Combustion Liner Sealing and Emissions Impact

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1. Introduction

Emissions are a major driving factor in commercial turbine design. As time passes emission standards become stricter, but the need for more powerful and thus more polluting engines is necessary. As emission levels drop the need to maintain tight tolerances and consistent flow parameters is key to ensuring predictable emission levels. While the main way to maintain a low emission level is to have a consistent flame profile that circulates and burns fuel at a low temperature, it is important to keep in mind that every component in the combustion section has the possibility of impacting emissions. Uncontrolled air flow into the combustion chamber can disrupt flow and quench the flame too early causing a rise in nitrogen oxides (NOx), carbon monoxide (CO), and unburnt hydrocarbons. As such sealing of the combustion chamber plays a key role in maintaining low emissions levels.

There are many methods to sealing the combustion chamber to other portions of the air flow traveling from the compressor to the turbine, as well as many different sections that need to be sealed. For this paper the focus will fall on the aft portion of the combustor. The liner used for testing is of an annular design and as such requires a large seal that goes around both the outer and inner section of the liner, and separates them from the turbine cooling flow. Specifically there are two types of seal being looked at for this study. The first is a fish mouth seal that requires the insertion of a sheet metal piece into a fish mouth to create a seal between the combustion section and the turbine cooling flow. The other seal is a brush seal that relies on a ring of bristles to seal the combustor from the turbine cooling flow.

The type of system used for this study was a dry low emissions system (DLE). A DLE system utilizes two fuel circuits to reduce emissions. The main circuit passes through a mixing changer where the fuel and air are allowed to mix and thus improve combustion characteristics. The other fuel circuit is a pilot circuit that injects fuel directly into the combustion chamber and burns via a diffusion process. This pilot circuit is mainly used to add stability to the system. The pilot circuit can be adjusted to help increase stability but at the cost of higher emissions. This is due to the diffusion flame created by the pilot does not burn as cleanly as the premixed flame from the main circuit.

Most of the tests outlined in this report are proprietary, so information is limited.

2. Fish mouth Fish Mouth Seal

The first type of seal to be looked at is the fish mouth fish mouth seal. This seal is made out of bent and machined sheet metal pieces that are inserted into one another (see figure 1). Due to this construction method there are variations in the seal circumferentially about the annulus. These irregularities can open or close due to the heat cycling of the engine during operation. If one of these irregularities were to open up the hot flow from the combustion chamber could be quenched due to the leakage. On the other hand there is the possibility that the irregularities seal due to the expansion of the metal at the high temperatures seen during full load and part load operation.

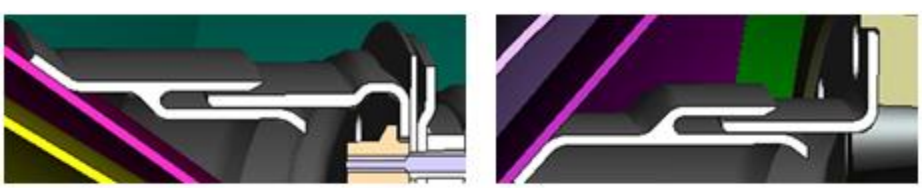

Figure 1: Outer fish mouth seal (left), Inner fish mouth seal (right)

The advantages of a design such as this are that theoretically there is a perfect seal between the combustor and the turbine section of the engine. This in theory would mean that there are low levels of leakage. The disadvantage of this seal type is that if an irregularity does open up and cause leakage there is a variation in the NOx level. This means that an engineer is incapable of reliably predicting the emissions levels when using this type of seal unless extreme tolerances are maintained which would drive up costs. If a leak does appear this could also cause the engine to go outside of the required emissions limit.

3. Brush Seal

The second type of seal being studied is a brush seal. In this sealing method a ring of stainless steel bristles is welded between two pieces of metal and then pressed against a bent piece of sheet metal attached to the combustion liner (see figure 2). As the heat from the combustor increases and the engine comes up to temperature the bristles expand and press onto the sheet metal attached to the combustion liner. This creates the seal between the liner and the turbine section of the engine. This method of sealing reduces irregularities by relying on multiple rows of bristles. If a single row doesn't make a seal with the sheet metal there are still many other rows capable of creating the seal.

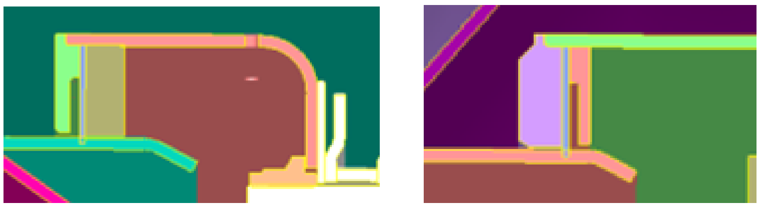

Figure 2: Outer brush seal (left), Inner brush seal (right)

The expected advantage of a brush seal is that it has a more consistent leakage level. The multiple rows of bristles are very effective at consistently creating a seal despite the load or temperature of the engine. The disadvantage of this type of seal is that it inherently has a higher level of leakage. The lifespan of a brush seal is also a point of concern as the bristles can deflect and deform during use. If a large enough deformation is created the seal will no longer be effective. While the end goal is to reduce emissions it is important to keep in mind that these emissions levels must be held at all times. If the brush seal is indeed more consistent that means that there is more confidence that an engine will always be within the emission limits.

4. Experimental Setup

To test the two different types of seals a series of test were preformed to check the emissions and vibration characteristics of the engine. Four different types of test were run. A full load pilot turndown, a part load pilot turndown test to as low as limit conditions would allow. Part load T5 turndown test from base-nominal to as far low as limit conditions would allow, where T5 is the temperature at the power turbine inlet averaged over several thermocouples located around the circumference of the engine. These T5 values are used to monitor engine load and monitor temperature variations which are undesirable. Finally load sweeps were preformed form idle to full load taking data point at every 10% increment of load. A turndown test is where the variable of interest is started high and then lowered gradual under the same load conditions to examine the effects of changing one of the engines control parameters. For example a pilot turndown test would consist of starting the pilot circuit above its nominal value and gradually lowering to below its nominal value till one of the limit conditions are met or pilot can be reduced no more. Limit conditions placed on the experiments to protect the engine were a max rumble amplitude (10-100 hz), oscillation amplitude (100-1000 hz), and a T5 spread limit.

Each of the tests was preformed multiple times both forwards and backwards. The goal of doing this was to create conditions where load swings and pilot swings may create leaks from inconsistencies opening during heat cycling. All tests were performed on similar engine models as well as under similar atmospheric conditions. All of the important engine parameters were monitored live to ensure that if a problem were to arise the proper actions could be taken to protect the engine. Borescope checks were done periodically though out the testing period to check on the condition of the brush seals. So long as the seals appeared to be in good condition was testing permitted to continue.

4. Experimental Results

First and foremost there is a notable difference in the seal NOx levels at full load (figure 3) as expected. There is only about a 1.5 ppm difference in NOx levels but it should also be noted that there is a large variation in the brush seal NOx levels depending on the day of testing. By looking at the T5 spread vs time graph (figure 4) we can see a downwards trend in T5 spread. This is indicative of brush seal break in. Testing of other brush seals in previous builds shows a similar 1 ppm difference in NOx levels as well as a similar break in period; as such the reported values are reliable. As expected there is a larger amount of leakage from the brush seal as evident from the increase NOx level.

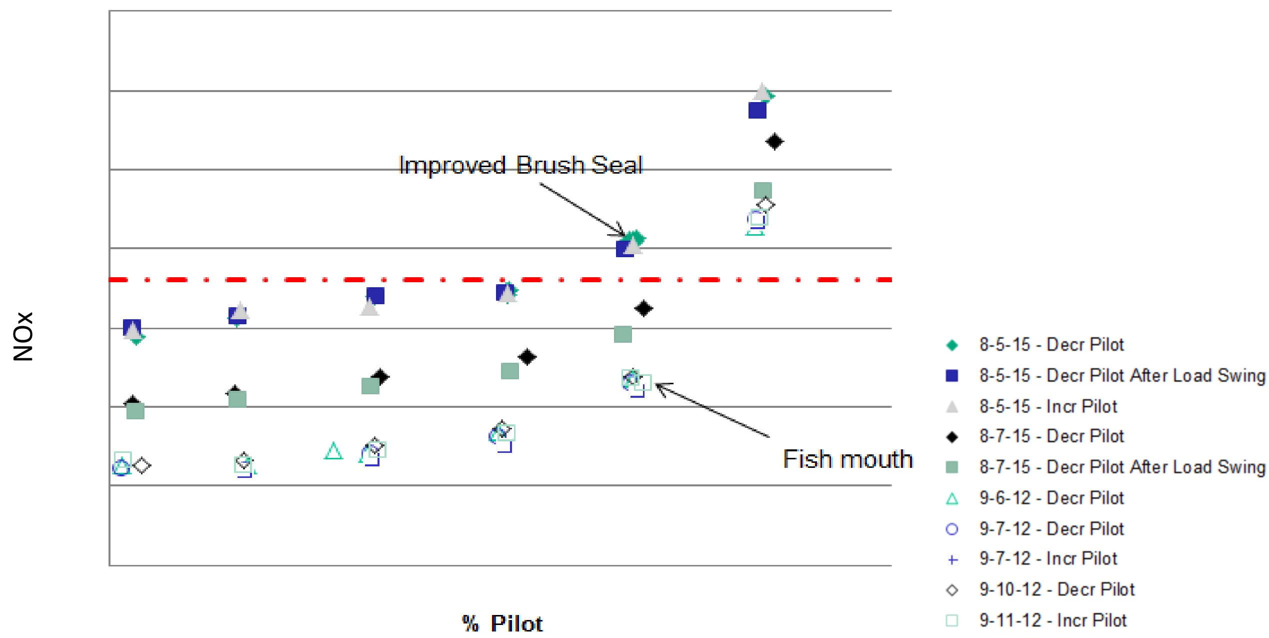

Figure 3: Full Load NOx vs Pilot (NOx values redacted)

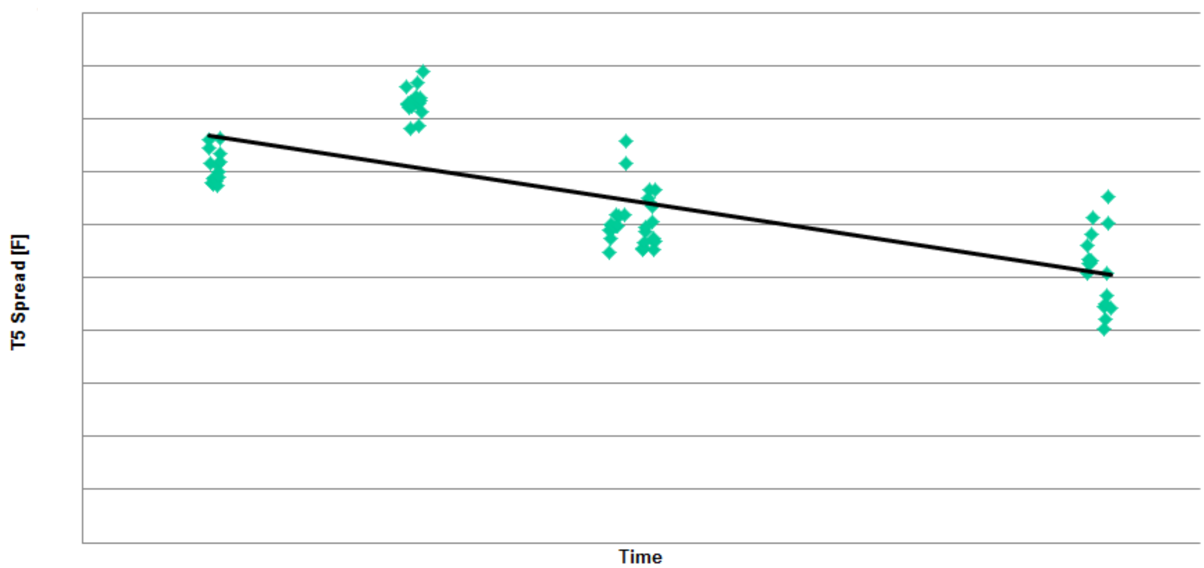

Figure 4: T5 Spread vs Time (each cluster is a day of testing)

One of the unexpected results that came from this testing was the decrease in rumble seen with the brush seal. With the fish mouth seal there is a large peak at low pilot that exceeds the limit conditions, as well as a large spread in values. The brush seal also as a peak at the same pilot level but the peak amplitude is much lower. This decrease in rumble could allow for a lower pilot setting as the engine is not as sensitive to decreases in pilot during operation with the brush seal.

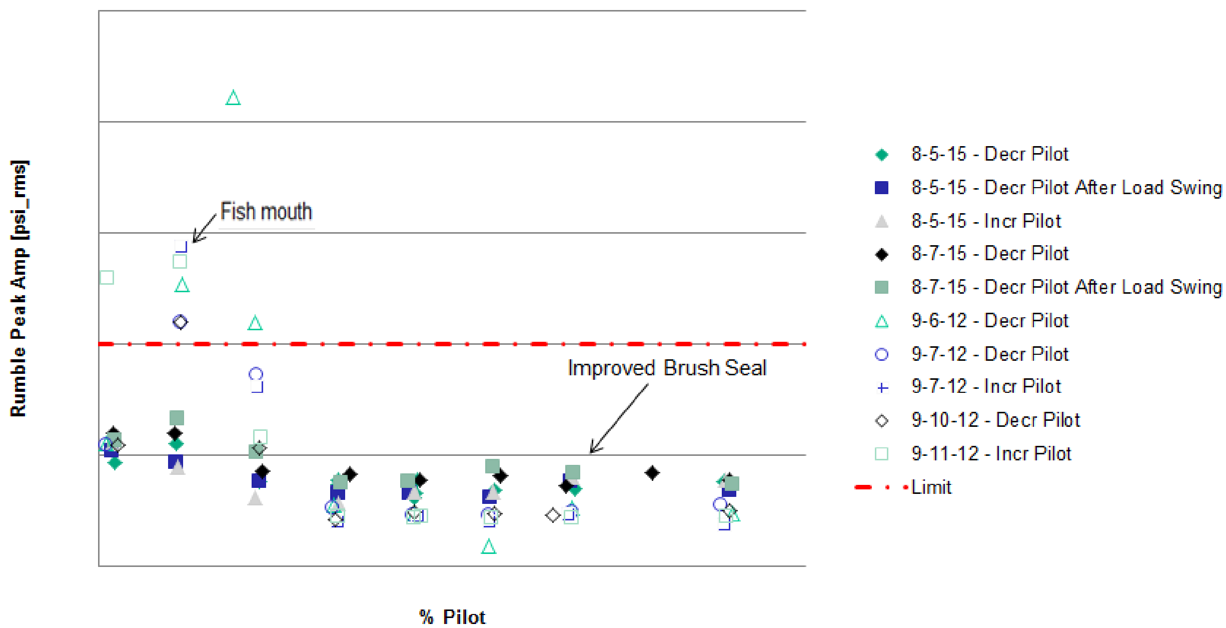

Figure 5: Full Load Rumble vs Pilot

After these major differences there is little else to be said about the advantages or disadvantages of either seal type. The levels of carbon monoxide (CO) are roughly the same for both seals at full load (figure 6). The same can be said for T5 spread at Full load (figure 7). Full load oscillation also shows very little variation between the fish mouth seal and the brush seal (figure 8). As such there is very little difference between these two sealing methods expect for NOx levels and rumble levels.

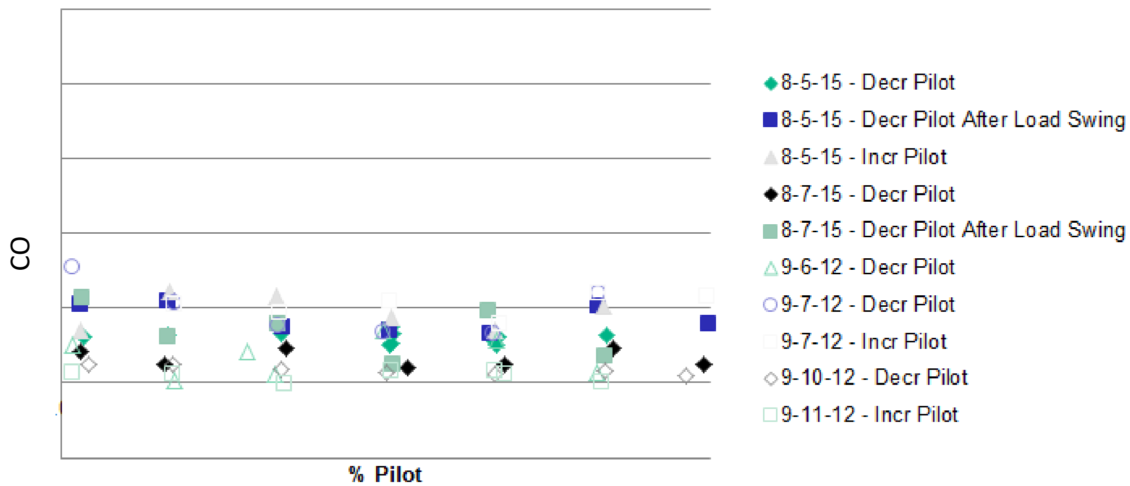

Figure 6: Full Load CO vs Pilot (values redacted, solid symbols represent the brush seal)

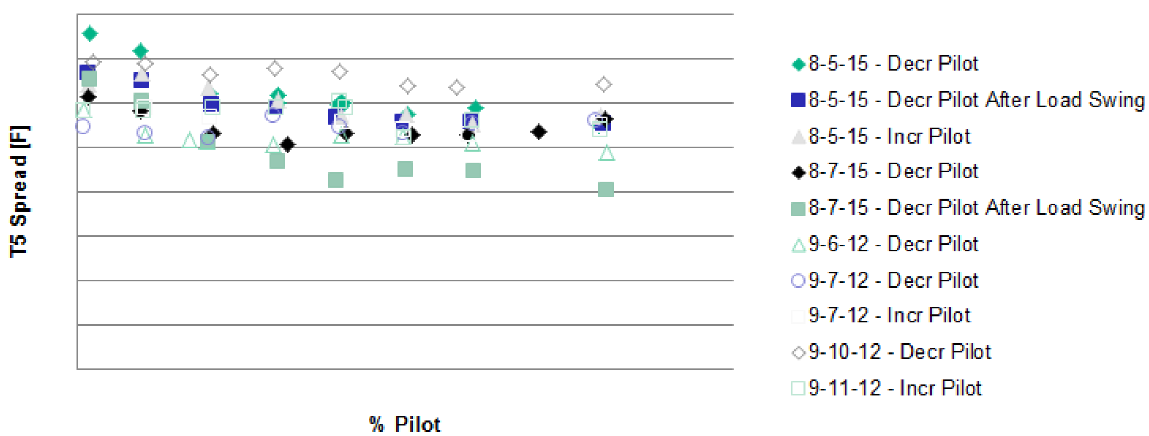

Figure 7: Full Load T5 spread vs Pilot (solid symbols represent the brush seal)

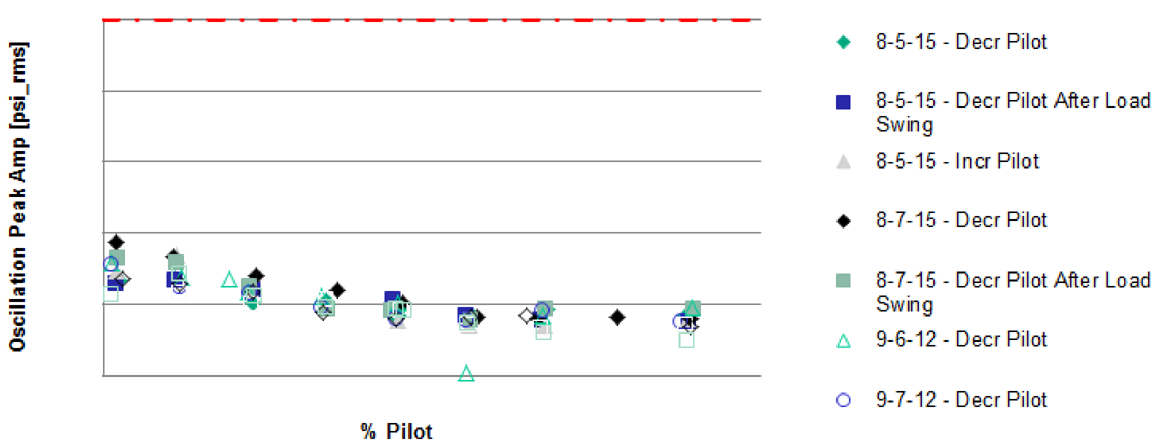

Figure 8: Full load Oscillation vs Pilot (solid symbols represent the brush seal)

After all the testing was performed a series of borescopes was taken in order to inspect the brush seals at a multitude of locations. Figure 9 shows a characteristic picture from the final borescope check. This is after several fast stops and load swings put on the engine with the goal of attempting to evaluate the durability of the brush seals.

Figure 9: Borescope of brush seal

5. Conclusion

After an extensive week of testing there were a total of 34 hours of run time with 16 hours at full load. 160 data points were taken and 15 different tests were run. As expected the brush seals demonstrated a lower level of sealing when compared to the fish mouth seal. This is evident from the increase NOx levels seen when using the brush seals. The increased leakage leads to a quenched region at the rear of the combustor causing the fore mentioned increase in NOx levels. Unexpectedly there was an improvement in rumble when using the brush seal, a decrease of roughly 75 % in some cases. This shows that there is a possibility for a more optimized design with the brush seals installed. If the brush seal was run at slightly lower pilot from the standard setting the NOx levels of the brush seal and fish mouth seal would be identical. This could be a possibility as the brush seal didn’t show the large spike in rumble seen in the fish mouth seal testing.

Besides these major differences there is little else to differentiate the two seals from one another. The only other major concern that needed to be addressed during the testing was to ensure the durability of the brush seal. Looking at the borescope pictures between each day of testing it was clear the brush seal took very little damage between tests. Most of the damage was inflicted during installation, and as such is a concern when using this type of seal. Removing the seal post testing showed more damage than seen in the borescope pictures, but where there was damage the bristles still were capable of creating a seal. As mentioned before one of the advantages of the brush seal is its consistency. Despite some damage being inflicted to the seal it was still able to perform at the same level.

Both seals show promise for use. The NOx variation is a known problem with the fish mouth design, but the brush seal eliminates this problem by offer a consistently higher level of leakage and as such increased emissions. Another consideration that should be noted is that the brush seal offers fewer vibrations traveling though the engine. As such the engine takes fewer cycles of stress and could improve engine longevity as vibrations can be the cause of crack prorogation. In the end it is not clear as to which seal is better. For better emission levels the fish mouth seal if preferable, but if one desires a more consistent seal brush seal appears to be the preferable choice after break in.

If this testing were to be repeated it would be recommended to use a seal that already gone through a period of break in. This would expedite testing and give more data points that are useful for comparison. It would also be recommended to perform more load swings from idle to full load and from part load to full load with the goal of inducing NOx variation. Several of these were performed during the test but more would be desirable in order to get more data for comparison.

6. References

1. Lefebvre, Arthur H. *Gas Turbine Combustion*. 3rd ed. Washington: Hemisphere Pub., 1983. Print.
2. Caron, Timothy J: *Solar Turbines Bld 112 Report*
3. Dillard, Luke: *Solar Turbines Exit Presentation*