Experimental Investigation of the Near Field in Sooting Turbulent Nonpremixed Flames at Elevated Pressures

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Abstract

A recently commissioned high-pressure combustion duct is used to investigate a family of ten, piloted, sooting, turbulent nonpremixed flames over a range of pressures and Reynolds numbers. For all conditions, the central jet is composed of 35% ethylene and 65% nitrogen by volume. In one series of flames, the Reynolds number is kept constant while the pressure is increased, whereas in the other series, the bulk jet velocity is maintained. The maximum pressure, p , is 5 bar and the maximum Reynolds number, Re , is 50,000. A DSLR camera and 10-kHz OH-PLIF are used to characterize the near field. DSLR camera images show that the length of the blue region immediately downstream of the nozzle decreases as the pressure increases, rapidly in the constant Reynolds number series, and gradually in the constant velocity series. Analysis of OH-

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PLIF images in the near field show that corrugation of the flame front is fairly insensitive to changes in pressure if the Reynolds number is held constant. As the Reynolds number (and pressure) is increased, the flame front becomes more corrugated and the frequency of OH layer extinction increases. This leads to smaller “islands” of OH that are separated by shorter distances. However, despite increased local extinction, the flames remain attached even as the Reynolds number is increased to more than twice the maximum Reynolds number that is possible at atmospheric pressure.

Keywords: high pressure, turbulent nonpremixed flames, OH-PLIF

1. Introduction

The need for measurements in turbulent flames suitable for comparisons with computational results has been a major focus of the combustion community for many years. In an effort to advance understanding in turbulent combustion in
5 an organized way, the International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames (TNF Workshop) [1] seeks to provide a framework for collaboration between experimentalists and modelers, and to construct a database of flames that are well-documented and appropriate for model validation. The younger International Sooting Flame (ISF) Workshop [2]
10 has very similar goals, however, its focus is on understanding the development of soot in laminar as well as turbulent environments.

One critical component of the complex physics of practical combustion devices that has not been captured by the flames of the TNF Workshop is the high pressure. Due to the important role of pressure in the soot formation process,
15 the ISF Workshop includes flames operated at elevated pressures, such as laminar flames [3, 4] and turbulent premixed swirl flames in a gas turbine model combustor [5, 6], but no turbulent nonpremixed flames. In general, there have been very few studies of turbulent nonpremixed flames at elevated pressures. The earliest study examined ethylene diffusion flames at pressures up to 8 bar
20 in a vessel intended for laminar flames, thus requiring that the turbulent flame

burner have a very small inner diameter (< 1.2 mm) [7]. Some years later, an effort was made to design a rig for studying turbulent flames with a flow field that could be accurately computed at pressures up to 17.5 bar [8]. This rig had an inner Pyrex tube with a diameter of 155 mm, four 75-mm fused silica windows, four instrument ports, and the ability to traverse the burner
25 vertically within the vessel. Experiments focused primarily on soot measurements in piloted, kerosene diffusion flames ($D = 1.5$ mm) up to 6.44 bar [9], kerosene spray flames up to 13 bar [10], and piloted, methane flames ($D = 4.07$ mm, $Re = 5,000$) at 1 bar and 3 bar [11]. Subsequently, there were several
30 attempts to model the soot formation in the methane flames [12–18] and the piloted, kerosene flames [19]. Experiments on non-sooting turbulent nonpremixed flames at elevated pressures are nonexistent and numerical simulations are rare [20–22].

To address the dearth of experimental data in turbulent nonpremixed flames
35 at elevated pressures (both sooting and non-sooting), a new rig has recently been commissioned in the high-pressure combustion lab at the Clean Combustion Research Center (CCRC) at KAUST. In this study, a series of piloted, ethylene-nitrogen jet flames, well-suited for model validation, are studied over a range of pressures and Reynolds numbers, extending the conditions of previous studies
40 performed at atmospheric pressure to conditions more relevant to real work-producing devices [23, 24]. The addition of nitrogen to the jet has two benefits. It reduces the total soot volume fraction, making it possible to increase the pressure (which increases the soot volume fraction) without forming so much soot that laser diagnostics become impossible. And it creates a blue, non-
45 sooting region in the near field, in which it may be possible to measure scalars such as temperature and major species concentrations, which are difficult, if not impossible, to measure in sooting environments. In addition to serving as an initial demonstration of the rig’s capabilities, the objective of this experiment is to gain better understanding of the effects of Reynolds number and pressure on
50 the flame structure in the near field of turbulent nonpremixed flames through the laser induced fluorescence of OH molecules. Ideally, simultaneous OH-PLIF

and CH₂O-PLIF could be used to visualize the reaction zone, but the wavelength and laser fluence needed for CH₂O-PLIF would inevitably cause the technique to suffer from excessive, unwanted PAH fluorescence and soot incandescence, rendering the results useless.

2. The High Pressure Combustion Duct at KAUST

The high pressure combustion laboratory was designed to support the simultaneous operation of multiple high-pressure, high-power experiments. Air is supplied by two large screw compressors (Kaesar DSD-238T) that operate in alternation to pump a 5000-L receiver up to 15 bar. This receiver feeds three booster compressors (Kaesar N 1400-GW) that pump a 2000-L receiver up to 45 bar. Water content may be removed from the air by passing it through a high pressure refrigeration dryer (Kaesar THP496-45). Each experiment in the laboratory has three sources of air: the 15-bar receiver, the 45-bar receiver, and the 45-bar dryer. At full capacity, the system is able to produce 0.56 kg/s of 45-bar air continuously. A compressor connected to the lab nitrogen supply fills a rack cylinders to very high pressure, providing similarly high, but transient, flow rates of N₂ to the facility. The lab has four primary fuel sources: two three-cylinder gas cabinets, and two ten-cylinder racks housed in a climate-controlled outdoor facility. The outdoor facility has space for four racks at a time, typically composed of 20 hydrogen cylinders and 20 methane cylinders in total.

The high pressure combustion duct (HPCD), one of the high-pressure rigs available at the KAUST high-pressure combustion laboratory, has been designed primarily for experiments on turbulent non-premixed flames, with the following design constraints:

1. It must be safe to operate.
2. The duct should be vertical to prevent buoyancy-induced asymmetries in the flames.
3. It should be wide enough to accommodate flames that require a large air coflow and to satisfy the condition that there be no interaction between

the walls of the duct and the flame itself.

4. As turbulent nonpremixed flames can be up to 1 meter or more in length, the duct should be tall enough to avoid interactions between the converging section at the top and the flame.
- 85 5. Most modern diagnostics for turbulent flames employ systems of lasers and cameras so the duct must have multiple, sufficiently large windows for optical access.
6. In order to probe the flames from the base to the tip, the duct must have the ability to translate the burners vertically by at least 1 meter, with
90 high resolution.
7. Some consideration should be given to the ease and speed with which burners may be removed and replaced.
8. Lastly, the duct must be able to handle the full capacity of the high-pressure air supplied to the lab.

95 The HPCD, shown in Fig. 1, is the result of an iterative design process that incorporates the above considerations. The majority of the duct is composed of 18-inch schedule-80 316L stainless steel pipe with class 600 flanges. The pipe schedule and flange class are determined by the requirement that the duct be able to contain air at 40 bar and 250°C. The size of the pipe was chosen to allow
100 for air coflows as large as 300 mm, the width of the square wind tunnel used for studies in turbulent nonpremixed flames at Sandia National Laboratories. The entire weight of the HPCD is supported by a table, with the bottom of four sections hanging below. The table includes an external linear translation system composed of a lifting platform attached to four threaded rods driven by a system
105 of gearboxes and a motor. This system allows the bottom section to be lowered from the table for easy removal and replacement of different burners. Burners are placed on an internal linear translation stage (Thomson MovoZ2) with a 1500-mm stroke length and the capability of moving in sub-mm increments. Above the table, the duct is divided into three sections, first of all, to split
110 it into shorter sections that are more manageable by the overhead crane, and

secondly, to make the complicated welding of optical section possible. At the top, the 18-inch pipe converges to a 6-inch tee, where on one branch a rupture disc is installed, and on the other branch, a back pressure regulator is installed and connected to the exhaust system.

115 Two 2-inch flexible hoses connect the HPCD to the high pressure air supply of the laboratory. One of the air lines is split into four smaller tubes inside the duct that connect to the air coflow of the burner. The other line supplies air to the annular region between the burner coflow and the walls of the duct. This serves three purposes: to prevent combustion products (especially H_2O) from
120 depositing on and heating up the windows of the optical section, to provide immediate cooling to the walls surrounding the flames, and to provide dilution of the downstream flame products in order to keep the back pressure regulator relatively cool. This is necessary because the HPCD does not have any method of active cooling incorporated in the design, although it could be added in the
125 future. As such, flames are currently limited to a maximum thermal power of roughly 70 kW. In addition to the air, there are four inputs of fuel, inert, or oxidizer (if premixing is required) to the base of the HPCD.

Figure 2 presents a top view of the optical section with its dimensions. Six arms provide optical access to the flames inside the duct. As this section
130 requires significant welding, the wall here is almost twice as thick as in the other sections of the duct, leading to a duct inner diameter of 410 mm. Four of the optical section arms are orthogonal. The windows labeled A_1 and A_2 , which are closest to and equidistant from the HPCD centerline, are the largest in diameter (150 mm) and are intended for signal collection. The windows labeled B_1 and
135 B_2 are slightly smaller (120 mm) and are intended for passage of the laser. Windows C_1 and C_2 are the smallest (95 mm) and the axes of their arms are oriented at 40° to the B_1 - B_2 axis. These windows are designed for experiments requiring stereoscopic particle image velocimetry (PIV) measurements, because according to Prasad (2000) [25], the optimum camera arrangement has both
140 cameras operating in forward scatter (with laser sheet path in B_1 - B_2 direction). A set of six BK7 windows, housed in stainless steel flanges, are available for

Figure 1: The high pressure combustion duct (HPCD) at KAUST.

applications in which very good transmission in the visible and near-infrared spectrum is needed. Windows A and B are also available with UV fused silica which has greater than 90% transmission from $200 \text{ nm} < \lambda < 2000 \text{ nm}$. All
145 windows are tested up to 60 bar and 100°C .

Figure 2: Top view of the HPCD optical section with some critical dimensions.

The back pressure regulator (Equilibar NLB Series) utilizes a dome loaded design which provides excellent control over a wide range of flow rates. An internal diaphragm is used to control the pressure. The set point is delivered to the backside of the diaphragm via a small tube of air or N_2 pressurized to the
150 correct amount by an electronic pressure regulator (Proportion-Air GP1) that is controlled remotely from the lab control room. A rupture disc (Fike SCRD Series) exists to burst and release the pressure in the HPCD if the set point ($50 \text{ bar} @ 250^\circ\text{C}$) is exceeded. The diameter of the rupture disc has been sized to ensure total evacuation of the duct in 0.5 seconds.

155 Safe operation of the duct is monitored by a programmable logic controller (PLC) and the laboratory control system (LCS). The PLC monitors the toxic gas monitoring (TGM) system of the lab as well as the following HPCD sensors:

- Pressure transducer
- 4 internal temperature probes
- 160 • 8 surface temperature transmitters
- 2 LEL (lower explosive limit) gas detection systems
- Rupture disc burst indicator

If any of the sensors report a reading that is outside the acceptable limits, the PLC automatically takes the appropriate action. In most cases, that action
 165 involves shutting off all of the fuel inputs and possibly the air inputs via solenoid valves.

3. Experiment

3.1. Flame Conditions

The piloted turbulent nonpremixed jet flames investigated in this study use a
 170 burner geometry similar to the International Sooting Flame 4 (ISF-4) Workshop turbulent target flame 2 (Sandia) [26]. The inner diameter of the central jet is $D = 3.4$ mm and the total length of the tube is 530 mm. The jet is surrounded by three concentric rings of small, premixed pilot flames formed by a pilot plate, with dimensions given in Fig. 3. For all operating conditions, the jet is composed
 175 of C_2H_4/N_2 with N_2 composing 65% by volume. For this reason, flames in this family are referred to by the acronym KEN (KAUST Ethylene-Nitrogen). The pilot flames are composed of a premixture of C_2H_4 /Air at an equivalence ratio of 0.9. A co-annular flow of air is provided by a 3-D printed nozzle with an exit diameter of 250 mm, featuring a honeycomb section and four separate wire
 180 mesh flow conditioners as well as a converging exit section, to reduce the velocity fluctuations of the coflow at the test section. In addition to the conditioned coflow, an airflow of similar velocity is generated in the annular area between the burner and the walls of the HPCD. A schematic of the burner inside the HPCD, as well as the diagnostics employed in this study is given in Fig. 4.

Figure 3: Geometry for the KEN burner. All dimensions in mm.

Figure 4: Schematic of the KEN burner inside the HPCD and the equipment for OH-PLIF and DSLR camera imaging.

185 Two series of flames are examined in this work. The baseline flame (01-01B
in the present study) has a Reynolds number of 10,000 with the pilot providing
6% of the heat release of the jet. In one series of flames, the bulk jet velocity
is kept constant as the pressure is increased from 1 to 5 bar in increments of 1
bar. In the other series of flames, the Reynolds number is kept constant as the
190 pressure is increased to 5 bar. Because it was not possible to conserve a pilot
power of 6% for the constant Re series, due to the potential for flashback of the
pilot premixture at the highest pressure, this series features a larger pilot power
of 18%, instead of 6%. For all conditions, the ratio of jet velocity to coflow
velocity is 61. The full operating conditions of the ten KEN flames are given in
195 Table 1.

Table 1: Operating conditions: p is the operating pressure, Re is the Reynolds number based on the jet diameter ($D = 3.4$ mm), U_j is the bulk jet velocity, P_p is the power of the pilot flame relative to the power of the jet, and U_{cf} is the bulk coflow velocity.

Designation	p (bar)	Re	U_j (m/s)	P_p (%)	U_{cf} (m/s)
KEN 01-01A	1	10,000	36.6	18	0.60
KEN 02-01	2	10,000	18.3	18	0.30
KEN 03-01	3	10,000	12.2	18	0.20
KEN 04-01	4	10,000	9.15	18	0.15
KEN 05-01	5	10,000	7.32	18	0.12
KEN 01-01B	1	10,000	36.6	6	0.60
KEN 02-02	2	20,000	36.6	6	0.60
KEN 03-03	3	30,000	36.6	6	0.60
KEN 04-04	4	40,000	36.6	6	0.60
KEN 05-05	5	50,000	36.6	6	0.60

Mass flow controllers (Brooks SLA series) are used to set flow rates for the
burner gases. Because the gas conversion factor for ethylene is sensitive to
pressure, it is convenient to use individual back pressure regulators on each gas
line between the mass flow controller and the pressurized duct. In this way,
200 the upstream and downstream pressures on the mass flow controller can be kept
constant, as well as the gas conversion factor, regardless of the setpoint pressure
required by the condition. Each mass flow controller was calibrated for an inlet
pressure of 20 bar, an outlet pressure of 15 bar, and for the optimum full scale

flow rate, such that the flow rate would be set at 100% of the calibration range
 205 at the most extreme condition (KEN 05-05), thus keeping the measurement
 error less than 1% for all conditions. The flow rates of air supplied to the coflow
 and the annular region around the coflow are set by large quarter-turn valves
 and monitored by thermal mass flow meters (FCI STP100). Careful observation
 shows that the air coflow mass flow rate varies sinusoidally with time, but always
 210 by less than $\pm 15\%$ of the mean. A hot wire anemometer is used to measure
 the air coflow velocity at $p = 1$ bar at many locations near the coflow exit,
 confirming that a tophat profile is achieved for the desired velocity.

Ignition is achieved by translating a spark plug, that is normally recessed
 into one of the arms of the HPCD optical section, into the center of the HPCD
 215 and initiating a spark downstream of the pilot. After ignition, the spark plug
 is recessed back into the arm. The spark plug is positioned on a rod that
 is translated through a shaft seal embedded in a flange. The rod is pushed
 from outside the HPCD by an assembly (see Fig. 4) that includes an ACME
 round nut, ACME threaded rod and a remotely-controlled motor. A variable
 220 transformer and ignition transformer, with a variable output voltage of up to 10
 kV, are connected to the spark plug via high-voltage 1-pin bulkhead connectors
 (Kemlon 16-B-8083) in the flange.

3.2. Diagnostics

The arrangement of equipment used for the diagnostics in this study is
 225 shown in Fig. 4. For the laser-induced fluorescence of OH, a dye laser (Sirah
 CREDO-DYE-N) is pumped by the second harmonic of a Nd:YAG laser (Edge-
 wave IS200-2L). The dye laser produces a fundamental beam near $\lambda = 566$ nm
 with Rhodamine 6G. The frequency doubled beam is tuned to $\lambda = 282.945$ nm
 to excite the OH molecules using the $Q_1(6)$ line of the $A^2\Sigma - X^2\Pi$ (1,0) tran-
 230 sition. The operating condition of the laser is approximately 2.6 W at 10 kHz.
 The laser beam is expanded through two cylindrical lenses, then passed through
 one of the UV fused silica windows, creating a sheet of approximately 100 mm
 in height at the flame location.

An intensified CMOS camera (LaVision HighSpeedStar 8 with HighSpeed
 235 IRO, 12 bit, 1024×1024 pixel) is used to acquire the fluorescence signal through
 another UV fused silica window at an angle of 90° . The signal is filtered through
 a high-transmission band-pass interference filter centered at 310 nm. The spatial
 resolution of the camera is 7.8 pixels/mm. For each flame, a set of 2000 images
 and another set of 1000 images are taken for analysis. The images are centered
 240 on the burner nozzle tip and cover the first 65 mm of the flame, after cropping
 out the weakly fluorescing portions.

In addition to OH-PLIF, 50 images of each flame at each of four different
 axial locations were recorded with a Canon EOS 7D DSLR camera with EF 28-
 135mm f/3.5-5.6 IS USM lens using an aperture of f/3.5 and ISO 100. Depending
 245 on the luminous intensity of each flame condition and axial location, shutter
 speeds between 1/25 s and 1/500 s were used. Each image covers over 100 mm
 of the flame.

3.3. OH-PLIF Data Processing

For each set of OH-PLIF images, corrections are made by removing the aver-
 250 age dark current background noise and by normalizing for energy fluctuations of
 the Nd:YAG laser. OH-PLIF in a laminar flame is used to estimate laser sheet
 spatial inhomogeneities and a correction based on these images is then applied
 to the images of the turbulent flames. Finally, the images are smoothed using a
 2-D Gaussian smoothing kernel with a standard deviation of 1, and each is split
 255 along the centerline to form a left and right image, which are then analyzed
 separately.

Polycyclic aromatic hydrocarbons (PAHs) are well-known soot precursors
 that can fluoresce over a very wide range of excitation wavelengths, including in
 the UV [27]. Therefore, some contamination of the OH-PLIF images with PAH
 260 molecules is expected, especially at elevated pressure. Indeed, in many studies,
 the same dye laser for OH-PLIF is used explicitly for PAH-PLIF by detuning
 the laser off the OH transition [6, 28–30]. In this study, some of the acquired
 OH-PLIF images are clearly capturing some PAH fluorescence as well. In order

to properly analyze the OH structure, it is necessary to remove the PAH. In
 265 Fig. 5a, the central image shows an instantaneous OH-PLIF image taken with
 the KEN 05-01 flame, and the left image shows PLIF at the same condition, but
 with the laser detuned from the OH transition. By comparing these images, it
 is clear that the OH forms two, narrow, highly-structured shapes on either side
 of the flame centerline, as is characteristic of non-premixed jet flames, whereas
 270 the PAH appears as unstructured bodies along the centerline. Some features of
 the PAH structures are then used to distinguish PAH from OH systematically:
 PAH tends to form along the centerline, the peak intensity of PAH is less than
 OH at all flame conditions, and the spatial gradient of OH is much greater
 than that of PAH. An algorithm that takes advantage of these features is then
 275 used to “erase” the PAH features from the region of interest in the OH-PLIF
 images. The result of this procedure is the post-processed image on the right
 side of Fig. 5a. Figure 5b shows the OH intensity radial profiles at a downstream
 location of $x = 40$ mm for the pre-processed image and the post-processed image
 in Fig. 5a. It is clear that the PAH removal algorithm significantly reduces the
 280 intensity of the PAH at the center while preserving both the intensity (important
 for the binarization algorithm) and the spatial gradient (important for the edge
 detection algorithm) of the OH layers at approximately $r = \pm 5$ mm.

Having removed any PAH interference from the OH-PLIF images, a 2-D
 flame front is generated as follows. Edges of the OH layer are detected using
 285 a gradient-based Canny algorithm with unspecified threshold values [31, 32].
 This method uses strong and weak gradient thresholds, minimizing the effects of
 noise, and by not specifying the thresholds, the algorithm chooses them heuris-
 tically. Edges on the air (lean) side of the OH layer are eliminated, leaving only
 edges with relatively sharp gradients on the fuel (rich) side of the flame. These
 290 contours closely follow the reaction zone and are defined as the flame front. Two
 examples of processed OH-PLIF images with the flame fronts highlighted in red,
 and labeled with their respective corrugation factors (to be defined below), are
 shown in Fig. 6.

Figure 5: (a) An instantaneous image as a result of OH-PLIF, detuned off the OH excitation line (left) and an instantaneous OH-PLIF image before (center) and after (right) processing to remove PAH. All images are from condition KEN 05-01. Note: the detuned image is not from the same instance as the other images. (b) Radial OH-PLIF intensity profiles at $x = 40$ mm for the pre-processed and post-processed images in (a).

4. Results

4.1. DSLR Camera Images

Figure 7 presents stitched instantaneous DSLR camera images of each of the flames in the constant Reynolds number series. The images are cropped to form segments of 100 mm in height. Differences in shutter speed from one axial station to the next are responsible for the apparent discontinuities in flame appearance between segments. The background has been artificially darkened in some cases,

Figure 6: Processed instantaneous OH-PLIF images for two conditions, with the flame front of each OH layer ($35 \text{ mm} < x < 65 \text{ mm}$ only) and its associated computed corrugation factor identified in red.

but not removed entirely, producing the circular features (reflections from the back side of the HPCD interior) behind the flame in many of the images. A comparison of this series of images reveals a few trends worth noting. The blue region in the near field of the flame shrinks considerably from 1 bar to 2 bar and is practically non-existent above 2 bar. The luminous intensity of the flames increases as the pressure increases, indicating an increase in soot production. Lastly, the flame length and flame volume appear to decrease slightly as the pressure increases.

Figure 8 presents stitched instantaneous DSLR camera images of each of the flames in the constant velocity series. As with the previous case, the luminous intensity increases with increasing pressure. However, in this series, the flame length and volume appear to grow as the pressure and Reynolds number increase. And the blue region shrinks with increasing pressure, but at a slower rate than with the constant Reynolds number cases.

To assess the length of the blue region of each flame, each DSLR camera image is binarized using a relative threshold (different for each set of images) on the blue RGB channel to distinguish regions of the flame from the background. A relative threshold (different for each set of images) on the red RGB channel is used to distinguish sooty regions from blue or dark regions. The blue region

Figure 7: Instantaneous DSLR camera images for flames in the constant Reynolds number set. Each flame image is composed of four images at different axial locations.

is then defined as locations where the flame exists but is not sooty. The length
 of the blue region, L_b , is defined as the maximum axial distance from the nozzle
 tip at which a blue flame is present in 50% of the binarized images. Because a
 range of threshold values could reasonably be used to isolate the blue region, a
 higher and a lower value were used for each set of images, yielding a range of
 lengths for each flame. Figure 9 shows the results of this analysis. As seen from
 the instantaneous images, the length of the blue region in the constant Reynolds
 number series decreases dramatically at elevated pressures, and asymptotes to
 roughly 25 mm in length at 5 bar. Thus, the soot inception zone moves upstream
 as a result of the increasing pressure and/or the decreasing bulk jet velocity.
 With the constant velocity series, the length of the blue region decreases almost
 linearly, at a rate of roughly 15 mm/bar, as the pressure increases. At 5 bar,
 the ranges of lengths of the blue region of both the $Re = 10,000$ flame and the
 $Re = 50,000$ flame are overlapping. These trends suggest that pressure plays a

Figure 8: Instantaneous DSLR camera images for flames in the constant velocity ($U_j = 36.6$ m/s) set. Each flame image is composed of four images at different axial locations.

significant role in not only the amount of soot produced, but also the residence
 335 time necessary for soot to be produced in appreciable concentrations.

Figure 9: Measured lengths of the blue flame region for all operating conditions. A higher and lower threshold were used to generate the range at each condition.

4.2. OH-PLIF Images

Pre-processed instantaneous OH-PLIF images from the constant Reynolds number series are shown in Fig. 10a. The colormap for each image is relative to the maximum intensity of that image, so it is not possible to compare the intensity from image to image using Fig. 10. The OH signal intensity does drop as the pressure increases, due to molecular line broadening of OH transitions, but the SNR at $p = 5$ bar remains high enough to make use of the data. One salient feature of this figure is that the presence of PAH in the OH-PLIF images becomes significant above $p = 3$ bar. As noted previously, PAH is systematically removed from all images before proceeding further with the analysis of the OH images. A trend of decreasing OH layer thickness as the pressure increases is observed. This can be attributed to an increase in reactivity due to molecular collisions [33]. The corrugation of the OH layer in the five images appears to be relatively insensitive to changes in pressure.

The instantaneous OH-PLIF images from the constant velocity series in Fig. 10b show a trend of increasing corrugation of the OH layer as the pressure, and thus the Reynolds number, increase. This is in conjunction with what appears to be increasing fragmentation of the OH layer. These two effects are quantified in the next section. The trend of decreasing OH layer width is less apparent in this series than in Fig. 10a, but still present. Furthermore, the presence of PAH in the near field is much more subtle at high Reynolds number than at low Reynolds number, for the same pressure; an observation that could be anticipated from the behavior of the blue regions in the DSLR camera images.

4.3. Flame Corrugation

In order to quantify the corrugation of the OH-PLIF images, a flame front is extracted using the method described in Section 3.3. Observing the trends in Fig. 10, it is clear that there is little variation in the structure of the OH layer in the pilot region of the flames. Therefore, the flame front analysis is only applied to the range $35 < x < 65$ (mm). The flame front is a pixel-wide contour along the rich (fuel) side of the OH layer. A mean flame front is calculated by taking the

Figure 10: Instantaneous OH-PLIF images for flames in the (a) constant Reynolds number set and (b) constant velocity set. Note: the colormap for each image is normalized by the maximum intensity of that image.

mean of all OH images for a given flame and using the same procedure to identify the rich-side contour of the OH layer. Then a corrugation factor, CF, may be defined for each image by taking the ratio of the length of the flame front in that image to the length of the mean flame front. The corrugation factor is a simple

370 non-dimensional metric for quantifying the degree of corrugation of the flame front in any image. If a break in the OH layer occurs, a representative length of the mean flame front is removed to avoid underestimating the corrugation factor. Referring again to Fig. 6, examples of flame front extraction from two different

conditions are shown, along with the computed corrugation factors. On the left
 375 is an image from a flame at a pressure of 1 bar and the lowest Reynolds number
 and on the right is an image from a flame at a pressure of 5 bar and the highest
 Reynolds number. The low Reynolds number image shows less corrugation and
 this is reflected in corrugation factors very close to 1, whereas the high Reynolds
 number image reveals a finely convoluted and broken flame structure and thus
 380 has significantly higher corrugation factors.

The corrugation factor for each side (left and right) of each image is com-
 puted separately. For each flame, two sets of images are recorded (2000 images
 in the first set and 1000 in the second), to ascertain if the short acquisition
 time from high-speed imaging is possibly failing to capture any longer timescale
 385 fluctuations. In comparing the PDFs from the left and right side and from two
 different sets (4 PDFs total) for each condition, no distinction can be made
 between the PDFs. Therefore, the corrugation factors from the different sides
 and different sets are merged to create PDFs of 6000 measurements for each
 flame. Furthermore, in confirming that left and right side PDFs are identical for
 390 the high pressure conditions, there is evidence that the procedure for calculat-
 ing the corrugation factor is not susceptible to the influence of OH-PLIF signal
 attenuation through the flame.

Corrugation factor PDFs at each condition in the constant Reynolds number
 series and the constant velocity series are shown in Fig. 11a and Fig. 11b, respec-
 395 tively. In the constant Reynolds number series, very little distinction between
 flames at different pressures is seen, with the peak probability occurring near a
 corrugation factor of 1.05, indicating that pressure does not play a significant
 role in wrinkling of the reaction zone. However, in the constant velocity series,
 the PDFs have similar shape but are separated. Higher pressure and higher
 400 Reynolds number conditions tend to have slightly higher levels of corrugation,
 with the biggest jump from $p = 1$ bar to $p = 2$ bar.

Referring to Fig. 10, there is a noticeable difference between the two $p = 1$
 bar conditions, despite having the same Reynolds number. This is clearly due
 to the influence of the pilot, which is three times more powerful in the constant

Figure 11: PDFs of corrugation factor for the constant Reynolds number series (a) and constant velocity series (b). Each PDF includes corrugation factors from the left and right side OH layer from each image in two different sets of data for each condition.

Reynolds number case, on the flame structure in the near field of piloted jet
 flames. The increased velocity and heat release of the pilot in flame 01-01A
 should have the effect of shifting the region of intense turbulence downstream
 of the nozzle relative to flame 01-01B and, consequently, a direct comparison
 between corrugation factors in the interrogation region used in this study is not
 justified. Nonetheless, qualitative differences in the behavior of the OH layer in
 the near field of these flames warrant an explanation. Two possible explanations
 have been identified. One reason could be that the increased heat provided to
 the flame base with a large pilot results in higher temperatures within the

jet, downstream of the pilot flame region. The increased viscosity reduces the
415 local Reynolds number. This would enhance laminarization and result in a less
corrugated flame structure. Such a reduction in local Reynolds number due
to heating effects in turbulent flames has been observed previously, where the
Reynolds number decreases locally at the regions of higher probability of OH
radicals [34]. Another mechanism that could explain the effect of the pilot is the
420 difference in gas velocities between the pilot and main jet. As the velocity of
the pilot gases is increased, the shear between the pilot and main jet is reduced,
causing less disruption in the OH layer downstream of the pilot flame region.

Whereas the difference in corrugation factor distribution between flames 01-
01A and 01-01B is entirely attributable to the power of the pilot, since they are
425 defined by the same Reynolds number and pressure, the pilot flame conditions
are exactly the same at $p = 3$ bar for flames 03-01 and 03-03. This means that
the difference in corrugation factor distribution between these flames is entirely
attributable to the different jet Reynolds numbers; $Re = 10,000$ versus $Re =$
 $30,000$.

430 4.4. Local Extinction

Local extinction has been found to occur as a result of large fuel vortices
breaking through the OH layer or because of sustained high local strain fields
[35]. Previous experiments have used OH-PLIF [35–41] or CH-PLIF [42] to
identify breaks in an otherwise continuous OH/CH layer as local extinction
435 events. Adopting this approach, further information may be extracted from
the OH-PLIF images by examining the frequency with which the OH layer
breaks in the region of interest, $35 < x < 65$ (mm). From the process for
identifying the flame front, a threshold for binarizing the OH-PLIF intensity
images is defined. From the binarized images, the number of OH “islands”
440 can be identified, and from this, the number of separations in the OH layer,
a measure of local extinction, is determined. The number of separations per
image are used to generate probability distributions that indicate the frequency
of OH layer separations for each condition. The probability distributions at

each condition in the constant Reynolds number series and the constant velocity series are shown in Fig. 12a and Fig. 12b, respectively. For the constant Reynolds number series, there is a small difference in the frequency of these separations, with the likelihood of breaks increasing as the pressure increases. This could be a result of the decreasing thickness of the OH layer. The differences in frequency of separations in the constant velocity series are much more significant. While the decreasing thickness of the OH layer could be a factor here as well, differences in the Reynolds number are primarily responsible for this behavior.

Figure 12: Probability distributions of OH separations per image for the constant Reynolds number series (a) and constant velocity series (b).

As mentioned previously, one should exercise caution when making direct

comparisons between the measurements in flames 01-01A and 01-01B. However, increasing the power of the pilot appears to reduce the frequency of local extinction in the near field. Measurements further downstream of the nozzle in flame 01-01A could strengthen this observation. The effects of different pilot flame parameters on the stability of CNG/air and LPG/air flames in the Sydney inhomogeneous inlets burner have been systematically studied [43]. For nonpremixed jet conditions (zero recess distance in the burner), they observed that increases in the heat release of the pilot enhanced flame stability while changes in the bulk velocity of the pilot had no effect. Because blow-off in piloted jet flames is generally preceded by high rates of local extinction, these results imply that increasing the heat release of the pilot should lead to fewer local extinction events, as suggested by the results presented here. While the bulk velocity of the pilot in flame 01-01A is three times higher than in flame 01-01B, the conclusions of [43] would indicate that this effect is negligible compared to the threefold increase in heat release. Lastly, it is interesting to note that although changes in the pilot appear to have a dramatic effect on the OH layer in the near field, the general appearance of the flame and the flame length (see Figs. 7 and 8) as well as the length of the blue flame region (see Fig. 9) are largely unaffected.

In addition to the frequency of OH separations, it is also instructive to observe the details of these separations. Figure 13 shows the PDFs of the OH “island” areas for the constant velocity series. Not only does the frequency of OH layer separation increase with the Reynolds number (and pressure), but the layers break into smaller “islands” of OH.

Related to the area of the OH “islands” is the separation distance between them. The separation distance is defined by finding the two closest points on neighboring “islands” and measuring the length of a straight line between them, a methodology similar to the one employed in [37]. Figure 14 shows the PDFs of the separation distance between adjacent OH “islands” for the constant velocity series. The mean separation distance decreases monotonically as the Reynolds number (and pressure) increases.

Figure 13: PDFs of the area of OH “islands” in OH-PLIF images for the constant velocity series.

Figure 14: PDFs of the separation distance between adjacent OH “islands” in OH-PLIF images for the constant velocity series.

Local extinction in a turbulent flame is an inherently 3-D phenomenon, and
485 caution must be exercised when drawing conclusions from 2-D measurements in
such environments. Even so, disruptions in an otherwise continuous OH layer
in a plane are widely used as a marker of local extinction. On the other hand,
re-ignition may occur as result of edge-flame propagation or turbulent trans-
port, and proper interpretation of re-ignition events in a plane must account
490 for out-of-plane motion [39, 41]. Consequently, studies that analyze re-ignition
events often rely on strict procedures, in the absence of additional information,

to eliminate instances where out-of-plane motion may play a role [38, 41], or utilize complementary data from stereoscopic-PIV to measure the out-of-plane motion directly [35, 39]. In the present study, no complementary flow field data
495 is available, so re-ignition is not analyzed. Of course, the OH “islands” are not true islands as they may or may not connect to other parts of the flame front outside of the OH-PLIF plane. And the separation distances are actually the lengths of chords drawn in an arbitrary plane across circular, elliptical, or irregularly shaped holes in the flame sheet. Nonetheless, such metrics offer a good
500 qualitative understanding of the 3-D flame dynamics in the near field. As the flames in this study are useful as targets for model validation, it is important to note that the metrics discussed here could be generated by analysis of simulations. For example, an LES study attempted to replicate the experiments in [38], and by considering a plane in the simulation and using the same processing
505 procedure as with the OH-PLIF images, they found good agreement with the experimental local extinction results, indicating that 2-D measurements in a 3-D turbulent flame are useful for quantitative comparisons with simulations [44].

The overall analysis of the OH-PLIF results may be summed up as follows.
510 Increasing the pressure, while maintaining the Reynolds number, has very little, if any, effect on the flame front corrugation and only limited influence on the frequency of OH layer separations as a result of the decreased thickness of these layers. Increasing the Reynolds number, in conjunction with the pressure, increases the level of flame front corrugation. However, as the corrugation in-
515 tensifies, the frequency of OH layer separations increases as well. When this occurs, the corrugation factor alone cannot explain the changes in flame structure. Other metrics, such as the frequency of OH layer separations, the OH “island” area, and the “island” separation distance, are needed to understand the full picture. As the Reynolds number increases beyond $Re = 20,000$, ad-
520 ditional corrugation is limited and the increased mixing leads instead to more frequent breaks in the OH layer, resulting in smaller “islands” of OH separated by shorter distances. It is also possible that the observed insensitivity of the

corrugation factor to changes in Reynolds number above $Re = 20,000$ reflects a limitation on the spatial resolution of the technique. In order to verify this, higher resolution measurements are necessary.

5. Conclusions

A recently commissioned pressurized combustion rig has been used to test piloted, ethylene-nitrogen turbulent diffusion flames, that are well-suited for model validation, over a moderate range of pressures and a wide range of Reynolds numbers. DSLR camera images show that the length of the non-sooting region of the flames decreases quickly above atmospheric pressure if the Reynolds number is held constant, whereas it decreases more gradually if the bulk jet velocity is held constant. In both cases, the blue region is virtually nonexistent at $p = 5$ bar. OH-PLIF images in the constant Reynolds number series show that corrugation of the flame front is insensitive to changes in pressure. Changes in Reynolds number as the pressure increases have a dramatic effect on the corrugation of the flame front and the frequency of separations in the OH layer. As the Reynolds number increases beyond $Re = 20,000$, the corrugation of the flame changes only slightly, whereas the frequency of OH layer separations continues to increase while the areas of OH “islands” and the separation distances between those “islands” continue to decrease.

This study shows that the HPCD makes it possible to test canonical turbulent diffusion flames not only at elevated pressures, but also at high Reynolds numbers that are more relevant to practical operating conditions (of gas turbines, for instance) and are otherwise inaccessible. It is notable that experiments at atmospheric pressure have shown that, for the same composition and pilot power as the constant velocity series, the maximum Reynolds number that can be reached before blowoff is only slightly more than $Re = 20,000$ [23]. From the trends discussed here, it is certain that the flames in the constant velocity series will eventually reach total blowoff if the pressure is increased beyond $p = 5$ bar, but these experiments have already shown that pressure can be used to push

the Reynolds number at least $2.5\times$ higher than is possible by changing the bulk jet velocity at $p = 1$ bar.

Future work on this family of sooting flames should focus on characterization
555 of the soot properties as the pressure and Reynolds number change. Subsequent
applications of OH-PLIF could also benefit from higher resolution (as opposed
to a large field of view in this study) to ensure that the flame front is truly
resolved at elevated pressures. Simultaneous measurements of OH and PAH
560 while simultaneous measurements of OH and soot should yield some insight into
the role of OH in the oxidation of soot in the near field, and how changes in
pressure and Reynolds number could affect such interactions.

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