High-Speed Imaging of Turbulent Nonpremixed Syngas Flames at Elevated Pressures

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Received: date / Accepted: date

Abstract Despite the success of the Turbulent Nonpremixed Flames Workshop, a noticeable lack of data at elevated pressures persists. A high pressure rig has been used to explore turbulent nonpremixed syngas flames at elevated pressures and very high Reynolds numbers. Composite images of the flames reveal small changes in flame length that are in agreement with previous empirical correlations. OH-PLIF images are used to visualize the flame structure, revealing an OH layer that gets progressively thinner as pressure increases. A corrugation factor is defined and used to show that flame front corrugation is influenced by increases in Reynolds number and axial distance from the nozzle, but not pressure.

Keywords High pressure · Turbulent nonpremixed flames · Syngas

1 Introduction

Modern engineering of practical combustion devices is increasingly reliant on design evaluation by high-fidelity numerical simulations of turbulent reacting flows. Combustor design was originally a “black art” which relied on experience and judgement; it was aided by the rise of the digital computer and mathematical models of turbulent flow [1]. Currently, the majority of modeling strategies employ Reynolds-averaged Navier-Stokes (RANS) approaches. However, RANS models are typically developed for mean stationary flow, making them ill-suited for increasingly complex combustor flows that include unsteadiness and inhomogeneities [2]. With significant advances in computing power in recent decades, alternative strategies, particularly large eddy simulation (LES), offer a way to study coupled mixing and combustion processes with greater

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accuracy than RANS [3]. Direct numerical simulation continues to be far too computationally expensive for combustor design.

In LES, the large-scale coherent eddy structures, which comprise a major part of the Reynolds stresses, are fully resolved and geometry dependent, offering great advantages in comparison with RANS. These fully-resolved features determine entrainment rates into the mixing layers, thereby controlling the composition of resulting reactive gas pockets [4]. The smallest scales remain unresolved, requiring subgrid-scale (SGS) models. The mixing and dissipation processes at these scales are thought to be more universal in character, reducing the need to tune model constants [3]. Nonetheless, LES faces the same closure problem as RANS because the coupling between reaction and molecular mixing still occurs at the smallest scales [5]. In fact, many of the SGS models for LES have been used previously in RANS calculations [6].

Because LES requires SGS closure schemes that must model the temporal and spatial characteristics of a flow system accurately, the models must be validated with appropriate test cases before being implemented in simulations of practical combustion devices.

The search for and identification of turbulent flame test cases suitable for model validation began many years ago. In 1983, a study conducted by the Air Force Office of Scientific Research began a program to establish a well-documented database in turbulent reacting flows. A report by Strahle (1986) [7] summarized the results, concluding that no available databases were available that could meet all of the established criteria: measurements of a vector, scalar, and some turbulence quality at many streamwise and cross-stream locations, high measurement accuracy or at least an accuracy estimate, measurement of initial conditions, fully turbulent flow everywhere in the computational domain, and several others. Along with this report, more detailed papers were delivered summarizing existing databases, including fast-reaction (where characteristic transport times are large in comparison to characteristic times of reactions) nonpremixed flames [8], and slow-reaction nonpremixed flames [9]. Facilitated by advances in laser diagnostics [10] as well as turbulence modeling and computer technology [11], the need for a better set of flame databases led to the establishment of the International Workshop on Measurement and Computation of Turbulent Nonpremixed Flames (TNF Workshop) in 1996 [12].

The TNF Workshop has strived to establish a database of flames that are relatively easy to create in the laboratory and to model, but that retain the complex physics of reacting flows often encountered in real work-producing devices. Experimental data can then be compared directly with models, without the need for oversimplified geometries or unwarranted assumptions. The database covers a range of chemical complexity including H_2 and H_2/He [13], $CO/H_2/N_2$ [14], $CH_4/H_2/N_2$ [15], and DME [16]. The database also ranges in geometric complexity from simple or piloted jet flames [17] to bluff body burners [18] and, more recently, to turbulent stratified flames [19,20] and a piloted jet flame with inhomogeneous inlets [21].

There have only been a few examples of experiments on turbulent diffusion flames at elevated pressures [22–25], and as of yet, all of the TNF Workshop flames have been operated at atmospheric pressure. As numerical models are being developed to simulate devices working at high pressures, it is imperative that such models be validated first with simple flames at relevant operating conditions. Furthermore, by exploring such flames at elevated pressures, experimentalists gain the ability to operate at Reynolds numbers that are otherwise unachievable (aside from the piloted hydrogen diffusion flames in [26]) due to flame blowoff, but highly desirable for model validation [27].

In this study, a new high-pressure rig at KAUST is used to explore an existing, atmospheric-pressure flame in the TNF database at elevated pressure and very high Reynolds numbers. The simple jet flame composed of syngas [14] was chosen due to the ease of burner construction and the fuel composition, which is moderately more complex than a hydrogen flame, but resists sooting better than hydrocarbon mixtures. As this study is intended to serve as a proof of concept of the high-pressure rig and an introduction to this family of flames at elevated pressures, the diagnostics employed are relatively simple. A DSLR camera is used to identify the contours of the visible flames and measure the flame length. Planar laser-induced fluorescence of hydroxyl radicals (OH-PLIF) is used to characterize the flame structure as the Reynolds number and/or pressure are increased.

The study of flame length (also referred to as flame height) in turbulent jet flames and the formulation of empirical flame-length equations has a long history. One of the earliest known examples of a rigorous study of turbulent jet diffusion flames is given by Hawthorne et al., in which they obtain a relationship between the visible flame length and properties of the mixture that is independent of the fuel flow rate, provided the jet is turbulent [28]. Becker and Liang extended such studies to cover the range of operation from forced convection to natural convection while offering updated flame-length correlations [29], and Kalghatgi found that these non-dimensional groupings were appropriate for collapsing their flame length results onto a single curve [30]. Delichatsios used dimensional analysis to correlate entrainment with flame height data and derived expressions to describe global-flow characteristics for both buoyancy- and momentum-dominant cases [31]. According to that analysis, flame lengths may be converted to non-dimensional flame lengths and plotted versus the Froude number of the flame. The flame Froude number (Fr_f) is a non-dimensional number relating the flow inertia to the buoyancy forces and is defined as

$$Fr_f^2 = \frac{U_j^2}{\frac{\Delta T_{fa}}{T_0}(S+1)^3 g D \sqrt{\rho_s/\rho_0}}, \quad (1)$$

where $\overline{\Delta T_{fa}}$ is a modified mean flame temperature, approximated in this analysis by the difference between the adiabatic flame temperature and the ambient air temperature. S is the air-to-fuel mass stoichiometric ratio, g is the gravitational acceleration, ρ_s is the fuel density at the nozzle, and T_0 and ρ_0 are

the ambient air temperature and density, respectively. The flame length (L_f) is converted to a non-dimensional flame length (L^*) as follows:

$$L^* = \frac{L_f}{(S+1)D\sqrt{\rho_s/\rho_0}}. \quad (2)$$

A empirical correlation equation for the data was found to be:

$$\frac{L_f}{(S+1)D\sqrt{\rho_s/\rho_0}} = \frac{13.5\text{Fr}_f^{2/5}}{(1 + 0.07\text{Fr}_f^2)^{1/5}}. \quad (3)$$

The transition from buoyant to momentum jet flames occurs for $3 < \text{Fr}_f < 5$ and flame length is approximately constant for $\text{Fr}_f > 5$. The lengths of a number of syngas flames in the buoyancy-momentum transition regime are measured by Hwang et al., and good agreement is found with the Delichatsios correlation if the coefficient in Eq. (3) is changed from 13.5 to 11.3, the justification being a discrepancy in the method of flame length measurement [32]. Hu et al. find that this correlation works well for flames in a reduced pressure atmosphere, provided that a correction factor of $\alpha_T = 0.8$ is introduced to account for observed reduced entrainment and increased turbulent fluctuations in the low pressure cases [33]. The present work seeks to address the question of how well the Delichatsios correlation applies to jet flames at elevated pressures.

Planar laser-induced fluorescence (PLIF) of the OH radical has long been a favorite tool for obtaining qualitative information about the flame structure of turbulent diffusion flames. Seitzman et al. used OH-PLIF to image the structure of turbulent hydrogen nonpremixed jet flames up to $\text{Re} = 50,000$ [34]. In an extension of this study, Clemens et al. used OH-PLIF on piloted H_2/Ar jet diffusion flames with Reynolds numbers ranging from 30,000 to 150,000 [26]. In both cases, the OH zones appear as thin filaments connected by diffuse regions when the Reynolds number is low, but as the turbulence intensity increases, the OH zones become more diffuse and highly corrugated on a small scale.

In hydrocarbon flames, however, OH alone is not an ideal marker of the flame front. Combined CH/OH-PLIF experiments have shown that the reaction zone (marked by CH) is limited to a thin region on the fuel side of the OH layer, whereas the OH layer itself marks the somewhat thicker radical recombination zone on the lean (air) side of the flame [35]. The overlap of OH and CH_2O is also commonly used as a marker for the flame front [36]. A DNS study has suggested that the product of CH_2O and OH concentrations provides a good reconstruction of the heat release rate in turbulent syngas flames, however, they find that CH_2O is a very minor species [37]. Laminar flame simulations in Chemkin indicate that CH_2O concentrations for the proposed syngas flame composition are essentially undetectable. With the tools currently available, OH is the only viable marker for the flame front, and the structure of the flame can be approximated by focusing on the rich side contour of the OH layer.

Fig. 1 View of the CHN burner and coflow nozzle inside the HPCD with the diagnostics setup for DSLR camera imaging and high-speed OH-PLIF.

2 Experiment

The high pressure combustion duct (HPCD) at KAUST is used to perform the experiments. This is a vertically-oriented, 8-m tall, 400-mm inner diameter rig designed especially for operating long turbulent diffusion flames at pressures up to 40 bar. Burners are placed inside the duct from below. The optical section of the HPCD, shown in Fig. 1, features six UV fused silica or BK7 windows (up to 150 mm diameter), making it possible to perform advanced optical diagnostics, including stereoscopic PIV. Burners sit atop a vertical translation stage capable of sub-millimeter movement over a range of 1500 mm, allowing examination of flames from base to tip. The top section of the duct is outfitted with a large back pressure regulator, which allows fine pressure adjustments over a wide range of mass flow rates. For the current study, a spark plug is used for flame ignition. The spark plug is situated on a rod, which passes through the back flange, and is pushed back and forth by a motor outside of the duct, allowing the igniter to be recessed into the back arm of the HPCD once the flame is present.

2.1 Flame conditions

The turbulent flames have a geometry identical to the CO/H₂/N₂ flame A (chnA) studied at Sandia and ETH-Zurich as part of the TNF Workshop [14]. The nozzle is constructed from 1/4-inch precision stainless steel tubing with a squared off exit. The nozzle inner diameter is $D = 4.6$ mm and the total length is 572 mm. For all conditions, the fuel composition is 40% CO, 30% H₂,

Table 1 Bulk flow parameters for the CHN flames; p is operating pressure, Re is Reynolds number based on the jet diameter ($D = 4.6$ mm), U_j is the bulk jet velocity, P is the thermal power, and U_{cf} is the bulk coflow velocity.

Series	Designation	p (bar)	Re	U_j (m/s)	P (kW)	U_{cf} (m/s)
Baseline	CHN 01-01	1.0	16,700	77.3	9.75	0.70
Constant Re	CHN 02-01	2.0	16,700	38.7	9.75	0.35
	CHN 03-01	3.0	16,700	25.8	9.75	0.23
	CHN 04-01	4.0	16,700	19.3	9.75	0.18
	CHN 05-01	5.0	16,700	15.5	9.75	0.14
Constant U_j	CHN 02-02	2.0	33,400	77.3	19.5	0.70
	CHN 03-03	3.0	50,100	77.3	29.3	0.70
	CHN 04-04	4.0	66,800	77.3	39.0	0.70
	CHN 05-05	5.0	83,500	77.3	48.8	0.70

30% N₂ by volume (thus the designation CHN). Surrounding the fuel nozzle is a 250-mm coflow nozzle that provides well-conditioned air to the flame. Additional air is provided through the annular space between the coflow and the HPCD walls for cooling. The baseline condition (CHN 01-01) is identical to the TNF chnA flame. Two series of flames are explored. In one series, the Reynolds number is kept constant at 16,700 for pressures up to 5 bar. In the other series, the bulk jet velocity is kept constant at 77.3 m/s for pressures up to 5 bar. All flame conditions are listed in Table 1.

2.2 Diagnostics

The diagnostics setup is shown with the HPCD and CHN burner in Fig. 1. Images of each flame are recorded with a Canon EOS 7D DSLR with EF 28-135mm f/3.5-5.6 IS USM lens using shutter speeds between 1/50 s and 1/25 s, an aperture of f/3.5 and ISO 100. To adequately characterize and cover the entire flame, fifty images are captured at four different axial positions.

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 (Edgewave IS200-2L). The dye laser produces a fundamental beam at 566 nm with Rhodamine 6G. The frequency doubled beam is tuned to $\lambda = 282.945$ nm to excite the OH molecules using the Q₁(6) line of the $A^2\Sigma - X^2\Pi$ (1,0) transition. The operating condition of the laser is approximately 2.6 W at 10 kHz. A small fraction of the beam is directed into a power meter to monitor the shot-to-shot energy. The laser beam is expanded through a cylindrical lens and a spherical lens, creating a focused sheet. After it is expanded using a third cylindrical lens ($f = -50$ mm), this sheet is then passed through a UV fused silica window into the HPCD and through the center of the burner, where the beam has expanded to roughly 100 mm in height. A beam stop on the other side of the CHN burner prevents the beam from reflecting off the inside surface of the other window.

An intensified CMOS camera (LaVision HSS8/IRO) 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. For each flame, a set of 3000 images are taken for analysis at two different stations, each covering about 70 mm of the flame, with an overlapping region of 10 mm. For each set, the images are corrected by removing the average background noise and by normalizing for energy fluctuations of the Nd:YAG laser. A laminar flame is used to estimate laser sheet inhomogeneities and a correction based on these images is then applied to the images of the turbulent flames to produce the fully-processed results. After this, a smoothing operation is applied to remove pixelated features.

The corrected images are then used to generate a 2D flame front as follows. Each image is split along the centerline to form a left and right image, which are then analyzed separately. Edges of the OH layer are detected using a gradient-based Canny algorithm with unspecified threshold values [38, 39]. This method uses strong and weak gradient thresholds, minimizing the effects of noise, and by not specifying the thresholds, the algorithm chooses them heuristically. 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 contours closely follow the reaction zone and are defined as the flame front.

3 Results and Discussion

The HPCD was used to successfully operate all nine flame conditions, showing that unpiloted, fully-attached, very high Reynolds number (up to 83,500) flames can be achieved if elevated pressures are possible.

3.1 DSLR images and flame length

Fifty DSLR camera images at four different axial locations have been averaged and stitched together to create a composite image of the full flame for all nine conditions. The resulting images are presented in Fig. 2 and Fig. 3 for the constant Re flame series and the constant U_j series, respectively. The baseline case has a bluish base which fades to white and then has an orange tip. This trend is maintained for the constant velocity cases, whereas for the constant Reynolds number flames, the orange region moves upstream and occupies the entire flame at 4 and 5 bar.

The flame length is defined as the maximum height at which a flame is detected 50% of the time in the DSLR images. Flame lengths are plotted as a function of pressure in Fig. 4a. There is little change in length for constant Reynolds number flames, whereas the length increases gradually with increasing pressure in the constant velocity series, with the flame at 5 bar being roughly 10% longer than the baseline flame.

The non-dimensionalized flame lengths are plotted as a function of the flame Froude number according to the Delichatsios equations (1-3) in Fig. 4b.

Fig. 2 Composite images of CHN flames in the constant Re series.

Fig. 3 Composite images of CHN flames in the constant U_j series.

Fig. 4 Measured flame lengths: (a) as a function of pressure, and (b) non-dimensionalized and plotted against flame Froude number with the Delichatsios correlation curve.

The Delichatsios correlation is plotted as a black dashed line. The constant Reynolds number points are almost in a straight line, with the Froude number decreasing as the pressure increases, due to the decreasing bulk jet velocity. The constant velocity points are practically indistinguishable, with L^* increasing slightly as pressure increases. All of the data points lie very close to the Delichatsios curve, indicating excellent agreement with the existing correlation, which is based solely on results at atmospheric pressure. All of the constant velocity flames are clearly in the momentum-dominated regime, while the constant Reynolds number flames at pressures of 4 and 5 bar are close to the buoyancy-momentum transition.

3.2 Instantaneous OH-PLIF images

Instantaneous OH-PLIF images at two different axial locations are shown for each flame in the constant Reynolds number series in Fig. 5 and for each flame in the constant bulk jet velocity series in Fig. 6. The images at stations 1 and 2 are uncorrelated. The colormap for each image is normalized to the

Fig. 5 Instantaneous OH-PLIF images of CHN flames in the constant Re series.

maximum value in that image, so intensities cannot be compared. It may be seen from the images that the intensity is usually greatest near the vertical center, indicating that, while the spatial correction dramatically improved the quality of the images, the correction was only partial. This, however, does not appreciably affect the following analysis.

In examining the constant Reynolds number images in Fig. 5, many of the trends noted in [34] and [26] may be observed. Each flame consists of thin filaments of OH which are connected by thicker zones. The OH layers tend to exhibit relatively large structures (compared to the width of the layer), which suggests they are distributed by moderately-sized eddies. In general, the layers increase in thickness and become more convoluted further downstream of the nozzle. It is also noted that the gradient on the fuel side of the layer tends to be steeper than on the lean side, a feature of OH profiles that has been noted previously [40]. The most striking feature of this set of images is the reduction in the width of the OH layer as pressure increases. Both simulations and experiments have confirmed that pressure reduces OH layer thickness by enhancing radical recombination rates [41].

The images from the constant velocity series in Fig. 6 are remarkably different than those in Fig. 5. The thin filaments are mostly absent, replaced by thickened blobs of OH joined by much shorter segments. Some large-scale structures remain, but the salient feature is the presence of highly corrugated layers, clearly influenced by small-scale turbulence. Furthermore, the fineness and degree of corrugation appears to increase as the Reynolds number (and

Fig. 6 Instantaneous OH-PLIF images of CHN flames in the constant U_j series.

pressure) increase. It is interesting to note that even the most extreme case ($Re = 83,500$) exhibits very little local extinction.

3.3 OH layer corrugation

In order to quantify the corrugation of the OH-PLIF images, a flame front is extracted using the method described in Section 2.2. The flame front is a pixel-wide contour along the rich side of the OH layer. A mean flame front is calculated by taking the 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 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 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. Two examples are given to illustrate the technique, in Fig. 7. Red lines representing the flame fronts are overlaid on the OH images. On the left 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. Each flame front is labeled with the calculated corrugation factor. As expected, the low Reynolds number image shows less corrugation and this is reflected in corrugation factors close

Fig. 7 Illustration of flame front contours (red lines) overlaid on OH fields, with left and right corrugation factors (CF) labeled.

to 1, whereas the high Reynolds number image reveals a finely convoluted flame structure and thus has significantly higher corrugation factors.

Corrugation factors are computed for each of the flames over different ranges of x/D . In doing so, it is possible to assess the effects of pressure, Reynolds number, and axial location on the corrugation (wrinkling) of a 2D slice of the OH layer. This is done for three axial locations: $5 \leq x/D \leq 10$, $10 \leq x/D \leq 15$, and $15 \leq x/D \leq 20$. Beyond $x/D > 20$, this metric ceases to be useful due to excessive large-scale mixing.

Figure 8 shows the resulting probability density functions (PDFs) for the corrugation factors of each flame (roughly 6000 values per flame). The probabilities are grouped by constant Reynolds number (left column) and constant bulk jet velocity (right column). In considering the constant Reynolds number corrugation factors, it is apparent that the distributions change very little with pressure. This is true regardless of axial location in the flame. As the region of interest moves downstream, the OH layer becomes slightly more corrugated. For the $p = 1$ bar case, the mean corrugation factor changes from 1.13 close to the nozzle, to 1.29 slightly further away, and finally to 1.43 in the region $15 \leq x/D \leq 20$. This progression is representative of all of the flames in the $Re = 16,700$ series.

In the constant velocity series, on the other hand, analysis reveals that the corrugation of the flame front changes considerably as the Reynolds number (and pressure) are increased. This was anticipated from the OH-PLIF images in Fig. 6. For instance, the $p = 5$ bar, $Re = 16,700$ flame has a mean corrugation factor of 1.11 at $5 \leq x/D \leq 10$, whereas the $p = 5$ bar, $Re = 83,500$ has a mean corrugation factor of 1.29. As with the constant Reynolds number series, the corrugation of the OH layer in the flames of the constant velocity series tends to increase as the distance away from the nozzle increases. However, the progression is slower, particularly for the high Reynolds number flames, and

Fig. 8 Probability density functions of corrugation factors for each CHN flame in the constant Re series (left column) and the constant U_j series (right column) over ranges of x/D that are progressively further away from the nozzle.

at $15 \leq x/D \leq 20$, there is much less distinction between the PDFs in the constant velocity series. At this location, there is little distinction with regard to Reynolds number at all: the $p = 3$ bar, $Re = 16,700$ flame has a mean corrugation factor of 1.48 and the $p = 3$ bar, $Re = 50,100$ flame has a mean corrugation factor of 1.57. The PDF of the lowest Reynolds number case, however, tends to be distinct from the other PDFs in the constant velocity series at each of the axial locations.

The trends in corrugation factor PDFs describe well some phenomena of turbulent nonpremixed flames that have been observed elsewhere. OH layer corrugation is strongly affected by the small-scale turbulence, which increases with the Reynolds number [26]. At the two lowest axial positions, the mean

corrugation factor monotonically increases from the lowest Reynolds number case to the highest Reynolds number case, indicating that the corrugation factor, as defined here, is a useful analytical tool in that it provides quantitative data from mostly qualitative OH-PLIF images. Furthermore, corrugation factors near a value of 1 (where 1 is representative of a laminar flame) are indicative of laminarization in the near field of the jet as a result of increases in kinematic viscosity resulting in a reduction of the local Reynolds number [42]. Pressure appears to have little influence on flame corrugation if the Reynolds number is held constant.

There are inevitably some limitations to the analysis provided here. The first is that this analysis relies entirely on OH-PLIF images. A better estimation of the flame structure could be obtained with an additional spatially-resolved scalar, such as CH_2O or CO [37], or temperature [43]. However, experiments show that the fuel side contour of the OH layer is a reasonable approximation of the flame contour and, in the near field of turbulent non-premixed jet flames, the fuel side of the OH field is readily identified even without direct measurement of fuel concentration. Turbulence is an inherently three-dimensional phenomenon in jet flames, and simulations coupled with experiments have shown that extinction and re-ignition, for instance, are influenced by 3D effects [44]. For the purposes of this analysis, it should be recognized that the corrugation of a line in a 2D plane is only a rough approximation of the wrinkling of a surface in three dimensions. Lastly, it is possible that the measured corrugation of the OH layer is influenced by limitations in the spatial resolution of the OH-PLIF technique. For the purposes of this study, the intent was to demonstrate the ability to investigate jet flames at conditions relevant to practical combustion devices and to broadly characterize the behavior of such flames. Therefore, a large field of view was preferred over high spatial resolution.

4 Conclusions

Nine flames that are variations of the chnA flame from the TNF Workshop have been explored in the high pressure combustion duct at KAUST. The flames cover entirely new territory in the framework of the TNF Workshop, both in terms of pressure and Reynolds number. Analysis of DSLR images reveals that the flame length behavior is in agreement with the correlations offered by Delichatsios [31]. OH-PLIF images show an unbroken OH layer at 1 bar, which becomes thinner as pressure increases, and more corrugated as the Reynolds number increases. A corrugation factor is defined to quantify the degree of corrugation of the flame front in the OH-PLIF images. Probability density functions of the corrugation factors show that pressure has little influence on the flame front corrugation, whereas changes in Reynolds number have a dramatic effect.

Future work should focus on pushing the conditions to higher pressures and higher Reynolds numbers. Flame length measurements on higher-pressure, low

Reynolds number flames will test the Delichatsios correlation in the buoyancy-dominant regime. OH-PLIF could be aided by higher resolution (especially at higher pressures), as it is currently unknown if the flame front is truly resolved in this study. Finally, better statistical convergence of corrugation factors may be achieved by low speed OH-PLIF as opposed to the high-speed OH-PLIF utilized here.

Acknowledgements The research reported in this publication was supported by funding from King Abdullah University of Science and Technology (KAUST).

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