all power levels

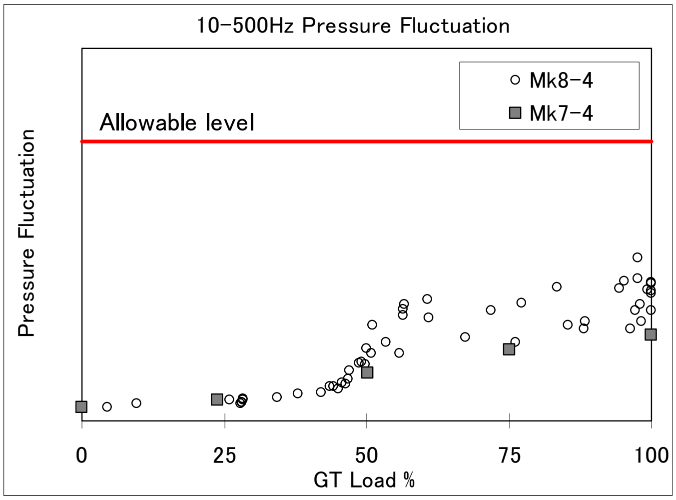


Figure 23-A. Engine pressure fluctuation level 10-500 Hz

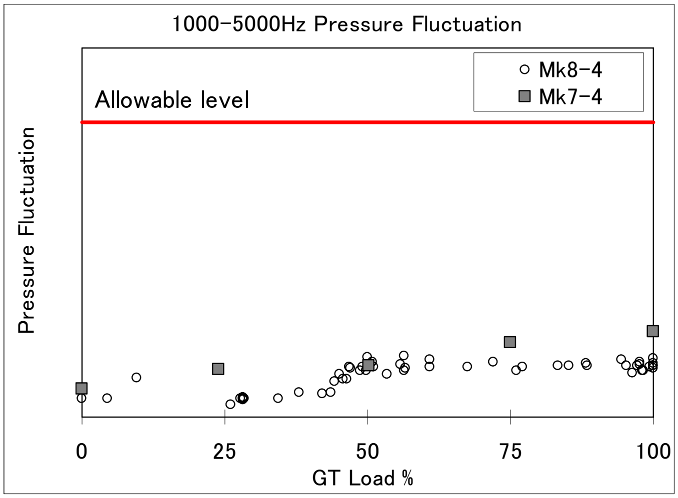


Figure 23-B. Engine pressure fluctuation level 1000-5000 Hz

V-nozzle

Swirler assembly

Figure 24. Picture of hot parts at scheduled combustor inspection after 2,340 hrs and 148 start/stop cycles

4. CONCLUDING REMARKS

A new DLN combustor design that achieves less than 15 ppm of NOx has been presented. Several features of the design are summarized below:

- The use of advanced aerodynamic methods in the inlet flow system enabled increased performance while reducing size, part count, cost and weight. The size and weight reduction leads to reduced manufacturing and transportation cost, and assembly time.
- The use of turbine aerodynamics design tools for the integrated fuel injector-swirl vane (V-nozzle) lead to improved fuel/air mixture uniformity at the exit of the pre-mixer, while reducing the danger of flashback.
- In order to achieve further NOx reduction, the pilot/main fuel ratio was decreased. Increased flame holding is added to maintain flame stability. A wide range of stable combustion with improved emissions was confirmed with Pilot to Main ratio lower than 1%.
- Further NOx reductions can be obtained by reducing the main flame recirculation zone average temperature. The combustor outer wall shape was the key to reducing the temperature and the NOx.
- The design has tested on MHI's M501G1 based Combined Cycle Power Plant (T-Point) for long term verification. The tests confirmed lower emission levels and improved combustion dynamic characteristics of the new design.
- The long term verification also demonstrated that the new design does not induce any negative side effect on the unit, including starting reliability, operating parameters and durability of the hot gas components.

5. ACKNOWLEDGMENTS

The support of T. Saitoh and K. Kurihara for the CFD and CAD to MESH is greatly appreciated.

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