Pressure Effects and Transition in the Stabilization Mechanism of Turbulent Lifted Flames

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44 **Abstract**

45 This study reports novel measurements on the effects of pressure on the lift-off behavior and the
46 stabilization mechanism of turbulent non-premixed methane jet flames. A high-pressure combustion
47 duct (HPCD) was operated within the range of pressure $P = 1$ to 7 bar using jet velocities of 4 m.s^{-1}
48 $^1 \leq U_j \leq 30 \text{ m.s}^{-1}$ and co-flow velocities of $0.23 \text{ m.s}^{-1} \leq U_c \leq 0.60 \text{ m.s}^{-1}$. Lift-off heights were
49 measured from chemiluminescence pictures while joint images of hydroxyl and velocity, performed
50 using joint PLIF-OH/PIV, were used to extract information about the stabilization mechanism. It is
51 shown that while the lift-off height generally increases with pressure, the impact of pressure depends
52 on the magnitude of the co-flow velocity. For $U_c = 0.30 \text{ m.s}^{-1}$, the flame's base remains near the
53 nozzle over the entire pressure range and the measured flame speeds indicate that edge-flame
54 stabilization is dominant. The slope of the lift-off height vs jet velocity curves is positive. For
55 $U_c = 0.60 \text{ m.s}^{-1}$ and $P > 2$ bar, the flame stabilizes further downstream and a transition to turbulent
56 premixed flame propagation appears to have occurred. At these conditions, the slope of the lift-off
57 height vs jet velocity curves becomes negative. This reversal at high pressure is a new result for
58 methane. More importantly, the transition in the stabilization mechanism with increasing U_c is
59 consistent with results reported earlier for ethylene and appears to be independent of the fuel.

60

61 **Keywords**

62 Lift-off; Co-flow; Elevated pressure; Edge flame; Stabilization mechanism

63 1. Introduction

64 The mechanism of stabilization of lifted flames remains a controversial topic despite extensive
65 research that has provided some clarity on issues of near-field stability at ambient pressures [1, 2,
66 3]. It is now established that edge-flames play a key role in the near-field, and at sufficiently low co-
67 flow velocities [4, 5, 6, 7, 8, 9]. Both measurements and calculations confirm that at the
68 stabilization point, the velocity is less than three times the laminar flame speed S_L , which is the
69 equivalent edge-flame speed. This result is consistent for a range of fuels tested with the canonical
70 configuration of an axisymmetric fuel jet issuing into quiescent or co-flowing oxidizer, all at
71 atmospheric pressure.

72 In a parametric study of the effects of the co-flow velocity on lifted flames, Brown *et al.* [10], have
73 reported a transition in the stabilization mechanism of ethylene with increasing co-flow velocity U_c .
74 Below $U_c = 2.0 \text{ m.s}^{-1}$, increasing the jet velocity U_j at a given U_c increases the lift-off height h .
75 Above $U_c = 2.0 \text{ m.s}^{-1}$, increasing U_j at a given U_c decreases h , which is inconsistent with edge-flame
76 stabilization. It is notable that, at atmospheric pressure, this transition was observed for ethylene
77 only and not for methane and propane. This paper reports that such transition does indeed occur for
78 methane but at higher pressures of $P \geq 3 \text{ bar}$.

79 Studies of lifted flames at pressures different than atmospheric are scarce [11, 12, 13] but highly
80 relevant given that most practical combustors operate at elevated pressure and flames become lifted
81 either by design or induced by instability [14]. Wang *et al.* [12] reported that the lift-off height is
82 sensitive to pressure but only sub-atmospheric pressure conditions were examined. Kasabov *et al.*
83 [11] studied lifted flames at pressures up to 6 bar and observed that the lift-off height decreases
84 with pressures up to 6 bar. However, the configuration used by Kasabov *et al.* [11] featured
85 preheating, swirl, and a confinement, rendering the data not readily comparable to other studies
86 dealing with more canonical configurations.

87 This paper employs the new versatile high-pressure combustion duct (HPCD) at KAUST to study
88 the effects of pressure on both the lift-off heights and stabilization mechanisms of turbulent jet lifted
89 flames of methane. The pressure is increased from 1 bar to 7 bar and lifted flames are examined for

90 different co-flow and jet velocities. Flame chemiluminescence imaging as well as OH-PLIF and PIV
91 are employed to study the lift-off heights and the flame structure at the stabilization base. These data
92 are used to make inferences about the stabilization mechanisms aided by estimates of edge and
93 turbulent flame speeds.

94 2. Experimental setup and methods

Fig. 1: Schematic of the experimental setup.

95 A schematic of the experimental setup is shown in Fig. 1. Methane fuel issues from a 0.57-m long
 96 tube with inner and outer diameters of $D = 4.58$ mm and 6.35 mm, respectively. This is located in a
 97 co-flow nozzle with a 0.25-m diameter supplying a uniform air co-flow. The entire assembly sits in
 98 a high-pressure combustion duct (HPCD) with a 0.4-m inner diameter and equipped with six 0.15-m
 99 diameter fused silica windows.

100 The HPCD is air-cooled and its pressure is regulated by a dome-loaded back-pressure regulator.
 101 Therefore, co-flow air must be supplied continuously to dissipate the flame's thermal power and
 102 maintain the desired pressure set-point. The pressure range investigated is $1 \text{ bar} \leq P \leq 7 \text{ bar}$. The co-
 103 flow velocity range is $0.23 \text{ m.s}^{-1} \leq U_c \leq 0.60 \text{ m.s}^{-1}$. Temporal and spatial fluctuations of the co-flow
 104 velocity are less than 10 %. The methane mass flow rate is regulated with thermal mass flow
 105 controllers (Brooks SLA series) providing an accuracy better than 1 %.

106 The lift-off height h is measured by recording and post-processing the flames' OH*
 107 chemiluminescence signal. The latter is collected with a 1024×1024 intensified CCD camera
 108 (Princeton Instruments PI-MAX4), equipped with a UV-lens and a band-pass filter centered at
 109 320 nm (LaVision 1108760). A total of 700 images are recorded at a frame rate of 5 Hz for each
 110 condition, allowing statistical convergence of the data. Images are first binarized using Otsu's
 111 method [15] and are then averaged to yield the probability to find a flame for each pixel. Due to the

112 line-of-sight nature of these measurements, the height above the nozzle giving a probability of 0.5 at
113 a radius $r = 0$ defines h .

114 Joint OH-PLIF and PIV measurements are also conducted (see Fig. 1). The OH-PLIF system
115 comprises a Nd:YAG laser (Continuum Powerlite DLS9010) pumping a dye laser (Continuum
116 ND6000+UVT) at a repetition rate of 10 Hz. The output wavelength is tuned to the $Q_1(6)$ transition
117 of the OH radical at 282.930 nm and the available energy is 15 mJ per pulse. Images are collected
118 on an intensified CCD camera (Princeton Instruments PI-MAX4) and two lenses are used to relay
119 the OH-PLIF signal outside of the HPCD. The spatial resolution, measured using a logarithmic bar
120 pattern method [16], is better than 0.15 mm. The OH-PLIF laser sheet is 18-mm high and 0.17-mm
121 thick. Images are corrected for temporal and spatial variations of the laser energy density using a
122 photodiode and a CCD camera located outside the HPCD. The CCD camera images the fluorescence
123 of a portion of the laser sheet deviated into a cuvette filled with a mixture of ethanol and Coumarin
124 120.

125 The PIV system comprises a dual cavity Nd:YAG laser (Litron Nano L200-15 PIV) operating at
126 10 Hz. Mie scattering is imaged through the two relay lenses onto a 1376×1024 pixels dual frame
127 CCD camera (LaVision Imager Intense). Methane and air streams are seeded with silicone oil
128 (Huber SilOil M40.165.10). A multi-pass technique is used for image processing with a 32×32
129 pixels final interrogation area and a 50 % overlap, yielding a 0.44 mm vector spacing. The PIV laser
130 sheet is 1.0-mm thick to maintain particles within the laser sheet between the two pulses.

3. Results and discussion

First, the effects of pressure P and co-flow velocity U_c on the lift-off height h are presented for a range of jet velocities U_j . This is then followed by sample images of joint OH-PLIF and PIV and some statistics on the flame base velocities.

3.1. Effects of pressure

Fig. 2: Lift-off height h as a function of the jet velocity U_j for different pressures for $U_c = 0.30 \text{ m.s}^{-1}$ (a) and 0.60 m.s^{-1} (b).

Figure 2 plots h as a function of U_j for different pressures for $U_c = 0.30 \text{ m.s}^{-1}$ (a) and 0.60 m.s^{-1} (b). Error bars are omitted for clarity but h is measured with an accuracy better than $\pm 3 \text{ mm}$. At any given pressure and co-flow velocity, the relationship between h and U_j is linear, albeit the slope varies with pressure and co-flow velocity. The linear increase of lift-off height with jet velocity observed for $U_c = 0.30 \text{ m.s}^{-1}$ is not new and is consistent with the literature [1]. The novelty here is that this increase only prevails at low U_c where the lift-off height is somewhat low $h < 0.09 \text{ m}$. At higher $U_c = 0.6 \text{ m/s}$, the lift-off height shifts to $h > 0.09 \text{ m}$ if $P > 2 \text{ bar}$ and the slope transitions from positive to negative. In addition, it decreases rapidly and monotonously with pressure for $3 \text{ bar} \leq P \leq 6 \text{ bar}$.

Fig. 3: Lift-off height h as a function of the jet velocity U_j for different co-flow velocities for $P = 2$

bar (a) and 6 bar (b).

Figure 3 plots h as a function of U_j for $P = 2$ bar (a) and 6 bar (b) and a range of co-flow velocities. At 2 bar, the slope is positive, regardless of U_c . At 6 bar, the slope is positive for $U_c \leq 0.37$ m.s⁻¹ but is negative for $U_c \geq 0.49$ m.s⁻¹. For the same lift-off height $h \approx 0.08$ m, the slope is positive at 2 bar and $U_c = 0.6$ m.s⁻¹ and is negative at 6 bar and $U_c = 0.49$ m.s⁻¹. This transition from positive to negative slope was observed earlier for ethylene [10] (albeit at a higher co-flow velocity $U_c = 2.0$ m.s⁻¹) but not for methane (or propane). It is attributed to a transition in the flame's stabilization mechanism. Our findings show that the transition in stabilization behavior with increasing co-flow velocity occurs for other fuels although the threshold co-flow velocity and pressure at which it occurs seems to be fuel-dependent. Further details about the possible flame stabilization mechanisms are discussed in the next sections in light of OH-PLIF and PIV data coupled with Reynolds-Averaged Navier-Stokes equations (RANS) results.

Fig. 4: Example of instantaneous OH-PLIF and velocity field recorded for $P = 6 \text{ bar}$, $U_j = 8.1 \text{ m.s}^{-1}$, and $U_c = 0.30 \text{ m.s}^{-1}$ (a) or $U_c = 0.49 \text{ m.s}^{-1}$ (b).

158 First, data recorded for conditions where the slope is positive are analyzed. Figure 4a shows an
 159 example of instantaneous OH and velocity fields recorded for $P = 6 \text{ bar}$, $U_c = 0.30 \text{ m.s}^{-1}$, and
 160 $U_j = 8.1 \text{ m.s}^{-1}$. Velocity vectors are not available along the centerline because their magnitude is too
 161 large and particles escape the interrogation window during processing. The OH contour (black line)
 162 and the curve following the position of the maximum signal intensity along the flame (blue line) are
 163 also shown and the intersection defines the flame edge (blue circle). It is possible to probe the
 164 velocity component, along the normal of the flame contour, immediately upstream (0.5 mm) of the
 165 flame edge (red circle). This value is referred to as the edge-flame speed. This processing is

performed on 700 OH-PLIF and PIV images recorded for two operating conditions where the slope is positive: $P = 2$ bar, $U_c = 0.23$ m.s⁻¹, and $U_j = 13.5$ m.s⁻¹ and $P = 6$ bar, $U_c = 0.30$ m.s⁻¹, and $U_j = 8.1$ m.s⁻¹ (see Fig. 2).

Figure 5 shows the measured probability distributions of the axial (left column) and radial (middle column) positions of the flame edge as well as the edge flame speed (right column) for the 2 bar (top row) and 6 bar (bottom row) conditions. All the distributions are unimodal and the distributions of flame-edge position are consistent with those measured by others in the near-field at atmospheric pressure [17, 18]. Regardless of pressure, the edge-flame speed is bounded by 0 and 3 times the laminar flame speed S_L , whose values are computed here with Chemkin-Pro [19] and the USC-II chemistry mechanism [20]. The most probable edge-flame speed is close to the co-flow velocity in both cases. These features are consistent with observations of Muñiz and Mungal [7] for methane and ethylene lifted jet flames. This suggests that edge-flame propagation controls the flame stabilization up to 6 bar when $U_c \leq 0.30$ m.s⁻¹ for methane.

Figure 4b shows an example of instantaneous OH-PLIF and velocity fields recorded for $P = 6$ bar, $U_c = 0.49$ m.s⁻¹, and $U_j = 8.1$ m.s⁻¹, where the slope is negative (see Fig. 3). Due to the more intricate nature of flames that stabilize further away from the nozzle at this condition [8, 17, 21], it was not possible to accurately measure the velocity immediately upstream of the flame (note that OH images shown in Fig. 4 are typical samples and not selected extremes). Therefore, histograms of flame speed such as those shown in Fig. 5 could not be plotted. However, examination of many snapshots, such as the example shown in Fig. 4b, suggests that, in most cases, the flame stabilizes in a region where the velocity is larger than $3S_L$. This indicates that edge-flame propagation cannot be the mechanism driving flame stabilization for this condition where the slope is negative. Information provided by non-reactive RANS simulations is now used to reinforce this argument.

Fig. 5: Measured probability distributions of the axial (left column) and radial (middle column) positions of the flame edge as well as the edge-flame speed (right column) for the $P = 2$ bar, $U_c = 0.23$ m.s⁻¹, and $U_j = 13.5$ m.s⁻¹ (top row) and $P = 6$ bar, $U_c = 0.30$ m.s⁻¹, and $U_j = 8.1$ m.s⁻¹ (bottom row) conditions.

190 3.4. Stabilization mechanisms

191 For the edge-flame theory to apply, the flame edge must sit along the stoichiometric contour where
192 $u \leq 3S_L$ [5, 22]. Figure 6a shows the spatial distribution of mean axial velocity u and the iso-
193 contours of mean axial velocity $u = 3S_L$ (green lines) and equivalence ratio $\phi = 1$ (blue dashed line)
194 computed with RANS (see supplemental material for details on the RANS simulations) for the case:
195 $P = 6$ bar, $U_c = 0.30$ m.s⁻¹, and $U_j = 8.1$ m.s⁻¹. The measured flame edge position (blue circle)
196 overlaps well with the iso-contours $u = 3S_L$ and $\phi = 1$, meaning that edge-flame stabilization can
197 occur [7]. However, it is worth mentioning that the measured most probable edge-flame speed is
198 $1.7S_L$ and not $3S_L$ as predicted by RANS simulations. A potential explanation for this behavior is
199 that RANS simulations do not account for effects of heat release that redirect the flow and modify
200 the velocity immediately upstream of the flame edge [4, 5, 22, 23].

201 When the jet velocity is increased, the velocity along the stoichiometric contour increases and,
202 consequently, the flame is pushed downstream. This behavior explains the positive slope measured
203 in the near-field.

204 Conditions for which the slope is negative are now analyzed. Iso-contours $\phi = 1$ and $u = 3S_L$ are
205 shown in Fig. 6b for the case $P = 6$ bar, $U_c = 0.49$ m.s⁻¹, and $U_j = 8.1$ m.s⁻¹. Contrary to the case with
206 $U_c = 0.30$ m.s⁻¹, the two iso-contours do not overlap and the iso-contour $\phi = 1$ sits in a region where
207 $u > 3S_L$. The condition $\phi = 1$ and $u \leq 3S_L$ cannot be met and an edge-flame cannot stabilize [7],
208 pushing the flame downstream. A similar conclusion is reached for case $P = 6$ bar, $U_c = 0.60$ m.s⁻¹,
209 and $U_j = 8.1$ m.s⁻¹ (Fig. 6c) where the condition $u = 3S_L$ cannot be reached anywhere in the near-field
210 because $U_c > 3S_L = 0.52$ m.s⁻¹.

211 Figures 6d-f show the iso-contours $\phi = 0.4$ (black), 1.0 (blue), and 2.0 (green), spanning the
212 flammability range of methane [24], for the same three co-flow velocities examined previously but
213 for a larger region extending to $z/D = 32$. For $U_c = 0.30$ m.s⁻¹, the flame stabilizes at $h/D = 5.3$ (see
214 Fig. 2) where the width of the flammable region is very narrow and does not provide adequate
215 conditions to stabilize a premixed flame. Conversely, for $U_c = 0.49$ m.s⁻¹ and $U_c = 0.60$ m.s⁻¹, the

216 flame stabilizes at $h/D = 16.5$ and 27.3 , respectively, where the width of the flammable region is
 217 much larger because some mixing has occurred [25]. This suggests that the flames stabilized at
 218 $h/D = 16.5$ and 27.3 are premixed and that the transition from positive to negative slope of the
 219 h vs U_j curves is associated with a transition from edge-flame to premixed flame stabilization
 220 mechanisms

Fig. 6: (a)-(c) Spatial distribution of computed u and iso-contours $\phi = 1$ and $u = 3S_L$ for three conditions at 6 bar. (d)-(f) Spatial distribution of computed S_T and iso-contours $\phi = 0.4, 1$, and 2 .

Fig. 7: U_c as a function of U_j for different lift-off heights h for $P = 2$ bar (a) and 6 bar (b). Data interpolated from Fig. 3.

222 Inversion of the slopes of lift-off curves with increased co-flow velocity was observed earlier in
 223 [10] for ethylene. Data was not plotted with h vs U_j axes but instead with axes showing U_c vs U_j and
 224 where each curve corresponds to a given h . It is interesting to verify if data presented in Fig. 3 show
 225 a similar slope inversion if it is plotted with the alternative axes used in [10], U_c vs U_j . This is done
 226 in Fig. 7. Experimentally, it is difficult to maintain h while varying U_j and U_c . Changing the axes to
 227 yield Fig. 7 was achieved by interpolating between the data points showed in Fig. 3. The negative
 228 slopes observed in Figure 7a (2 bar) are similar to those reported earlier for methane [10] albeit for
 229 atmospheric pressure. Figure 7b clearly illustrates that at 6 bar and for lift-off heights above
 230 ~ 0.07 m, the slopes for methane transition from negative to positive. This is a new result not
 231 observed in [10] for methane and only observed for ethylene at 1 bar. There exists a critical co-flow
 232 velocity ($U_c \approx 0.50$ m.s⁻¹ for methane at 6 bar and $U_c \approx 2.0$ m.s⁻¹ for ethylene at 1 bar) above which
 233 the slope of the U_c vs U_j curves becomes positive. Transition corresponds to $h \approx 0.07$ m for methane

234 at 6 bar and $h \approx 0.09$ m for ethylene at 1 bar. These direct comparisons allow using the findings of
235 [10] to explain our experimental observations.

236 Using self-similarity laws, it was shown in [10] that the condition $u = S_T$, where u is the mean axial
237 velocity and S_T is a turbulent flame speed, was met at the base of ethylene flames with $U_c > 2.0$ m.s⁻¹.
238 ¹. This means that stabilization is controlled by turbulent premixed flame propagation. Using RANS
239 simulations, it is also possible to compute S_T . This is done here with the same expression used in [
240 10], repeated in Eq. (1) for convenience [26]:

$$241 \quad S_T = S_L + 0.62 S_L^{\frac{1}{2}} u^{\frac{1}{2}} \left(\frac{u' L_T}{\nu} \right)^{\frac{1}{4}} \quad (1)$$

242 where, u' is the velocity turbulent fluctuation, ν is the kinematic viscosity, and L_T is the integral
243 length scale computed using the correlation proposed by [26]. The color-scale in Figures 6d-f show
244 the spatial distribution of S_T . At any z/D , maximum S_T is found near the stoichiometric contour and
245 is $S_T \approx 1.0$ m.s⁻¹. Comparison with the computed axial velocity confirms that the condition $u \approx S_T$ is
246 met at the respective stabilization heights for cases with $U_c = 0.49$ m.s⁻¹ and $U_c = 0.60$ m.s⁻¹. From [
247 10] and RANS estimates, it can be inferred that turbulent premixed flame propagation is the
248 mechanism most likely responsible for flame stabilization for methane at 6 bar and $U_c \geq 0.49$ m.s⁻¹.
249 A more direct demonstration requires the combined knowledge of flame front position, equivalence
250 ratio, and velocity. However, these are very challenging measurements, particularly in high pressure
251 jet flames and, to the best of our knowledge, have never been achieved. Further imaging of relevant
252 scalars is planned for the future.

253 An explanation for the h vs U_j negative slope observed when turbulent premixed flame propagation
254 occurs is also suggested in [10]. When U_j is increased, both u and S_T increase at the flame base.
255 However, if U_c is large enough, S_T increases faster with U_j than u and the condition $u = S_T$ is met
256 further upstream, yielding a negative h vs U_j slope. This behavior is verified with RANS simulations
257 conducted here for methane at 6 bar and $U_c \geq 0.49$.

258 The slope inversion observed in Fig. 3b is gradual and there exists a transitional range of co-flow
259 velocities, roughly $0.37 \text{ m.s}^{-1} < U_c < 0.49 \text{ m.s}^{-1}$, where the flame is probably neither an edge-flame

260 nor a premixed turbulent flame but rather a partially-premixed flame. A full picture of this
 261 transitional range is not provided here.

262 In [10], a slope of zero for U_c vs U_j curves and ethylene at 1 bar corresponds to $U_c \approx 2.0 \text{ m.s}^{-1}$. This
 263 criterion corresponds to $U_c \approx 0.49 \text{ m.s}^{-1}$ for methane at 6 bar. In both cases, these values roughly
 264 correspond to $U_c = 3S_L$ implying that the critical co-flow velocity above which an edge-flame cannot
 265 stabilize is $U_c = 3S_L$. Other fuels and pressures will be investigated in the future to reinforce this
 266 statement.

267 Transition to turbulent premixed flame stabilization occurs when an edge-flame cannot stabilize.
 268 Therefore, increasing pressure promotes transition because S_L decreases with pressure [27]. At
 269 6 bar, $3S_L$ is 0.52 m.s^{-1} . At 1 and 2 bar, the critical co-flow velocities are $U_c = 3S_L = 1.02$ and
 270 0.78 m.s^{-1} , respectively, which were not investigated here. Data presented in [10] also show that for
 271 methane at 1 bar, and regardless of the jet velocity, blowout occurs for a co-flow velocity smaller
 272 than $U_c = 0.80 \text{ m.s}^{-1}$, which is smaller than $U_c = 3S_L = 1.02 \text{ m.s}^{-1}$. Flame blowout provides a
 273 competing mechanism and this explains why transition from edge-flame to premixed flame was
 274 never observed for methane at 1 bar.

275 Figure 3 showed that conditions with negative slopes are reached for $z < 0.07 \text{ m}$ ($z/D \approx 15$) at 6 bar.
 276 However, at 2 bar, flames stabilize up to $z = 0.09 \text{ m}$ ($z/D \approx 20$) but positive slopes are observed. This
 277 is because increasing pressure at fixed U_j and U_c increases the Reynolds number and enhances
 278 mixing, yielding conditions suitable for premixed flame propagation at earlier z .

279 4. Conclusions

280 Effects of pressure on the lift-off behavior of turbulent non-premixed methane jet flames were
281 analyzed. The main findings are:

- 282 • Effects of pressure depend on the co-flow velocity.
- 283 • For a relatively slow co-flow $U_c = 0.30 \text{ m.s}^{-1}$, edge flames are stabilized in the near-field
284 ($h < 0.06 \text{ m}$) for $1 \text{ bar} \leq P \leq 7 \text{ bar}$. The h vs U_j curves are linear and their slope is positive.
- 285 • When the co-flow velocity exceeds a critical value, function of fuel and pressure, the
286 condition $\phi = 1$ and $u \leq 3S_L$ cannot be met in the near-field. The flame is then pushed
287 downstream where sufficient mixing has occurred and the flame stabilization mechanism
288 transitions to turbulent premixed flame propagation. The h vs U_j curves are linear but their
289 slope becomes negative.
- 290 • Transition to turbulent premixed flame propagation is promoted by pressure due to reduced
291 laminar flame speed and enhanced mixing.
- 292 • Such transitional behavior was observed earlier for ethylene at atmospheric pressure but not
293 for methane. The present study shows that transition indeed occurs for methane if pressure is
294 increased at least to 3 bar. This suggests that transition can occur for any fuel providing that
295 specific conditions are met.

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302 **Figures Captions**

303 Fig. 1: Schematic of the experimental setup.

304 Fig. 2: Lift-off height h as a function of the jet velocity U_j for different pressures for $U_c = 0.30 \text{ m.s}^{-1}$
305 1 (a) and 0.60 m.s^{-1} (b).

306 Fig. 3: Lift-off height h as a function of the jet velocity U_j for different co-flow velocities for $P = 2$
307 bar (a) and 6 bar (b).

308 Fig. 4: Example of instantaneous OH-PLIF and velocity field recorded for $P = 6 \text{ bar}$, $U_j = 8.1 \text{ m.s}^{-1}$,
309 and $U_c = 0.30 \text{ m.s}^{-1}$ (a) or $U_c = 0.49 \text{ m.s}^{-1}$ (b).

310 Fig. 5: Measured probability distributions of the axial (left column) and radial (middle column)
311 positions of the flame edge as well as the edge-flame speed (right column) for the $P = 2 \text{ bar}$,
312 $U_c = 0.23 \text{ m.s}^{-1}$, and $U_j = 13.5 \text{ m.s}^{-1}$ (top row) and $P = 6 \text{ bar}$, $U_c = 0.30 \text{ m.s}^{-1}$, and $U_j = 8.1 \text{ m.s}^{-1}$
313 (bottom row) conditions.

314 Fig. 6: (a)-(c) Spatial distribution of computed u and iso-contours $\phi = 1$ and $u = 3S_L$ for three
315 conditions at 6 bar. (d)-(f) Spatial distribution of computed S_T and iso-contours $\phi = 0.4, 1$, and 2.

316 Fig. 7: U_c as a function of U_j for different lift-off heights h for $P = 2 \text{ bar}$ (a) and 6 bar (b). Data
317 interpolated from Fig. 3.

318

319 **List of Supplemental materials**

320 1. Details on RANS simulations:

321 Fig. S1: Details of the RANS geometry, mesh, and boundary conditions.

322 Fig. S2: Computed and measured radial profiles of mean (a) and r.m.s (b) axial velocity for

323 $P = 6$ bar, $U_c = 0.30$ m.s⁻¹, and $U_j = 8.1$ m.s⁻¹.

324 **Supplemental materials:** Details on RANS simulations

325 In this study, 2-D axisymmetric Reynolds-Averaged Navier-Stokes equations (RANS) isothermal
326 simulations are conducted with ANSYS® Fluent R17.1. Simulations are done with a pressure-based
327 solver in a second order upwind steady formulation. Closure relations for the Reynolds stress tensor
328 are provided by the $k-\varepsilon$ model in its standard version ($C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$, $S_{CT} = 0.7$). The mesh
329 includes 3.52 million identical square elements. The cell size is 0.12 mm. Details about the
330 computational geometry, mesh, and boundary conditions are available in Fig. S1. Examples of
331 comparisons between computed and measured mean and r.m.s velocity profiles are provided for
332 validation in Fig. S2.

Fig. S1: Details of the RANS geometry, mesh, and boundary conditions.

333

Fig. S2: Computed and measured radial profiles of mean (a) and r.m.s (b) axial velocity for $P = 6$ bar,

$U_c = 0.30 \text{ m.s}^{-1}$, and $U_j = 8.1 \text{ m.s}^{-1}$.