Prediction of Lean Blowout in a Gas Turbine Engine

UTSR Fellowship Program

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Introduction and Purpose

FlexEnergy Energy Systems, Inc. manufactures recuperated gas turbine generators that operate in the 250 kW range. The technology provides reliable, high-efficiency, low-emissions power from a wide variety of fuel sources. An updated version of the MT250 turbine is currently under development. Features of the upgraded engine allow it to operate with increased efficiency and stability over a wider range of operating conditions. One of my tasks at FlexEnergy was to conduct combustor blowout testing to establish the turbine operating envelope for the new design. Further, I was to develop a pilot flame schedule to extend the envelope of stable operation.

Background

FlexEnergy gas turbines operate in a lean-premixed combustion regime, allowing them to achieve extremely low emissions levels. As power and fuel flow decrease, the combustor flame is susceptible to extinction via blowout, in which the flow rates in the combustor are too rapid to allow the flame to stabilize. At these conditions, combustion can be stabilized by use of a pilot flame. This introduces a diffusion flame, which has undesirable characteristics from an emissions standpoint, but allows the turbine to continue operation in conditions that would otherwise be unstable. To minimize the impact of the pilot flame on emissions, the MT250 uses two distinct pilot levels. Pilot level 1 uses a small amount of fuel to partially extend the operating range of the turbine with a minimal impact on emissions levels, while pilot level 2 adds additional fuel and is designed to allow the engine to operate under zero generator load.

Blowout conditions may be described by a number of methods. One such method is through use of the Damköhler number, Da, which compares the reaction time scale to physical flow time scale, in this case, combustor residence time. Another technique for describing blowout is the combustor loading parameter, LP, defined as

$$LP = \frac{\dot{m}_{air}}{VP^n}$$

The loading parameter is also sometimes defined with an inverse exponential temperature dependence. A stable flame that is not near blowout will have a low loading. An unstable flame at or near blowout has a higher LP. Because calculation of the Damköhler number requires several unknown or difficult to measure parameters, the combustor Loading Parameter was employed to predict blowout. Although the loading parameter reaction volume, V, is not known, we can assume that it takes an arbitrary constant given the fixed combustor geometry.[1]

Testing

Procedure

Testing involved allowing the turbine to achieve steady-state operation at a specified inlet air flow rate. Power was adjusted to achieve a normal operating temperature for each test in order to accurately capture real-world operating conditions. Pilot valves were then set manually, before forcing the machine to reduce output and thereby fuel flow. Thermodynamic and performance data were recorded during the ramp down and the subsequent blowout event. As the purpose of the test was to determine when the pilot level should be increased, only no pilot and pilot level 1 were tested.

This procedure was repeated for a sampling of engine air flow rates that span the range of expected operating conditions. Both medium and low fuel heating content combustor arrangements were tested, and testing was repeated for a variety of fuels.

In addition to recording data leading up to and at blowout, data was recorded during steady-state operations at those conditions achieved during the test. This data served as a control to compare the blowout data against.

Steady State Analysis

In the steady state data, loading parameter values are very consistent, having a maximum standard deviation of about 0.5%, and typically much less, over a thirty second period. Additionally, when the only difference between two steady state data samples is the level of the pilot, they always have overlapping standard deviations. Thus there is no discernible effect on LP of the pilot level, alone. The loading parameter values at steady state were spread across a similar range as the no pilot blowout values.

Results

The results validate the effectiveness of the pilots in extending the turbine's stable operating envelope. Figure 1 illustrates this, showing the percentage of maximum power at which each blowout event occurred. The current pilot schedule is defined by opening pilot valves when operating under certain power percentage thresholds. Figure 1 shows that, while this technique may be effective, percent power is not a very precise predictor of blowout. This results in pilots being on when they do not need to be, increasing emissions unnecessarily. The imprecision of percent power as a blowout predictor motivates the decision to update the pilot schedule.

[1] Kesseli, J., Norster, E.R., & Landau, M., (1992). Low NO_x Combustor Design and Test with a Recuperated Gas Turbine Engine. In D.H. Cooke, S.H. Borglin, H.W Holland, & L.S. Langston (Eds.) *Asme Cogen-Turbo*. New York, N.Y: American Society of Mechanical Engineers, 1992. Print.

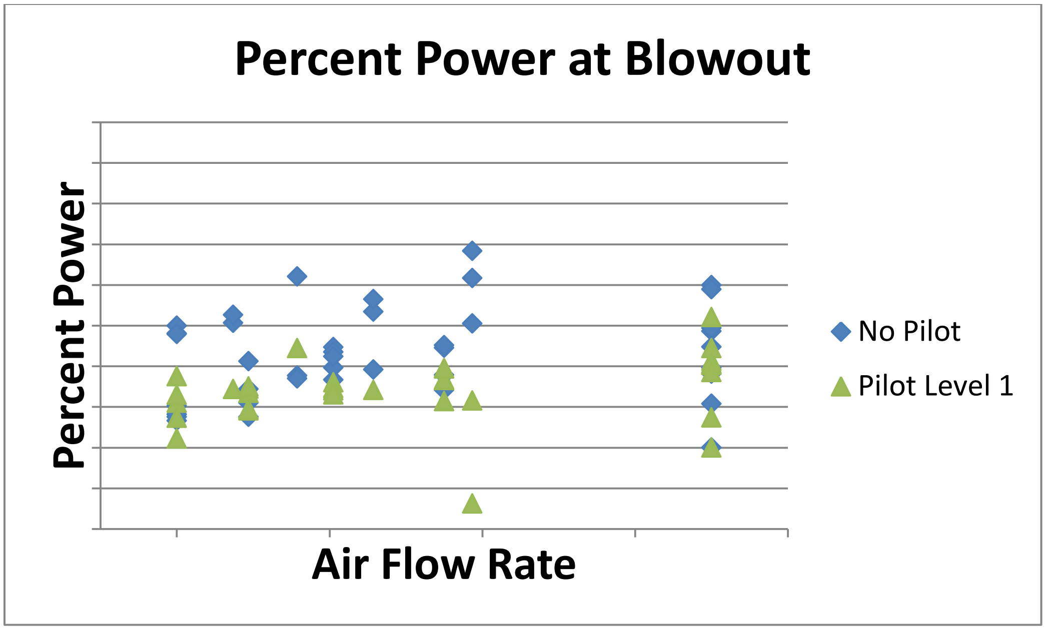

Figure 1 - Output percent power versus air flow at blowout conditions

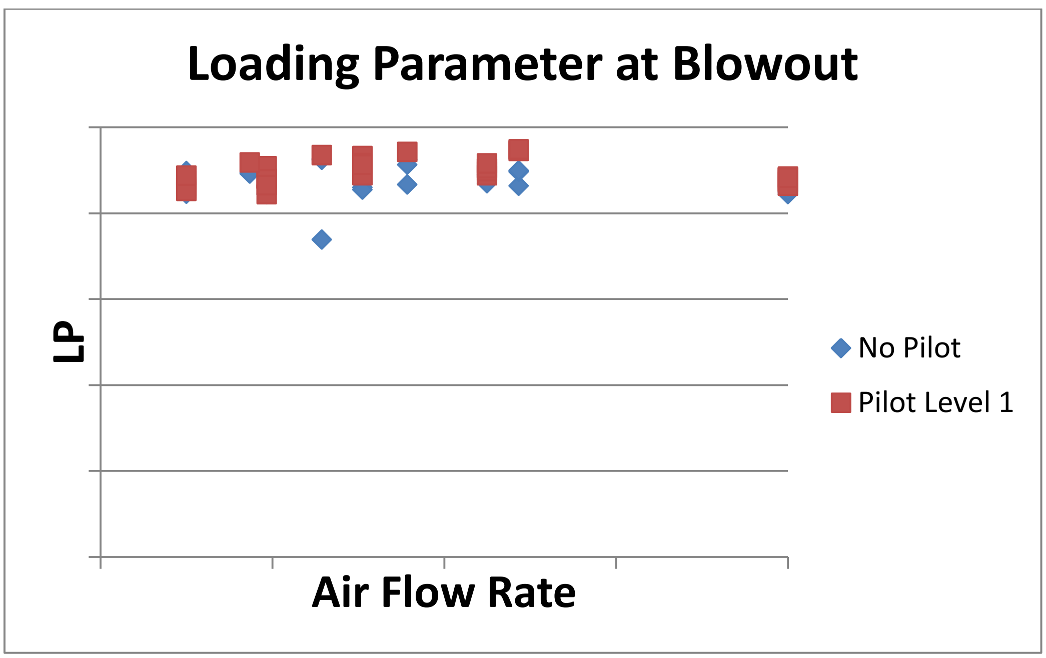

Figure 2 - Combustor Loading Parameter versus air flow at blowout conditions

Figure 2 shows the computed LP at blowout across all of the tests. The vertical scale is similar to that presented in Figure 1. It is readily apparent that LP correlates the blowout data better, as all of the data falls within a much smaller range. However, it is also notable that any significant separation between the blowout LP value with no pilot on and with pilot level 1 on is gone. This observation remains even when the vertical range of the plot is heavy reduced, as in Figure 3.

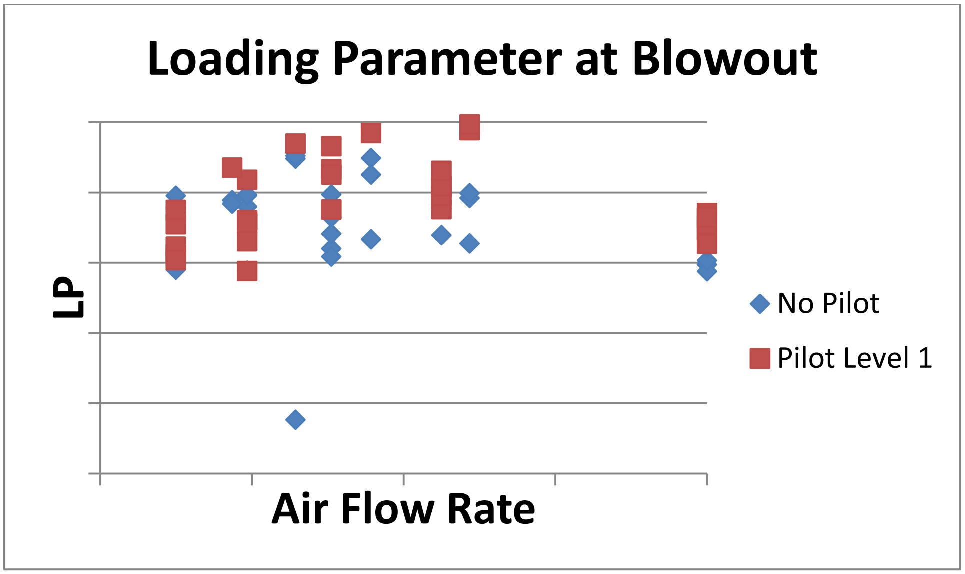

Figure 3 - Combustor LP versus air flow at blowout with a reduced vertical scale

Transient Analysis

The similarity between LP values at blowout with no pilot on and pilot level 1 on makes it difficult to stage the pilots. Empirically, and based on Figure 1, we know that pilot level 1 is sufficient to extend the operating envelope of the turbine without turning the pilot level 2 on as well. In order to attempt to differentiate between blowout conditions with and without pilot level 1 on, the time response of LP was investigated.

No Pilot Blowout

When there was no pilot on, the blowout transient followed a predictable pattern. Immediately before the blowout event, there was a step increase in LP with a magnitude many times the variation seen in the steady state data. This step consistently came shortly before blowout.

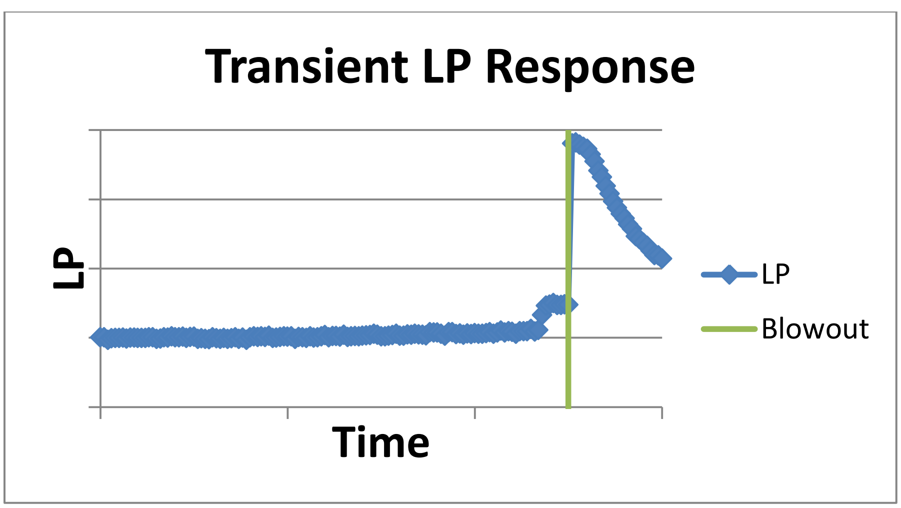

Figure 4 - Transient response of LP during a blowout with no pilot

Pilot Level 1 Blowout

In contrast to the predictability of no pilot blowout, blowout with pilot level 1 on showed inconsistent behavior. This is likely due to the diffusion flame introduced by the pilot. By moving the system away from the well-mixed regime, where the LP is better defined, spatial variations in the combustor flow make the qualities of the time response more unpredictable.

Pre-Blowout LP Values

The transient analysis showed patterns in the LP blowout response with and without pilot level 1 on, but they either were not consistent enough or did not give enough warning to reliably use in a pilot schedule. What we did find, however, was that the LP value at blowout was significantly elevated from its recent time-averaged value in cases where no pilot was on, while it was only slightly elevated from this value when pilot level 1 was on. Since the actual blowout LP values are very similar between these two cases, this suggested that there would be a difference in pre-blowout LP values for cases with and without pilot level 1.

Figure 5 shows the loading parameter values before blowout across all of the tests. The data has a spread that is similar to what was found at blowout, but there is more separation between the no pilot and pilot level 1 values, as predicted.

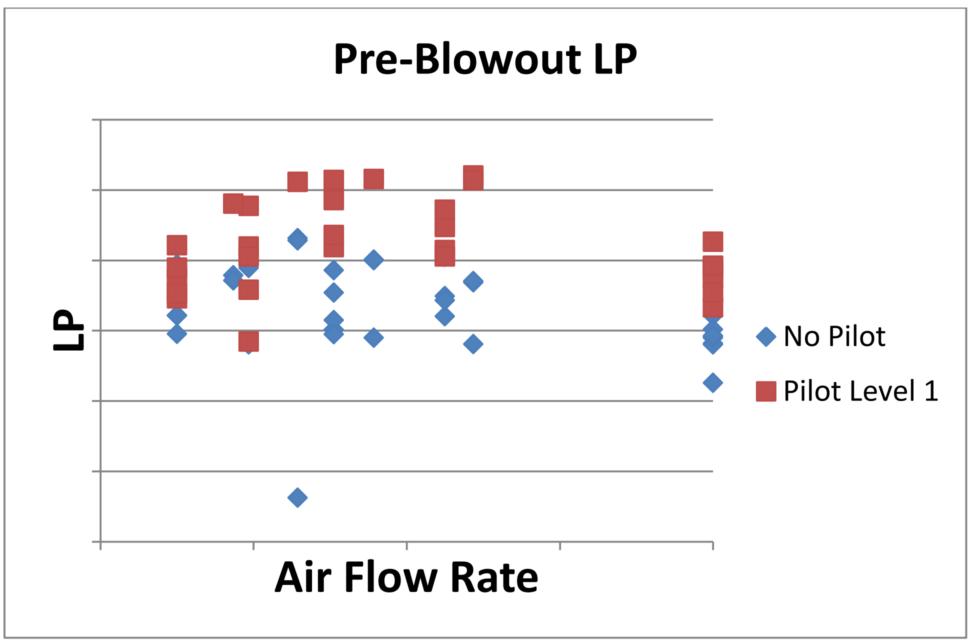

Figure 5 – Combustor LP versus air flow at conditions immediately before blowout

The pre-blowout LP values are found to be independent of combustor inlet pressure and air mass flow. This suggests that the loading parameter accurately captures the effects of these parameters on blowout, which is to be expected, since these parameters are components of the LP. However, further investigation showed that trends in the pre-blowout value of the loading parameter were related to trends in other combustor-related variables, such as temperature and fuel. Removing one or more of these trends should reduce the spread of the data. If there is a difference between blowout conditions with no pilot and with pilot level 1, as we expect there should be, the difference between the LP values at these two states should remain. The results of correcting the loading parameter to remove these trends can be seen in Figure 6.

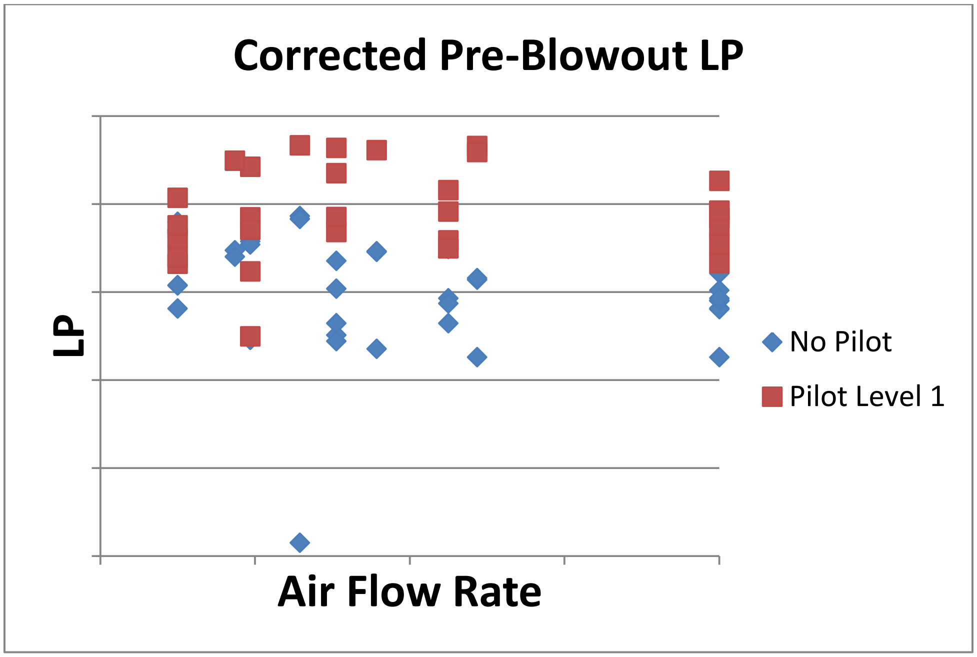

Figure 6 – Corrected combustor LP versus air flow at conditions immediately before blowout

Conclusions

The testing and analysis presented here shows that we can successfully describe the conditions of blowout using a single combustor loading parameter. The analysis also demonstrates that turning on pilot level 1 delays blowout until higher combustor loading levels are reached. This can be used to define LP values at which each pilot will be turned on in order to prevent blowout, without turning pilots on prematurely, which has an impact on emissions. The similarity between steady state loading parameter values and those at blowout with no pilot on make it somewhat difficult to establish a threshold at which pilot level 1 should be turned on. However, since pilot level 1 blowout occurs at higher levels than this, establishing a level for the second pilot is straightforward.

In the above analysis, blowout conditions are found to be significantly different across neither the fuels nor combustors used in these tests, by all metrics considered. Steady state operating conditions present similar ranges across these variables as well. These results suggest that the schedule may be consistent across all fuels and combustors used by FlexEnergy turbines. More testing will be required to verify that this remains the case outside of those fuels and combustors tested here.

Acknowledgements

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