DETERMINATION OF FLAME CHARACTERISTICS IN A LOW SWIRL BURNER AT GAS TURBINE CONDITIONS THROUGH REACTION ZONE IMAGING

A Dissertation
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
Guggenheim School of Aerospace Engineering

Georgia Institute of Technology
December 2012

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CHAPTER 1

LSB FLAME CHARACTERISTICS

In Chapter FIXME 2, we introduced the salient features of the Low Swirl Burner (LSB) flow field and discussed the mechanisms by which the LSB flame is stabilized. Further, various characteristics of the LSB flame that can be measured from flame images were outlined. To recapitulate, these are the flame location, flame shape and the flame structure. The first two are quantified by the flame standoff distance, X_f, and the flame angle, θ_f, respectively.

In the same chapter, we introduced the four flow parameters that describe an operating condition for the LSB — the combustor pressure, p, the preheat temperature, T, the mass-averaged inlet velocity (also called the reference velocity, U_0, and the equivalence ratio of the premixed reactants, ϕ. We further introduced a geometric parameter — the angle of the vanes of the swirler, α, which affects the amount of swirl present in the flow field.

The LSB flame is imaged over a range of operating conditions and the effect of flow and geometric parameters on the reacting flow field is investigated. This results of the investigation are presented in this chapter.

1.1 Effect of reference velocity

In typical gas turbine applications, varying the loading on the engine does not affect the reference velocity. However, since the reference velocity is a design parameter, the effect it has on the flame characteristics has implications for the design of future LSB-based gas turbine engines.

One of the key objectives of this thesis is to investigate how the LSB flame stabilization operates at high pressure conditions. The simple model described earlier

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predicts a self-similar flow field for the LSB at all reference velocities. This implies that the reference velocity will have no discernible impact on the flame standoff distance. This result is very desirable for gas turbine designers, since the flame location and shape can be assumed to be constant. Limited testing conducted in earlier works confirms this behavior at atmospheric pressure conditions with no preheat.

In order to verify the validity of this model at high pressure conditions in the presence of substantial preheat, the LSB was operated at a pressure of 6 atm over a range of reference velocities from 10 m/s to 40 m/s. For these tests, the $S_{37°}$ swirler was used. In a parallel series of tests, the $S_{45°}$ swirler was tested at a pressure of 3 atm at a reference velocities of 40 and 80 m/s. The location of the flame was measured from CH* chemiluminescence images and the results are presented in Figure FIXME.

There is essentially no systematic variation in the flame standoff distance or the flame angle for the low velocity, $S_{37°}$ tests. The increase in reference velocity continues to produces a concomitant increase in the turbulent flame speed at the flame stabilization location, negating any change in the flame's location. In other words, the flow field appears to retain its self-similarity, even at elevated pressures and temperatures.

However, when the $S_{45°}$ swirler was tested at higher reference velocities, the flame location shifted downstream sharply. This indicates potential limitations to the simple flame stabilization model that may not predict the behavior of the LSB flame at elevated pressures and temperatures, particularly at high reference velocities.

To examine the probable cause of this limitation more closely, consider the effect of increasing the reference velocity on the turbulent combustion regime where the LSB combustor operates. Previous studies have primarily operated the LSB in the flamelet regime where the modified Damköhler model predicts the behavior of the turbulent flame speed with reasonable fidelity. At elevated pressures, both the laminar flame speed of the reactants, S_L and the flame thickness, δ_f are diminished. This places the operating regime higher and more to the right on a Borghi diagram, as shown

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in Figure FIXME. While previously, increasing the reference velocity did not affect the turbulent combustion regime, at elevated pressures, the flame is more likely to transition into the thin reaction zone. This transition causes a drop-off in the S_T/S_L plot and the turbulent flame speed no longer increases in step with the increased levels of turbulence. This results in the observed downstream shift of the high pressure LSB flame at high reference velocities.

1.2 Effect of preheat temperature

1.3 Effect of swirler vane angle

As described in Chapter FIXME 3, the LSB swirlers tested for this study are designed to have the same mass flow splits. The $S_{45°}$ swirler has a higher vane angle, resulting in greater blockage to the flow passing through the annular section. In order to compensate for this, the perforated plate covering the central section has slightly smaller holes. The net effect retains the same mass flow split as in the $S_{37°}$ swirler.

Earlier, in Chapter FIXME 2, we discussed how the swirler vane angle relates to the amount of swirl imparted to the incoming flow. According to Equation FIXME, a swirler with a higher vane angle will produce greater swirl in the reactants. Previous work in swirl combustion[] has pointed out that increased swirl shortens the flame by enhancing the swirl-induced radial pressure gradients. The data acquired in the present investigation is in agreement with this observation. Operated at identical inlet conditions, the $S_{45°}$ swirler stabilizes a flame closer to the dump plane and with a larger flame angle compared to the $S_{37°}$ swirler.

This result highlights an interesting trade-off for the designers of LSB-based gas turbine engines. The $S_{45°}$ flame is located further upstream and has a more concentrated region of heat release. This enhances the strength of the toroidal recirculation zone near the dump plane, which may be powerful enough under certain conditions

(as we shall see in the Section FIXME) to even cause the flame to attach itself to the 77

lip of the inlet. All of this means that the $S_{45°}$ flame is more stable and will resist 78

perturbations in the incoming flow better than the $S_{37°}$ flame. However, the presence 79

of a strong recirculation zone in the flow field of the $S_{45°}$ swirler will entrain more hot 80

products and retain them longer near the zone of heat release. This is a recipe for 81

the production of thermal NO_x. While no emission measurements were made as part 82

of this study, it may be reasonably anticipated that the NO_x performance of the $S_{45°}$ 83

swirler is worse than the $S_{37°}$ swirler. The trade-off for gas turbine engine designers 84

is thus between flame stability and emissions performance. 85

1.4 Effect of equivalence ratio 86

The LSB is primarily intended for fuel-lean operation in order to utilize its low NO_x 87

emission performance. As a result, most of the testing was done as close to the target 88

ϕ of 0.56 as possible. However, limited testing was done at 12 atm at both a slightly 89

rich ($\phi \approx 0.58$) and a slightly lean ($\phi \approx 0.53$) condition to explore the sensitivity 90

of the lSB flame to limited changes in equivalence ratio. The $S_{45°}$ swirler was used 91

for these tests. The corresponding averaged and Abel-deconvoluted flame images are 92

presented in Figure FIXME. 93

Two characteristics of the flame are immediately obvious from these images. 94

First, the zone of heat release, marked by the region from which CH* chemilu- 95

minescence is observed, is increasingly compact at fuel-rich conditions. Virtually all 96

other flame images acquired at a leaner condition show a long flame, with the heat 97

release distributed over the entire visible area of the combustor. The compactness of 98

the heat release zone indicates potentially poor NO_x performance at these conditions. 99

Second, the fuel-rich flame brush can be observed to wrap around and anchor itself 100

on the dump plane. This is particularly observable in the Abel-deconvoluted image. 101

The attached region is not as bright as the rest of the flame brush, indicating that 102

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the flame may be attaching itself intermittently. This intermittent behavior can be ¹⁰³
confirmed from the instantaneous images where it is visible on some of the acquired ¹⁰⁴
images, but not others. This behavior was alluded to in Section FIXME as being the ¹⁰⁵
result of the enhanced toroidal recirculation zone produced by this swirler. Thus, the ¹⁰⁶
intermittent attachment of the flame to the inlet indicates the increased importance ¹⁰⁷
of the toroidal recirculation zone in stabilizing the flame. ¹⁰⁸

It should be noted that the reliance on a toroidal recirculation zone to anchor ¹⁰⁹
the flame to the inlet is one of the primary flame stabilization mechanisms used by ¹¹⁰
traditional swirl combustors. Thus, LSB swirlers with high vane angles tend to behave ¹¹¹
like traditional swirl combustors at fuel-rich conditions. ¹¹²

1.5 Effect of pressure ¹¹³

1.6 Flame structure ¹¹⁴

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