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Flame Structure and Stabilization Mechanisms in a Stagnation Point Reverse Flow Combustor

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ABSTRACT

A novel combustor design, referred to as a Stagnation Point Reverse Flow (SPRF) combustor, was recently developed to overcome the stability issues encountered with most lean premixed combustion systems. The SPRF combustor is able to operate stably at very lean fuel-air mixtures with low NOx emissions. The reverse flow configuration causes the flow to stagnate and hot products to reverse and leave the combustor. The highly turbulent stagnation zone and internal recirculation of hot product gases facilitates robust flame stabilization in the SPRF combustor at very lean conditions over a range of loadings. Various optical diagnostic techniques are employed to investigate the flame characteristics of a SPRF combustor operating with premixed natural gas and air at atmospheric pressure. These include simultaneous Planar Laser-Induced Fluorescence (PLIF) imaging of OH radicals. chemiluminescence imaging, Spontaneous Raman Scattering. The results indicate that the combustor has two stabilization regions, with the primary region downstream of the injector where there are low average velocities and high turbulence levels where most of the heat release occurs. High turbulence level in the shear layers lead to increased product recirculation levels, elevating the reaction rates and thereby, the combustor stability. The effect of product entrainment on the chemical timescales and the flame structure is quantified using simple reactor models. Turbulent flame structure analysis indicates that the flame is primarily in the thin reaction zones regime throughout the combustor. The flame tends to become more flamelet like, however, for increasing distance from the injector.

INTRODUCTION

Lean premixed combustion systems are advantageous because of their potentially low pollutant emissions. For example, NO_x emissions, which are highly temperature sensitive, are low since lean premixed combustion limits the maximum flame temperatures compared to more stoichiometric combustion conditions, which can occur in non-premixed combustion. A critical issue, however, in these combustors is stability, as the weaker combustion process is more vulnerable to small perturbations in combustor operating conditions.

Flame stability in such systems can be enhanced in various ways, including reactant preheating and exhaust gas recirculation. Preheating the combustion air with the exhaust gases from a combustor provides many benefits, such as enhanced efficiency and flame stability. Gupta^{1, 2} reported that flames with highly preheated combustion air were much more stable and homogeneous (both temporally and spatially) as compared to room-temperature combustion air and hence could operate at much leaner equivalence ratios. In most premixed combustors employed in land-based gas turbines, stabilization is partially achieved by swirl-induced internal recirculation of products and reactants.³ Very high levels of internal recirculation in combustors, combined with other restrictions such as significant combustor heat loss, can lead to "flameless oxidation," where no visually distinct flame is observed.^{4,5}

A new, compact combustor design that incorporates some aspects of these other approaches has recently been demonstrated.⁶ In its simplest configuration, a nearly adiabatic combustor consists of a tube with one end open and the other closed. Unlike most combustors, the reactants and products enter and leave this combustor at the same end. The reactants are injected (without swirl) along the combustor centerline, moving towards the closed end. The reactants burn as they reach the end wall and hot product gas reverse to exit the combustor. This opposing reactant and product gas stream configuration facilitates entrainment of a portion of the hot product gases back into the flame zone. This Stagnation-Point Reverse-Flow (SPRF) combustor has been shown to produce low NOx emissions for both gaseous and liquid fuels, and in premixed and non-premixed operating modes.⁶ In addition, the combustor operates stably without external preheating, even at very low fuel-air ratios and high loadings.

To better understand the combustion and stability mechanisms of the SPRF combustor, the flow field of a typical SPRF combustor operating at atmospheric pressure is characterized with various optical diagnostic techniques. Planar Laser Induced Fluorescence (PLIF)⁷ of OH radicals and chemiluminescence imaging is used to visualize hot product gases and the combustion (reaction) zone. Lastly Spontaneous Raman Scattering (SRS)¹⁰ is employed to quantify recirculation of products by measuring instantaneous mole fractions of all major species to quantify product entrainment.

EXPERIMENTAL SETUP

The SPRF combustor used here consists of a central injector located at the open end of a 70 mm diameter and 304.8 mm long quartz tube (Figure 1a). The 12.5 mm diameter (D) injector is formed by two concentric tubes, with premixed natural gas and air flowing through the annulus. For non-premixed operation (not employed for this work), the central tube is used for fuel injection. Fuel and air flow rates are monitored with calibrated rotameters, and the two flows are mixed well upstream of the injector.

A quartz base plate forms the closed end of the tube and allows introduction of a laser sheet for the OH PLIF measurements. The combustor is also insulated with a hollow alumina cylinder with an inner diameter that is slightly larger than the outer diameter of the quartz tube. The insulation is cut into four segments; one of these has a $\sim 150^\circ$ section removed to form a window for optical access. Thus only one-quarter of the length of the combustor can be imaged with the insulation installed; the complete combustor is mapped by moving the window segment to a different axial location.

The product gases exiting the combustor flow over the injector, increasing the temperature of the incoming reactants. To monitor this internal preheating, an unshielded thermocouple (K type) can be placed in the injector annulus, roughly 4 mm upstream of the injector exit plane. The thermocouple is not present during the optical diagnostic measurements.

As presented in detail in an earlier work²⁰, a Particle Image Velocimetry (PIV) system was used to characterize the velocity field in the SPRF combustor. For these measurements, the combustion air was seeded with 1-2 μ m aluminum oxide particles before being mixed with the fuel. The two PIV laser

pulses are provided by the second harmonic outputs of a dualhead, Nd:YAG laser (Continuum Surelite I-10). The output beams are converted into a sheet (68×0.6 mm) using three cylindrical lenses. The particle scattering images produced by a pair of laser pulses are recorded with a 12-bit interline CCD camera (MicroMAX, 1300×1030) equipped with a 50 mm Nikkor (f/1.8) lens and synchronized to the lasers. FFT based cross-correlation software (Insight 6, TSI) is employed to find the average particle displacement in a 64×64 pixel region with a 50% overlap in the interrogation areas. Each vector represents the average velocity in an interrogation volume 2.19×2.19×0.4 mm³.

OH PLIF and Chemiluminescence Imaging: The laser system for the OH PLIF measurements consists of a dve laser (Lambda Physik Scanmate 2) pumped by the second harmonic of a Nd:YAG as shown in Figure 1b. The dye laser output is frequency-doubled (Inrad Autotracker, BBO crystal) and formed into a thin sheet ($\sim 65 \times 0.3$ mm) with three fused-silica lenses. The laser sheet enters through the closed end of the combustor and cuts through the central axis. The laser is tuned to the $Q_1(6)$ line of the $A^{2}\Sigma^{+}(y'=1) \leftarrow X^{2}\Pi(y''=0)$ band of OH, with a sheet energy of 10-12 mJ/pulse. The emitted fluorescence is detected at right angles to the sheet with a 25 mm, intensified camera (PI-MAX, 1024×256 pixels) equipped with a UV-Nikkor lens (105mm, f/4.5). The detected fluorescence is limited to 300-370 nm with WG305 and UG11 Schott glass filters placed in front of the camera lens. The field-of-view is set such that it covers the whole width of the combustor, resulting in a pixel resolution of approximately 300 µm.

The natural chemiluminescence from the combustor is also collected at right angles to the sheet with a second intensified camera (Princeton Instruments ICCD-576-S/RB-E, 18 mm intensifier, 384×576) equipped with a narrow-band interference filter (430 ± 5 nm), which passes CH^{*} and CO₂^{*} chemiluminescence. This camera is synchronized such that the



Figure 1. Schematic of (a) SPRF Combustor and (b) layout of the OH PLIF and PIV setups.

exposure (250 μ s) begins 100 ns after the OH laser pulse, which allows for complete decay of the OH fluorescence. Thus the cameras record nearly simultaneous features of the combustor. In addition, the camera views the full width of the combustor (matching the OH field-of-view), which results in a pixel resolution of ~250 μ m.

Raman Diagnostics: As shown in the schematic for Raman measurements (Figure), a second harmonic (532 nm) of an injection seeded, O-switched Nd:YAG laser (Quanta-Ray Pro-250, Spectra Physics) is used. The pulse energy is restricted to 250 mJ at a 10 Hz repetition rate to prevent laser induced spark/plasma formation at the probe volume, which can occur due to breakdown of the gas under the intense electric field generated by tightly focusing a Q-switched laser, and to avoid damage to the combustor quartz walls. The laser beam is focused into a flattened $2 \times 0.3 \text{ mm}^2$ probe volume using a spherical (50 mm dia., f = 1000 mm) and cylindrical (25×50 mm^2 , f = 1000 mm) lens combination. Such a probe volume is chosen to keep the laser fluence under the breakdown threshold and still provide good spectral resolution by aligning the 300 um projection with the spectrometer slit. The laser beam enters the combustor through the transparent quartz base plate at the bottom of the combustor, similar to the PLIF setup, but in this case is not spread out into a sheet.



Figure 2. Optical layout Spontaneous Raman Scattering (SRS) setup.

The Raman scattering signal was collected at a 90° angle relative to the beam propagation direction using an 80 mm diameter and 160 mm focal length spherical lens. The collected light is focused onto the 300 µm slit of a 0.3 m spectrometer (f/4, SpectraPro-300i, Acton Research Corporation) at f/5.3 and a magnification of 0.5. A combination of two OG 550 Schott glass filters is used to attenuate Rayleigh and Mie scattered light (from dust particles) entering the spectrometer. The spectrometer dispersed the incident light using a 300 grooves/mm grating, and is then recorded on a PI Acton ICCD camera (512×512 pixels). This arrangement allowed us to capture a spectral range of 555-685 nm with a resolution of 0.256 nm/pixel. The camera is equipped with an 18 mm (Gen III, HB filmless) intensifier tube with 30% quantum efficiency in the visible range. The intensifier is gated on for a 100 ns window synchronized with the laser pulse. This short gate

timing helps reject background emissions from the flame and blackbody radiation from the combustor walls. The collected spectra were binned on chip over 170 pixels in the spatial direction to increase the signal-to-noise ratio of the measurements, resulting in a spatial resolution of 2 mm along the laser beam. The combustor and injector assembly are mounted on a vertical traverse, while the optics setup remains fixed. This configuration allowed us to make instantaneous single point Raman measurements from the injector to 170 mm into the combustor along the centerline.

Raman signals are obtained from the background subtracted spectra by integrating under the respective peaks for each species. Figure 3 shows a typical single shot spectrum recorded close to the injector in SPRF combustor operating on premixed CH_4 and air.



Figure 3. Typical single shot Raman spectra recorded close to injector in the SPRF combustor at $\phi = 0.58$.

The Raman signal (S_i) is proportional to the number density of the scattering species and can be expressed in terms of species mole fractions (X_i) and temperature (T), i.e.,

$$S_i = \frac{C_i X_i}{T}$$

Assuming CO_2 , O_2 , N_2 , CH_4 , H_2O are the only major species present, then including the additional constraint

$$\sum X_i = 1$$

provides a complete set of equations. The calibration constants C_i for CO₂, O₂, N₂, and CH₄ are determined from measurements obtained at the exit of a preheated laminar jet (300–800 K) with a known concentration gas mixture. The calibration constants are found to be constant to within 5% in the reactant temperature range of interest. The Raman signal for H₂O is calibrated with measurements at the exit of the SPRF combustor (at ϕ =0.58), where the equilibrium water concentration is known to be twice the CO₂ concentration. A matrix formulation¹⁰ is used to solve the above complete set of equations to find mole fractions of CO₂, O₂, N₂, CH₄, H₂O and local temperature. The error in major species concentrations calculated as above, neglecting CO and other minor species, is estimated from equilibrium calculations and found to be within 2% of the actual value.

Signal interpretation can be complicated by fluorescence interactions from PAH (Polycyclic Aromatic Hydrocarbons) and soot or due to overlap of Raman rotation and vibration bands from different species.¹⁰ The fluorescence interactions are expected to be negligible in the current work due to lean operation of the combustor. Overlap in Raman spectra is most prominent between CO_2 , O_2 and CH_4 . These interferences are corrected based on calibration spectra obtained at 300 K as outlined by Miles.¹¹

RESULTS AND DISCUSSION

As might be expected in lean premixed operation, the SPRF combustor has low NOx emissions. For example, Figure 4 shows the NOx emissions at the exit of the SPRF combustor for various equivalence ratios (ϕ) plotted as a function of the adiabatic flame temperature. The NOx (NO+NO₂) emissions are measured with a sampling probe and a Horiba (PG-250) gas analyzer.⁶ The uncertainty in the NOx concentration measurements with this system was 1 ppm, which translates to an uncertainty of 0.7 ppm corrected to 15 % excess oxygen at $\phi=0.5$ and 2 ppm corrected at $\phi=1$. The measurements at the exit of the SPRF combustor indicate NOx emissions of around 1 ppm for the leanest operating condition (ϕ ~0.51), and they are also seen to be nearly invariant of loading (mass flow rate) for a given operating temperature. The adiabatic flame temperatures shown are calculated based on the equivalence ratio and the reactant temperature determined from the injector thermocouple. For comparison, the figure also shows NOx levels from a laminar, one-dimensional, premixed flame, based on a CHEMKIN simulation and the GRIMech 3.0 mechanism¹² over a range of equivalence ratios and reactant temperatures.



Figure 4. Variation of NOx and CO emissions with adiabatic flame temperature for a total loading of 8.1 g/s in comparison to a laminar flame model.

The model results represent the prompt NOx produced in the flame front, i.e., up to the point where the heat release has dropped to 1% of its peak value, as opposed to thermal NOx produced in the product gases. In this sense, the model results represent a minimum expected emission level for a premixed flame. The measured emissions from the combustor are reasonably close to the minimum levels, until the flame temperatures exceed ~1800-2000 K, where thermal NOx formation in the post-flame region is expected to become dominant.¹⁹ One advantage of the SPRF combustor over other premixed combustors is its ability to produce a compact, stable flame even under very lean (low NOx) conditions, without external preheating or swirl. For example, the leftmost point in Figure 4 was acquired with the combustor operating at ϕ =0.51 and with a combustor power density of 20 MW/m³ (at atmospheric pressure). At these conditions, the combustor is still stable. Thus, we devote the remainder of this paper to examining the features of the combustor that contribute to its stability.



Figure 5. Velocity fields for a flowrate of 8.1 g/s (a) mean axial velocity contours, (b) mean centerline velocity and turbulence intensity profiles.

We begin by examining the velocity field in the combustor. As presented by Gopalakrishnan et al.,¹³ the time-averaged flow field in the combustor is shown in Figure 5a as a combination of axial velocity contours and interpolated streamlines. These results were obtained by averaging 300 instantaneous PIV images for a total mass flow rate of 8.1 g/s and at an equivalence ratio of 0.58, where the SPRF combustor was found to produce NOx emissions of around 1 ppm. The reactant temperature in the injector, after heating by the exiting products, was nearly 500 K. Thus the velocity right at the injector exit, based on the measured flow rate and temperature, should be 130 m/s. Velocity data obtained using PIV starts from an axial location (x) of 22 mm (x/D=1.8) from the injector exit plane. The average velocity measured at this location was 120 m/s closely matching the air injection velocity estimate. In some ways the flow field resembles that of a confined jet, but the presence of the closed end causes the axial velocity to decay rapidly. As seen in Figure 5b, the average axial velocity (U)

drops to half its initial value by x=150 mm (x/D=12). At the same time, the rms fluctuations (u'rms) and turbulence intensity rapidly increase, with the centerline u'rms/U increasing from 0.23 to 0.5 over a small distance (x/D=10-12.5). Thus the geometry of the SPRF combustor ensures the existence of a region of both "low" average velocity (though still 10's m/s) and high fluctuating velocity, which exists over a wide range of combustor loadings. The rapid decay in velocity results from the high shear between the incoming forward flow and the reverse flow of the exiting gases. This can also lead to entrainment of exiting high temperature products and flame radicals into the incoming reactants, which can significantly enhance chemical reaction rates.¹⁴ The temperature increase due to mixing with hot product gases along with the presence of radicals tends to increase the mixture reactivity, while the dilution of this reactant mixture with inert product gases tends to reduce it. As shown later, the net effect is an increase in reactivity with increasing product recirculation at the levels found in the SPRF combustor.



Figure 6. Instantaneous OH images of the near injector region of the non-insulated SPRF combustor for $\phi = 1$ with increasing mass flow rates, (a) 0.14 (b) 0.2 (c) 0.43 (d) 1.8 and (e) 5.7 g/s.

The influence of these flow field features on flame stabilization mechanisms was investigated by imaging the OH field in the SPRF combustor over a range of combustor loadings. These images were acquired at stoichiometric conditions so that we can explore all the possible stabilization mechanisms in the combustor, some of which are not evident in fuel lean conditions. In these instantaneous images (Figure 6), the reaction zone is usually indicated by the sharp gradients in the OH PLIF signal adjacent to the reactant gases. For the lowest loading (0.14 g/s), the velocities in the combustor are laminar, and the combustor flow is essentially an annular, Bunsen-like jet flame. Since the inner tube of the annular injector is closed-off upstream in premixed operation, the flame can stabilize on both the outer rim of the injector and the inner, bluffbody-like recirculation zone. For this low velocity condition, the flame sits just above the injector, and what is primarily seen in Figure 6a is the decrease in OH concentration as the products cool (since OH equilibrium concentrations are extremely temperature sensitive). For increasing injection velocity (Figure 6b,c), the increased strain causes the flame to progressively lift at the outer rim, while it remains anchored on the inner tube. For these low velocity conditions, the shear between the inflow and exhaust is low. In addition, the lack of OH PLIF signal in the exhaust gases indicates the combustion products are relatively cool, due to heat losses to the combustor walls.

Only at higher loadings (beyond ~1.8 g/s) does the entrainment of high temperature products appear to return the flame closer to the highly strained outer lip region (as indicated by the OH signal in the reverse flow of Figure 6d,e). At 1.8 g/s, there is still a small flame in the inner recirculation zone, but it does not stabilize the rest of the combustor. Beyond this loading, the inner region disappears and the flame appears stabilized on the outer shear layer (Figure 6e). The highest OH concentrations are seen towards the bottom of these images, which suggests that the highest temperatures (or most of the heat release) occurs in that region (x=80-140 mm). This roughly coincides with the low average velocity region observed in the PIV results for the insulated combustor operating lean and at high loadings. This suggests a second possible stabilization mechanism; high u' in the mid-region of the combustor creates a highly corrugated flame that can propagate against the local mean flow (which is still 20-50 m/s). Like the flame seen in the shear layer between entering and exiting gases, any entrainment of hot products into the reactants before reaching the low velocity region will also act to increase the flame speed.

These observations were verified by obtaining simultaneous OH PLIF and chemiluminescence fields in the insulated combustor under the same lean (ϕ =0.58) flow conditions as the PIV data. The dark central regions in Figure 7a represent unburned reactants (possibly mixed with some products). These regions of reactants seen in the OH PLIF image seem to match with the bright signal region in the simultaneously acquired chemiluminescence field (Figure 7b) representing heat release zones. The heat release zones surrounding reactant packets suggests a flame-like burning in this combustor. It should also be noted that most of the heat release occurs downstream of the cold reactant core, as opposed to the upstream edges of the jet, and that the main heat release zone coincides with the low U, high u' region. Unlike a standard confined jet, where vortices are initiated at the initial shear region and propagate downstream, the SPRF geometry allows vortices carried by the return flow to propagate back towards the injector resulting in higher turbulence levels. If the flame is lifted or the reaction zone is broken, as seen in Figure 7, this can allow entrainment of products into the reactant stream. The hot products entrained

and mixed into the reactants will tend to increase reaction rates (and flame speeds), enhancing flame stabilization in the downstream regions.



Figure 7. (a) Instantaneous OH and (b) simultaneous chemiluminescence images at $\phi = 0.58$ and a loading of 8.1 g/s in the premixed SPRF combustor acquired in different widows.

The possibility of hot product entrainment is further explored by making concentration measurements of all the major species in the combustor using Spontaneous Raman Scattering (SRS) at the same loading of 8.1 g/s and equivalence ratio of 0.58. Figure 8a,b shows the axial variation of mean mole fractions (averaged over 500 acquisitions) along centerline of the combustor. The data was acquired starting from close to the injector to half way into the combustor (x/D = 0.4 to 14). Results show the presence of product gases (CO_2 and H_2O) as early as x/D=5 along the centerline. The chemiluminescence images shown above rule out the possibility that significant reactant burning occurs in this region. Thus, the appearance of the products is primarily due to product entrainment which starts very close to the injector plane. The Raman temperature measurements acquired along the centerline (Figure 8c) indicate an inlet temperature 450 K, which matches the inlet temperature measured with the thermocouple at the injector to within 30K. Beyond x/D=5, the temperature is found to increase linearly, approaching the adiabatic flame temperature of 1750K in this case. The spike in temperature at x/D=12 is attributed to a decrease in laser power while acquiring data at this point.



Figure 8. Axial variation of mean species mole fractions (a) CO_2 , CH_4 , (b) O_2 and H_2O) and (c) temperature along the combustor centerline. Conditionally averaged values of these quantities over data points only in reactants are also plotted.



Figure 9. Histogram of product fraction (f_P) over 500 data points measured at various axial locations along the combustor centerline.

The decrease in average concentration of fuel and the appearance of product gases along the combustor centerline could either be due to mixing of hot product gases with the reactants or it could be the result of intermittent appearance of pure product packets. To isolate the first effect from the second, the data points are conditionally averaged eliminating points in pure product gases. Pure product gases were defined to be points when the CH₄ concentration is less than a threshold value chosen to be 10% of the injected global fuel fraction, which is at least twice the noise in the CH₄ mole fraction measurement. The mean axial variation of species mole fractions conditionally averaged in this fashion is also shown in Figure 8a,b. The results are nearly the same as the unconditioned averages up to $x/D\cong9$. The mixing of product gases into the reactants, as represented by the rising amount of CO₂ and H₂O, starts at x/D of 5 and reaches significant levels before reaching the flame zone in the second half of the combustor, where most of the heat release occurs. The oxygen and the fuel concentrations also are found to decrease due to dilution with the product gases. A reduction in oxygen concentration as seen here has been identified as possible source of reduced NOx emissions by Dally.¹⁵ The distribution of the reactant temperature (with entrained products) in Figure 8c is quite similar to the unconditional average close to the injector, but it saturates at ~1300 K before reaching the heat release zone. The lower temperature values found after conditional averaging are due to exclusion of data points with pure hot products.

In systems with recirculation of product gases, the amount of product entrainment is typically quantified by a single variable such as the product fraction (f_P), which denotes the ratio of mass of products to that of the reactants at a given point. Based on this definition, f_P of 0 corresponds to pure reactants while pure products have a f_P of ∞ . Histograms of product fractions at six different axial locations along the combustor centerline are shown in Figure 9. The product fraction not only increases (on average) with axial distance but also is characterized by a wider distribution. By x/D of 12, the product fraction reaches values as high as 2, which correspond to 67% of the incoming mixture being hot products by mass.



Figure 10. Variation of ignition delays in milliseconds with increasing product entrainment levels (f_P) over a range of equivalence ratios. Flow times to reach various axial locations estimated from the mean velocity field also shown for reference.

Combustors with large recirculation ratios and large residence times can have reactant mixtures that can reach the ignition temperature and thereby burn in what is called a flameless or mild combustion mode.⁴ To explore such a possibility, the current combustion process has been modeled with a plug flow reactor model (CHEMKIN)¹² and the time required for various reactant mixtures to autoignite is determined. The effect of hot product gas entrainment was simulated by adding a fraction of hot, adiabatic products (produced from a pure reactant mixture) into the inlet reactant stream. The initial reactant temperature (before addition of products) was set to the reactant temperature determined from the injector thermocouple. The reactor inlet temperature further increases as hot product gases are added, simulating the entrainment of products before reaching the flame zone in the SPRF combustor. The ignition delay as a function of product

fraction level in the reactant mixture is shown in Figure 10 for a range of equivalence ratios. With increasing recirculation ratio, the reactant temperature increases, reducing the ignition delays in the combustor. Also shown are three dotted lines at time delays that correspond to the average centerline flow time (calculated from the mean velocity fields) needed to reach a given centerline axial location in the combustor starting from x/D=5, where the product gases first appear according to the Raman data. Even with the worst case assumption that the reactants reach the near maximum product fraction level of 2 instantly at x/D=5, the simulations suggests that the flow times needed to reach the measured heat release region at x/D>12 are too short for the mixtures to autoignite at the operating equivalence ratio ($\phi = 0.58$).

Since the SPRF does not appear to operate in a flameless, or mild combustion, mode, we examine the turbulent flame structure of the SPRF combustor using the approach developed by Borghi¹⁶ and modified by Peters.¹⁷ This requires determining the total rms velocity (*u'*), laminar flame speed (S_{L}), integral length scale (L_T) and flame thickness (δ_L) in the SPRF combustor. The rms velocities were obtained from 400 instantaneous PIV images. Since only two velocity components were measured, the total rms velocity was estimated by assuming the out-of-plane velocity component was comparable to the in-plane, lateral component.¹⁸ Further, the integral length scale is found by integrating the turbulent velocity correlation function computed from the instantaneous velocities. The flow parameters and turbulence characteristics estimated at different locations are listed in table I.

The flame speed and thickness, S_L and δ_L , were estimated with premixed, laminar flame simulations (CHEMKIN PREMIX and GRIMech 3.0)¹² for conditions close to the measured entrainment levels, as listed in Table 2. The effect of hot product gas entrainment was simulated as in the plug flow case. The flame speed was defined to be the simulated approach velocity, while the flame thickness was assumed to be the difference between the burned and unburned gas temperatures divided by the peak temperature gradient in the preheat zone.

Table I. Flow conditions and spatial locations used for regime analysis

H	0.58			
	8.1 g/s			
Read	450 K			
Location	x/D	r/D	u' _{rms} (m/s)	$L_{T}(mm)$
1	3	1.1	14.4	2.7
2	9	1.8	13.3	5.6
3	15	0	15.9	10.4

The flame structure analysis was performed for five entrainment levels and three spatial locations in the combustor. The first two locations chosen are in the shear layer, at x/D=3 and 9. These regions are highly strained due to high incoming reactant velocities and reverse flow, product gas velocities. The third spatial location is x/D=15 on the centerline, where the OH and chemiluminescence images indicate most of the heat release occurs. It can be seen from Figure 11 that the conditions at all these locations (except with zero product entrainment) fall in the thin reaction zone regime suggested by Peters.¹⁷ In this region, one expects a distinct reaction zone unaffected by turbulence.

For comparison, typical flames in stationary gas turbines are also characterized by thin reaction zones, but with extremely high turbulent Reynolds numbers ($Re_T > 10^4$), Da~1 and Ka>10 (see Figure 11).¹⁸



Figure 11. Estimate of turbulent combustion regimes for the SPRF combustor: points shown for same axial locations, product fractions and flow conditions in Tables I-II.

The likely turbulent flame structure is seen to evolve through the combustor. Close to the injector, u'/S_L is high since there has been little chance for product entrainment, and $L_{\rm T}/\delta_{\rm L}$ is low because the shear layer is thin and the vortices are smaller. As the flow moves farther from the injector, $L_{\rm T}/\delta_{\rm L}$ increases and $u'/S_{\rm L}$ decreases because the characteristic eddy size increases, and because the amount of product entrainment is expected to increase (producing faster $S_{\rm L}$ and thinner $\delta_{\rm L}$). Hence we expect the combustion structure to evolve as indicated by the diagonal arrow in Figure 11; making the combustion more flamelet like farther from the injector. As mentioned before, the reactant temperature increase and the presence of radicals due to product entrainment boost the mixture reactivity more than the reduction in reactivity due to dilution. This is evident from the flame speeds calculated including all these effects, shown in Table II. Increasing product recirculation level from zero to two causes the reactant temperature to go up to 1300 K. This translates to an order of magnitude increase in flame speed despite the reactants being diluted with twice their mass in products. It should be noted that the flame calculations assume recirculation/entrainment of equilibrium products. In practice, the concentrations of flame radicals in the entrained products may be higher, which would increase $S_{\rm L}$ further and push the combustion structure even closer to the flamelet regime.

Table II. Flame properties obtained from CHEMKIN(GRIMECH 3.0)

f _P	Flame Thickness δ_L (mm)	Laminar Flame Speed S _L (m/s)	
0	0.73	0.27	
0.5	0.60	0.90	
1.0	0.57	1.6	
1.5	0.565	2.3	
2.0	0.58	3.0	

These results are consistent with the previous observations. In most of these regions, we see high OH gradients, consistent with thin reaction zone. Very close to the injector, the flame is lifted due to the high values of U/S_L . While the flame can exist further from the injector, in the shear layer between the forward flowing reactants and the reverse flow products, high intensity, small vortices may be able to extinguish the flame. This would permit products to be entrained into the unburned reactants. Further downstream, there would then exist reactant-product mixtures with high turbulent flame speeds, due to high S_L and u' (but $u'/S_L<10$). As the mean velocities drop in this region, the flame can be stabilized, even at very lean conditions where the NO_x emissions from the combustor are minimal.

CONCLUSIONS

The flow field and combustion characteristics of a premixed SPRF combustor with central injection have been studied. The SPRF combustor has been shown to operate stably over a range of equivalence ratios and loadings without the need of external preheating or swirl. Further, emission measurements performed on this combustor indicate that NOx levels around 1 ppm or less (corrected to $15\% O_2$) can be achieved due to its ability to operate very lean. Comparison of the measured emission levels with laminar flame calculations indicate that the NOx levels are close the minimum levels that would be expected just due to NOx produced in the heat release regions.

Measurements of the premixed velocity field show a low average velocity zone with high levels of turbulence in the bottom half of the combustor. Based on the geometry of the combustor, this zone is expected to exist over a range of flow conditions (for very low loadings, the flow is laminar and combustion occurs before the "stagnation zone" is reached). Chemiluminescence and OH PLIF fields indicate that the flame is indeed anchored in this region of high turbulence intensity, and that this is where most of the heat release occurs. This results in stable operation of the combustor even at high loadings and very lean equivalence ratios. Raman concentration measurements show entrainment of hot products from about 5 injector diameters into the combustor reaching an average reactant temperature of ~1300K just before the flame zone. This tends to increase chemical reactivity, especially of lean mixtures. Closer to the injector, a weaker flame exists in the shear and mixing layer between the forward flowing reactants and the reverse flow of products. Although the reaction rates are elevated due to product entrainment, the reactant mixture does not autoignite as in mild combustion due to relatively small flow times in the combustor.

An analysis of the turbulent combustion structure in the premixed SPRF combustor indicates that the flame is primarily in the thin reaction zone regime throughout most of the combustor. However, the flame tends to become more flamelet like farther from the injector, due to increases in the turbulent length scales and increases in the chemical rates due to entrainment of heated products and radicals into the reactants.

In summary, the geometry of the SPRF combustor creates a combination of a low velocity, high turbulence region, "the stagnation point," and internal product recirculation due to the "the reverse flow" that creates a stable combustion process under a large range of combustor operating conditions. In addition, most of the heat release occurs at conditions close to the thin reaction zone regime.

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