University Turbine Systems Research (UTSR)
2015 Gas Turbine Industrial Fellowship Program

Dynamic Instability Limitations in the Testing of an Advanced Premixed Combustor

Prepared for

Siemens Energy
Orlando, FL 32826

and

Southwest Research Institute
San Antonio, TX 728228

Prepared by

Christopher Reuter
Princeton University
Department of Mechanical and Aerospace Engineering
Princeton, NJ 08540

Abstract

A new premixed combustion technology aimed at reducing NO_x emissions was tested in a Siemens large gas turbine at the Siemens Berlin Test Facility. Two design variants were tested. The first design was successful in lowering NO_x compared to current technology but suffered from operational restrictions due to combustion instabilities. In the second design, however, a modified fuel nozzle allowed most of these instability problems to be avoided, and as a result further operational regions of even lower NO_x were successfully tested. The results of this testing period showed not only the potential of new premixed combustion techniques but also the far-reaching effects of persistent combustion instabilities.

1. Introduction

With natural gas production continuing to climb in recent years, large gas turbines have been an increasingly important source of power generation throughout the world due their operational flexibility and reasonable cost. Due to the enormous amounts of power being produced by these engines, even small technological improvements can result in substantial savings in fuel cost and emissions. One important area of research over the past few decades has been premixed combustion techniques, which can offer substantially reduced NO_x emissions compared to their diffusion counterparts. This is made possible by the fact that premixed flames can burn at lean (low fuel/air ratio) conditions with relatively low maximum flame temperatures, greatly reducing the thermal NO_x formed [1]. Diffusion flames, on the other hand, always burn at a stoichiometric ratio and therefore usually require the use of diluents in order to lower the flame temperature.

With this in mind, Siemens has been investigating a variety of new designs that improve mixing characteristics for emissions reduction in a premixed combustor. Several prototype concepts were analyzed, and the most promising concepts were tested in a single burner, high-pressure combustion test rig. After a further series of prototypes, two designs were selected for testing in a full-scale engine at their Berlin Test Facility. Design #1 showed the some of the greatest potential for lower NO_x emissions than the current premixed technology in use. Design #2 was a variant of the same overall concept as Design #1 but had a different fuel nozzle design, which is characterized by a different flame-acoustic interaction compared to Design #1. The change in fuel nozzle design offered improved combustion dynamics in certain frequency ranges at the cost of a minimal NO_x increase compared to Design #1. The overall goals of the full-scale engine tests were to confirm the emissions benefits of these two new designs and to evaluate the different combustion acoustic behaviors at realistic engine operating conditions as well as at off-design conditions.

Combustion instabilities are quite complicated, but the general mechanism can be often be simplified into a feedback loop between various flow and combustion processes. In a lean premixed combustion system, this feedback occurs between oscillations of heat release, pressure, and equivalence ratio [2]. Essentially, pressure waves (sound) are created by unsteady heat release in an engine. The combustor walls reflect these pressure waves back into the flow, leading to oscillations in the equivalence ratio of the mixture. These variations in equivalence ratio then cause the mixture to burn with an unsteady heat release rate, which starts the cycle over again. If left unchecked, instabilities of this type can produce enormous pressure oscillations, which may damage the combustor and prevent steady engine operation.

2. Test Results

2.1. Design #1 Testing

As anticipated from the rig tests, the full-scale test of Design #1 was successful in reducing NO_x emissions. It can be seen in Figure 1 that at the same turbine inlet temperature, the NO_x produced is noticeably lower in Design #1 than in the current premixed combustion technology. Moreover, this advantage is not only useful from the point of view of lowering emissions but from an efficiency standpoint as well. If both technologies were operating at the same NO_x threshold (say, 25 ppm), Design #1 would have a higher turbine inlet temperature and, in all probability, a higher level of efficiency.

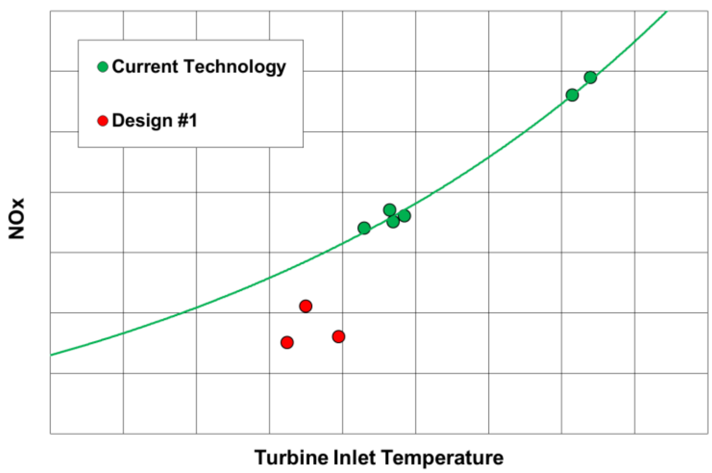

Figure 1: Engine test results comparing NO_x emissions as a function of turbine inlet temperature between current technology and Design #1.

In addition to overall lower NO_x emissions compared to the current premixed technology, Design #1 also showed a lesser sensitivity to ambient conditions. In particular, changes in the fuel and air temperature did not result in substantial shifts in the engine emissions. Figure 2 shows a direct comparison between the effects of fuel gas temperature on NO_x emissions in the current technology and Design #1. While the use of colder fuel caused a noticeable increase in NO_x for the current technology, it had little effect during the engine testing of Design #1. This result shows the potential for the new premixed combustion technology to be used in a wide variety of markets (particularly those in colder places) without encroaching upon emissions restrictions.

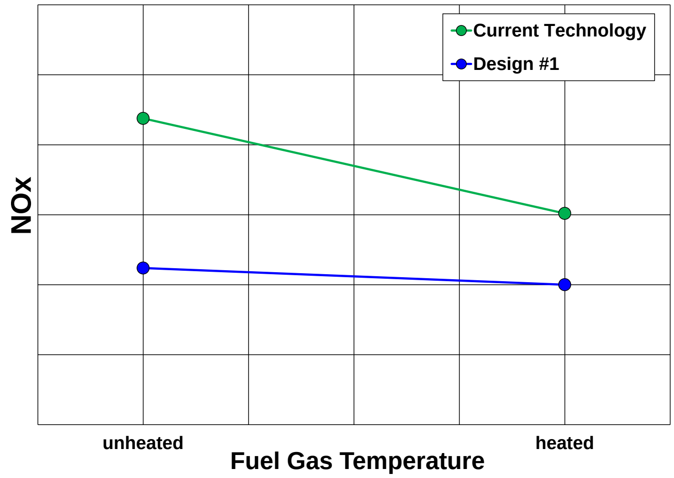

Figure 2: Impact of fuel gas temperature on NO_x emissions for current technology and Design #1.

In operating the full-scale engine, the level of NO_x emissions at a particular test condition was able to be modified through the use of certain combustion tuning parameters. Figure 3 reveals the strong correlation between NO_x and one of these tuning parameters during the testing of Design #1. For reducing NO_x, therefore, it was best to have this tuning parameter be fairly low (assuming that other parameters were more or less unchanged). During the testing period, however, the dominant instability mode inherent to Design #1 interfered with the thorough tuning of this parameter.

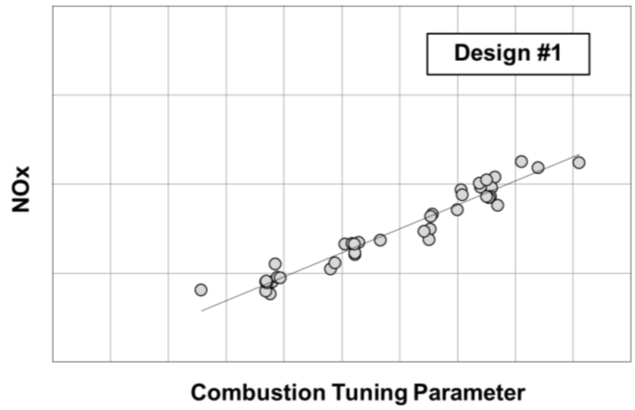

Figure 3: Correlation between NO_x and a combustion tuning parameter during the engine test of Design #1.

Figure 4 shows an instance of one of these instability events. When the aforementioned combustion tuning parameter from Figure 3 was reduced at full engine load, a large rise in combustion dynamic instability (measured by pressure oscillations) followed seconds later. This instability soon resulted in an engine trip to prevent further damage. As a result, Design #1 was not able to reach the lowest possible levels of NO_x emissions due to these combustion instability limitations. Throughout the testing of Design #1, these inherent instabilities not only affected tuning but also restricted certain operational regimes of the engine.

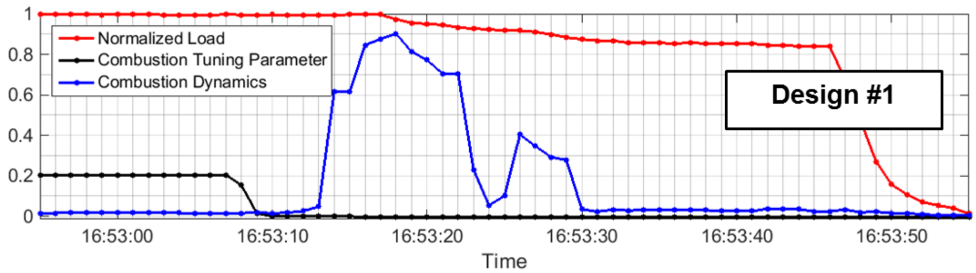

Figure 4: Combustion dynamic instability event following the reduction of a combustion tuning parameter during the engine test of Design #1.

2.2. Design #2 Testing

After the completion of testing Design #1, the full-scale engine testing moved on to Design #2, which possessed redesigned fuel nozzles with a primary objective to modify the combustion dynamics response (at the cost of a slight increase in NO_x). In particular, the dominant instability mode inherent to Design #1 was substantially lowered. As a result of the improved combustion dynamic response, the Design #2 engine possessed a wider operating envelope with improved tuning flexibility compared to Design #1.

As a direct comparison of the operational ability of the two designs, Figure 5 illustrates Design #2 undergoing a brief drop in the same combustion tuning parameter that is shown in Figure 4 for Design #1. It is apparent that the new design of the fuel nozzles in Design #2 kept the combustion dynamics low after reducing the tuning parameter, which stands in marked contrast to the dominant combustion instability spike that tripped the engine during the Design #1 test.

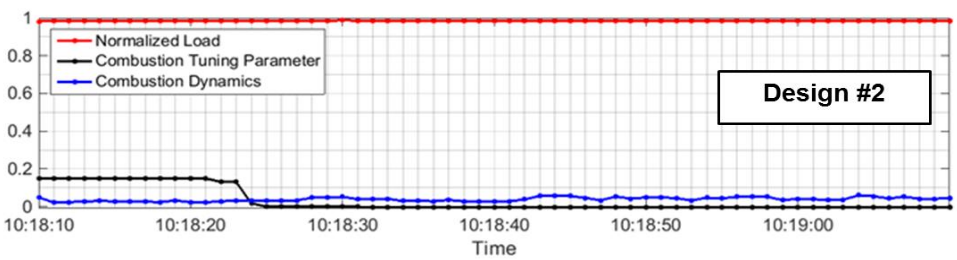

Figure 5: Steady dynamics following the reduction of a combustion tuning parameter during the engine test of Design #2.

Because of the increased ability to tune the engine in a stable manner, the NO_x penalty associated with the redesign of the fuel nozzles in Design #2 proved to be minimal, as Figure 6 indicates. Design #1 and Design #2 produced similar emissions at the same turbine inlet temperatures, and both were at substantially lower values than the current technology. Furthermore, the greater operational envelope of Design #2 allowed it to reach both lower turbine inlet temperatures (lower absolute NO_x values) and higher turbine inlet temperatures (high engine efficiency) than Design #1.

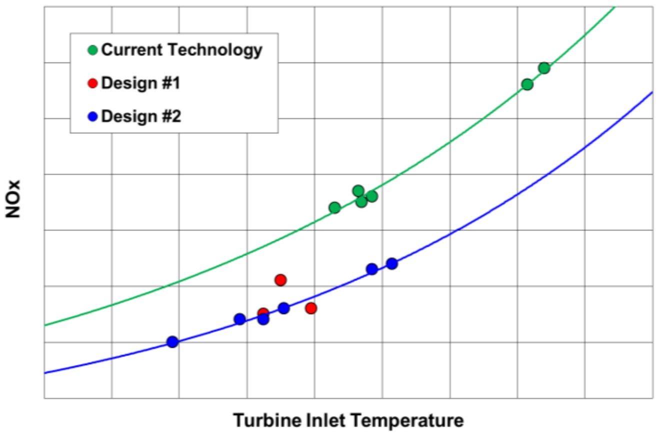

Figure 6: Engine test results comparing NO_x emissions as a function of turbine inlet temperature between current technology, Design #1, and Design #2.

3. Conclusion

Premixed combustion technologies have great potential for lowering emissions while maintaining high efficiency in a gas turbine. Engine test results from Siemens's Berlin Test Facility show a reduction in NO_x in both Design #1 and Design #2 of a new premixed combustion system. However, the testing of Design #1 was severely limited by combustion dynamic instabilities, preventing the engine from reaching various operational regimes. Design #2 was able to circumvent these instabilities through a change in the fuel nozzle design, allowing the full potential of the new premixed system to be displayed. Therefore, the control of combustion dynamic instabilities is crucial in the implementation of these new premixed technologies. Combustion instabilities can lead not only to problems in component lifetime, but its restriction of operational stability can affect both emissions and efficiency.

Acknowledgements

Special thanks to the University Turbine Systems Research program of the Southwest Research Institute and to Siemens Energy (in particular, Clifford Johnson and Jared Pent).

References

[1] I. Glassman and R. A. Yetter, *Combustion*, 4th edition, Academic Press (2008).

[2] T. C. Lieuwen, "Investigation of Combustion Instability Mechanisms in Premixed Gas Turbines," Doctoral Thesis, Department of Mechanical Engineering, Georgia Institute of Technology (1999).