Effect of partial premixing on stabilization and local extinction of turbulent methane/air flames

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Abstract
The stabilization characteristics and local extinction structures of partially premixed methane/air flames were studied using simultaneous OH-PLIF/PIV techniques, and large eddy simulations employing a two-scalar flamelet model. Partial premixing was made in a mixing chamber comprised of two concentric tubes, where the degree of partial premixing of fuel and air was controlled by varying the mixing length of the chamber. At the exit of the mixing chamber a cone was mounted to stabilize the flames at high turbulence intensities. The stability regime of flames was determined for different degree of partial premixing and Reynolds numbers. It was found that in general partially premixed flames at low Reynolds numbers become more stable when the level of partial premixing of air to the fuel stream decreases. At high Reynolds numbers, for the presently studied burner configuration there is an optimal partial premixing level of air to the fuel stream at which the flame is most stable. OH-PLIF images revealed that for the stable flames not very close to the blowout regime, significant local extinction holes appear already. By increasing premixing air to fuel stream successively, local extinction holes grow in size leading to eventual flame blowout. Local flame extinction was found to frequently attain to locations where locally high velocity flows impinging to the flame. The local flame extinction poses a future challenge for model simulations and the present flames provide a possible test case for such study.

Introduction
Partially premixed flames, defined as flames where the compositions of the mixture vary from fuel-rich to stoichiometry and fuel-lean [1], are found in many engineering applications. In modern internal combustion engines using multiple injections of fuel to control emissions, partially premixed charge are typically formed before ignition. Due to the presence of rich, lean and stoichiometric mixtures in partially premixed flames, lean and rich premixed flame fronts exist in the leading front followed by the main diffusion flame [2-4]. The combustion characteristics of partially premixed flames are not well understood and modeling of partially premixed flames is challenging [1,2,5].

Local flame quenching and re-ignition in laminar and turbulent flames is an issue that has attracted the attention of recent research. Once a non-premixed flame is locally quenched, edge flame exists at the extremity of the reaction zones, where the flame progressively evolves to partially premixed flames [6]. The critical strain rate for quenching of partially premixed flames is influenced by the degree of partial premixing. For laminar flames, experimental and theoretical studies [7,8] using a counter flow configuration showed that partial premixing of fuel to the air stream can increase the quenching strain rate, whereas partial premixing of air to the fuel stream can decrease the critical quenching strain rate. In high Reynolds number turbulent flames, the quenching process is more complex. In an experimental study of partially premixed flames [9], it was shown that premixing of air to the fuel stream can decrease the flame stability regime, which is consistent with the laminar flame results of [7,8], however, a moderate partial premixing of air to the fuel stream can also improve the combustion stability. The fundamental physics behind this requires further investigation.

The main objectives of this study are to investigate the stability characteristics of turbulent partially premixed flames for different level of partial premixing, and to examine the structures of local extinction of flames at different conditions. To generate turbulent partially premixed flames at high turbulent intensities, the concentric flow conical flame burner described in [9-11] is adopted. Previous studies, at a particular partial premixing condition, have shown that the flame is stabilized in the cone due to the presence of a triple flame at the leading flame front in the recirculation region induced by the entrainment of ambient air to the cone [12,13]. The main part of the flame is of diffusion flame type. Experiments showed that the flame is very stable as compared with the corresponding jet burner (removal of the cone) and that the stabilization position of the leading flame front in the cone was found to be rather independent of the Reynolds numbers and the fuels [13].

In the present study we focus on the effect of the partial premixing on the flame structure and the flame dynamic using experimental measurements of simultaneous OH-PLIF and planar PIV for methane/air mixtures at different degree of partial premixing and an overall equivalence ratio of 3. In addition, a stereo PIV technique is employed to obtain 3D information about the flame. The results are compared with numerical simulations using a two-scalar flamelet large eddy simulation model (LES) described in [12].

Experimental setup

The burner used in this study consists of two parts, a variable size mixing chamber and a quartz-glass conical nozzle, Fig.1. The mixing chamber is composed of two concentric tubes with the inner diameters d=6.8 mm and D=9.7 mm for the inner tube and the outer tube, respectively. Their respective lip-thicknesses are 1.2 and 2.3 mm. The airflow is supplied through the inner tube, whereas the fuel-flow is supplied through the outer tube (annulus). By adjusting the inner tube position, one can vary the size of the chamber (the mixing length L) to determine the level of partial premixing in the flames. A quartz-glass conical nozzle, with a half cone angle of 26°, is mounted at the exit of the mixing chamber. Detailed information about the burner can be found in [9].

In order to characterize the flame structure and the dynamics of the leading flame fronts, simultaneous OH-PLIF and PIV is carried out inside the cone. OH radicals are excited through the $Q_1(8)$ transition at 283.6 nm and the resulting fluorescence emission is collected around 308 nm. A frequency doubled dye laser (Continuum ND60) with Rhodamine 590 as dye solution is used to provide the required output energy pulse at 283 nm. The dye laser is pumped by the second harmonic of a Nd:YAG laser system (Continuum NY82). A laser sheet with 50 mm height and pulse energy of 12 mJ per pulse is utilized. The fluorescence signal was collected perpendicularly to the laser sheet employing an ICCD camera (Princeton Instruments PI-MAX, 512×512 pixels) equipped with a UV-lens (UV-Nikkor, f=105 mm) after being filtered through a UG 11 filter (Schott, 3 mm) combined with a long pass filter at 295 nm. The spatial resolution was 0.13 mm/pixel.

For the planar PIV, seeding is excited twice at 20 Hz (for each measurement) using a double-pulsed Nd-YAG Class 4 Gemini-PIV laser (New Wave Research, Inc.) operated with 50 mJ double pulse (25mJ per pulse) and at 532 nm. The laser sheet thickness of each pulse is about 1~2 mm. The signal is collected perpendicularly to the laser sheet employing a CCD camera (LaVision FM3S Double Shutter, 1280×1024 pixels) equipped with a bandpass filter (532 nm) with transmission up to 95% in order to minimize the noise effects of background light. Seeding of Titanium Dioxide powder particles of 20 nm diameter (ρ=4.23 g/cm^3) is continuously injected in the air stream in the upstream of the mixing chamber. The data is processed using LaVision software (Davis 7) with 32×32 pixels interrogation windows and 50% area overlap leading to a spatial resolution of 1.2 mm.

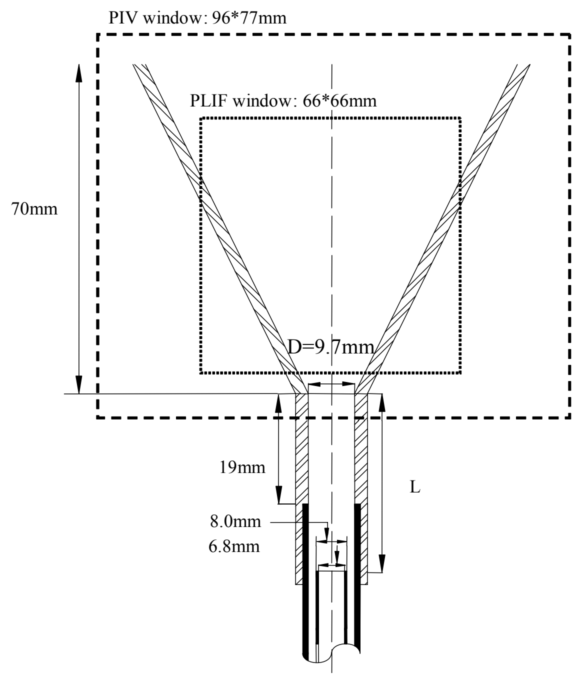

Figure 1. Schematic illustration of the burner and the PIV/OH-PLIF windows.

About 1000 images are recorded, simultaneously for the 2D OH-PLIF and PIV, for each L/D case at a rate of 2.5 Hz. All samples are used to compute statistics. The maximum intensity is observed for case L/D=7 with a value less than 10% higher than for L/D=3 and L/D=5. All OH signal intensities (instantaneous, mean and rms), after background noise subtraction, are normalized with respect to this overall maximum for consistency.

The planar PIV was tuned to best capture the seeding particles in the reaction zones. To generate statistical data of the flow field in a larger domain, a stereo PIV technique is used. The stereo PIV setup is a Dantec model with two CCD cameras and double pulse, two-head Nd:YAG laser with pulse energy of 50 mJ at the second harmonic 532 nm. The cameras are HiSense MkII PIV CCD cameras (model C8484-5205CP) with 1280 x 1024 CCD light sensitive array and equal number of storage cells. The objectives of the cameras are covered with interference filters at 532 nm with a bandwidth of 10 nm. The laser pulse duration is 6 ns and the pulse delay is controlled according to the flow velocity with a minimum of 0.2 μs.

Numerical modeling

A two-scalar flamelet model described in [12] is employed in the LES. The triple flame front propagation is modeled using a level-set G equation approach while the core of the flame is modeled using a diffusion flamelet approach. Local extinction is taken into account in flamelet tabulation using the scalar dissipation rate. The spatial filtered continuity, momentum and mixture fraction transport equations are discretized and solved on a staggered Cartesian grid using a fifth order WENO schemes for the convective terms and forth order central difference scheme for the diffusion terms. Time integration is made using a second order implicit scheme. The level-set G-equation is solved using a third order WENO scheme. Further details about the method and boundary conditions are referred to [12]. The computational domain outside the cone extends to $5.26D_0$ in the axial direction and $3.08D_0$ in the cross flow directions, respectively, where D_0 (=73 mm) is the diameter of the cone exit. In order to ensure finer resolution inside the cone grid stretching in the cross flow direction is used. This allows a resolution up to 0.35 mm in the cross flow directions while it is fixed to 0.75 mm in the axial direction.

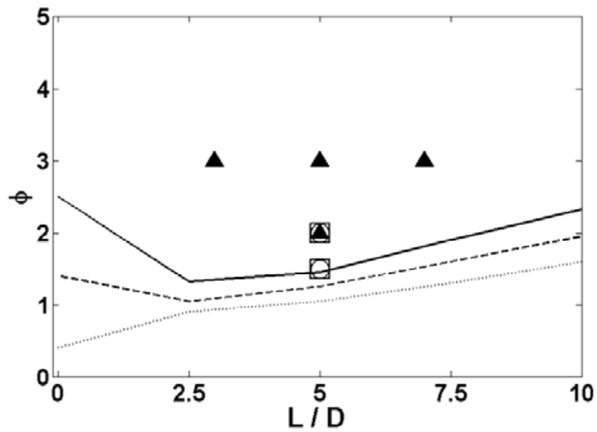

Figure 2. Stability regime of partially premixed flames stabilized in the conical burner at different Reynolds numbers, solid: Re=12000, dashed line: Re=8000, dot line: Re=4000. Symbols correspond to conditions of PIV and OH-PLIF measurements. Solid triangles: experimental points with simultaneous PIV/OH-PLIF; Square/circles: experimental points with only OH-PLIF.

Results and discussions

First, the stability behavior of the flame is studied by varying the mixing length (L/D) and the overall equivalence ratio successively for different Reynolds numbers. Figure 2 shows three lines defining the critical boundary between stable flames and blowout for the Reynolds numbers of 4000, 8000, and 12000, respectively. The Reynolds number, Re, is defined based on the bulk flow at the exit of the mixing chamber. At each point the equivalence ratio (Φ) is defined based on the mass of the fuel and the mass of air supplied to the inlets of the mixing chamber.

In Fig.2, stable flames correspond to the domain where the overall equivalence ratio is above a critical equivalence ratio, whereas below this critical equivalence ratio blowout occurs. It appears that when more air is premixed to the fuel stream while keeping the same Reynolds number and partial premixing (L/D), i.e. decreasing the overall equivalence ratio, the flame changes from the stable state to blowout. This phenomenon is consistent with the experimental and theoretical results for laminar counter flow flames [7,8], where it was shown that flame extinction becomes easier when air is premixed to the fuel stream, since it helps the oxygen leakage through the reaction zones to the fuel stream thereby decreasing the temperature and the radical pool in the reaction zones. Furthermore, one can notice in Fig.2 that with increasing Reynolds numbers, the critical equivalence ratio for flame stabilization increases. This means that with higher Reynolds numbers the flames are easier to be blown out when premixed air to the fuel stream.

The mixing length (L/D) determines the concentration gradient in the mixture at the exit of the mixing chamber, and as a result it controls the local degree of partial premixing and scalar dissipation rate in the reaction zone. The flame stability behavior is affected by the composition gradient in the fuel/air mixture. As shown in Fig.2, for the Reynolds number of 12000 flames, with L/D=0 (high composition gradient) and L/D=10 (low gradient), the critical equivalence ratio for flame extinction is relatively higher than the cases in between (with $0 < L/D < 10$). It appears that with certain composition gradient in the mixture (e.g. L/D=2.5) the stability of flame can be improved – with too low composition gradient or too high composition gradient the flames become less stable. For the Reynolds number of 4000 flames, however, increasing L/D (decreasing the composition gradient in the mixture) leads to a decrease of the stability domain, i.e., the larger the composition gradient in the mixture the larger the stability domain.

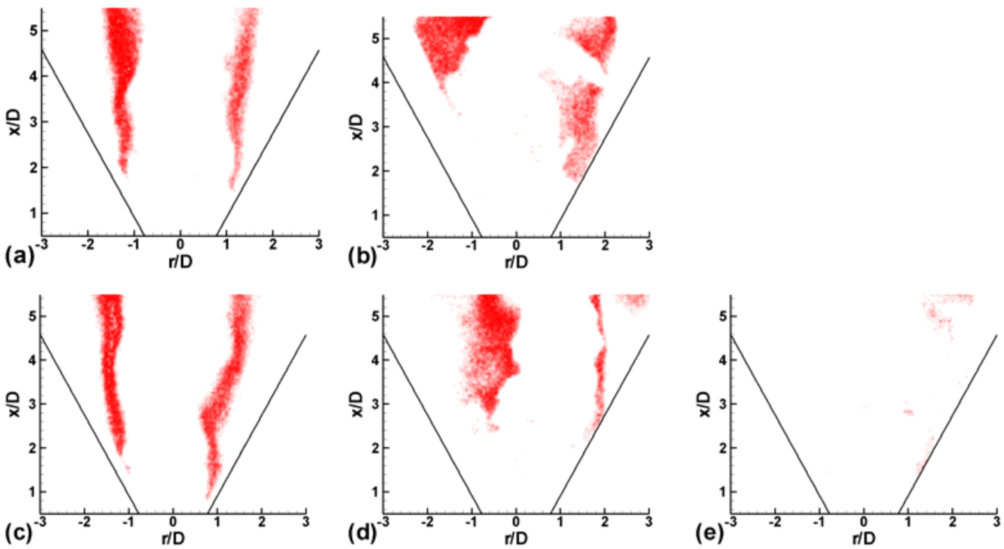

Figure 3. Snap-shots of OH-PLIF at different equivalence ratios and Reynolds numbers for L/D=5, (a) Φ=1.5, Re=4000; (b) Φ=1.5, Re=8000; (c) Φ=2, Re=4000; (d) Φ=2, Re=8000; (e) Φ=2, Re=12000.

To improve the understanding of the above flame stability behavior we examine the OH PLIF images taken at L/D=5 and Φ=1.5 and 2, Fig.3. At Φ=1.5 and Re=4000, the OH radicals are found in narrow and smooth zones. The flame is essentially laminar flamelet type. With Φ =1.5 and increasing the Reynolds number from 4000 to 8000, the OH radicals distribute in a much wider zone, and some part of the OH zone is disconnected indicating local flame extinction. Increasing the Reynolds number to 12000 with Φ=1.5 the flame is blown out, as indicated in Fig.2, where Φ=1.5 and L/D=5 is on the critical boundary between stable flame and blowout for the Re=12000 flames.

Similar trend can be seen for the Φ=2 flames (Fig.3c-e). For a given overall equivalence ratio (Φ=2) and L/D (=5), increasing the Reynolds number leads to local extinction and eventually blowout, thus moving up of the critical boundary of the stable flames and blowout to higher overall equivalence ratios. As seen in Fig.2, the flames shown in Fig.3 are close to blowout conditions. As the flames approach blowout conditions, the OH radicals are found in thicker zones.

Figure 4 shows the effect of L/D on the flame structures. At Re=12000 and Φ=3, the three flame cases (L/D=3, 5, 7) are in the stable flame regime as indicated in Fig.2. Despite this, one can notice the existence of local flame extinction holes in all these flames, Fig.4. It is typical when local extinction is encountered, the flow velocity is locally large as indicated by the small window at the low-right corner in each figure, e.g., Fig.4f. The local flow is typically impinging to the flame (shown in the figure as the OH layer), Fig.4a,c,f,i. It is likely that the locally high strain rate causes the local extinction of the flame. Direct numerical simulations of partially premixed flames [14] showed the same observation that local quenching is more often attained at the high strain rate regions.

Comparing the snap-shot of OH for the case of L/D=5 shown in Fig.4d-f and the corresponding one shown in Fig.3e, which has a lower equivalence ratio of Φ=2 and L/D=5 with Re=12000, one can identify the effect of partially premixing on OH broadening in the flames. Since the two flames have the same Reynolds number the intensities of turbulence in the two flames are on the same order; with high Φ and the same L/D, the composition gradient in the flames shown in Fig.4d-f is higher than that in Fig.3e. It appears that the OH layer is thinner with higher composition gradient. The same observation can be made from the three L/D flames shown in Fig.4. With smaller L/D, thus higher composition gradient, the OH layer is thinner, and the flame is more stable.

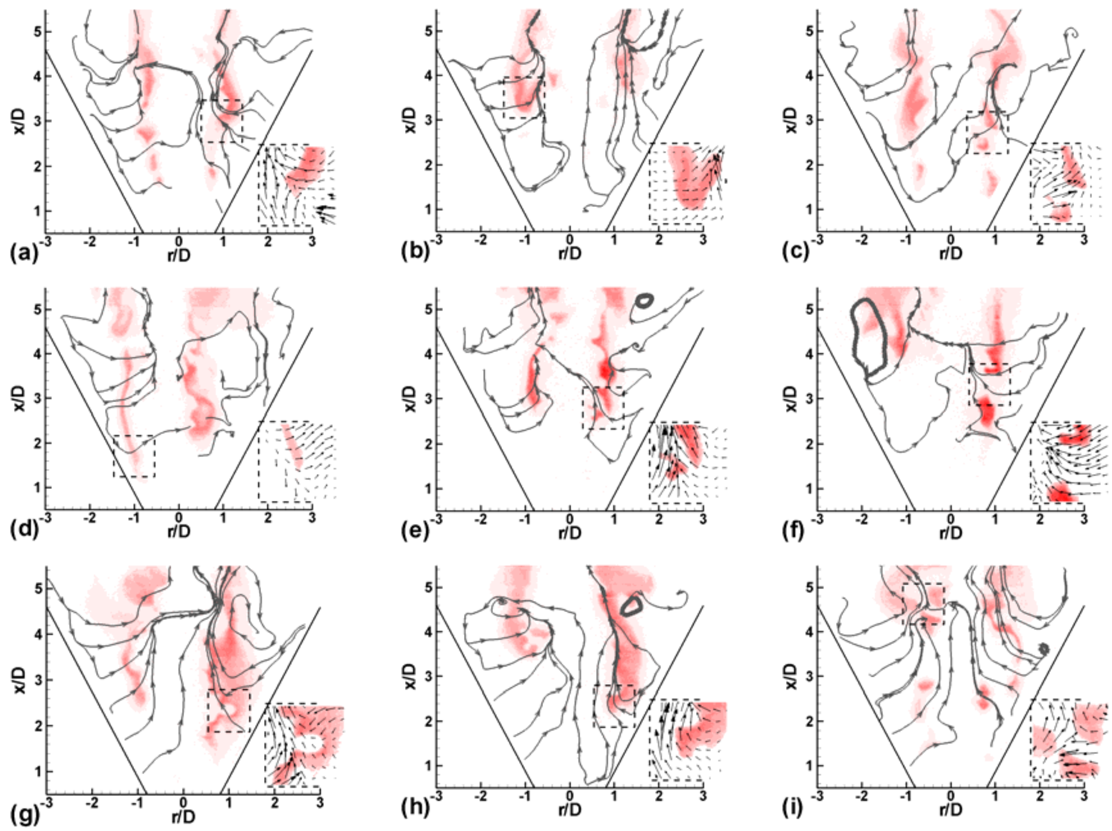

Figure 4. Normalized simultaneous OH-PLIF signal, instantaneous streamlines and velocity vectors from PIV (in the zoomed windows) showing three snap-shots for each flame with Φ=3, Re=12000 and different mixing lengths, L/D=3 (a,b,c), L/D=5 (d,e,f) and L/D=7 (g,h,i). Zoomed windows correspond to the marked regions (dashed line square).

One may note that the leading flame fronts are stabilized in the recirculation zones introduced by the entrained airflow near the wall of cone. The recirculation zones oscillate in the cone causing the flame fronts to oscillate, as seen in Figs.4d,e. The flame is flashing back to lower positions if the local flow is along downward direction (Fig.4d), or pushed upwards if the local flow is along upwards direction (Fig.4e).

LES using the level-set and mixture fraction formulation showed good agreement with the overall flame structures, especially the leading flame front stabilization in the recirculation zones introduced by the entrained ambient air for the case L/D=5 and Re=12000 [12]. The LES model is based on the assumption that the leading flame is essentially a premixed flame followed by a diffusion flame downstream (i.e. a triple-flame front). With this assumption the model can qualitatively simulate the stabilization of the leading flame in the recirculation zones [12,13].

Further comparison of the model results with the local extinction structures discussed above show that the model, which employs a stationary flamelet library approach with local extinction modeled using scalar dissipation rate, is not accurate in simulating the flame holes. Based on the LES data the scalar dissipation rate at the stoichiometric mixture fraction in the present flames is lower than 5 1/s, which is lower than the quenching scalar dissipation rate of the present flames estimated based on stationary laminar flamelet calculations. It has been observed in DNS studies that once a flame hole is formed, the required scalar dissipation rate for developing the flame holes further is lower than the quenching scalar dissipation of stationary flamelets [6]. To take into account such unsteady effect, potential models, e.g. those involving reaction progress variables [15-17] need to be developed and validated. Recently the progress variable approach of Bray et al. [15] has been applied to simulation of lifted jet flames and the approach shows promising features [18].

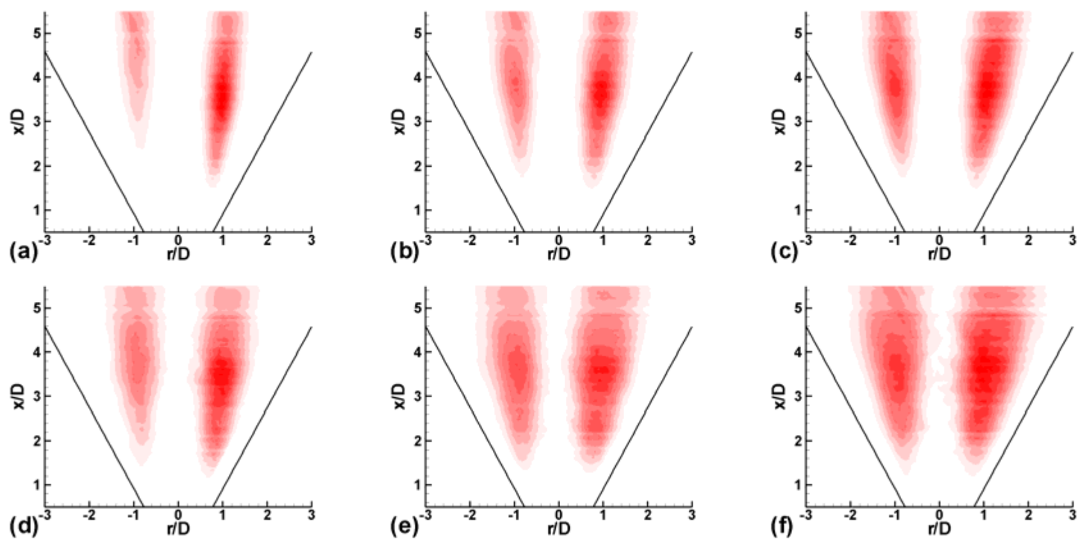

Figure 5. Normalized mean of OH-PLIF signal (a-c) and its rms (d-f) inside the cone for flames with Φ=3, Re=12000 and different mixing lengths, L/D=3 (a,d), L/D=5 (b,e) and L/D=7 (c,f).

To quantitatively compare the measurements and simulations, we examine the mean statistical properties of the flames. Figure 5 shows the normalized mean (a-c) and rms (d-e) of OH-PLIF signal for the flames with Φ=3 and Re=12000. The maximum signal intensity is almost the same in the three L/D cases. As an average, the OH signal is detected as early as x/D=1.5 for all cases. This shows that the mean leading flame front is stabilized in nearly the same position in the cone, independent of the degree of partial premixing. This observation is consistent with the previous experiments using different fuels and Reynolds numbers [13]. This is owing to the fact that the entrained airflow and recirculation zone structures are insensitive to the fuels and the degree of partial premixing when the Reynolds number is high enough so that the flow is developed to fully turbulent with self-similar large-scale recirculation zones formed from entrainment of the ambient air to the cone.

The effect of L/D is shown in the broadening of the mean OH layers. The mean and rms profile of OH signal is widened as the level of partial premixing increases. The mean flame thickness increases as x/D increases in all the cases. For the presently studied flames that have the same Reynolds numbers, the broadening of the OH layer as L/D increases is mainly an effect of the finite-rate chemistry. The broadening of OH layer is an indication of flames subjecting to flame extinction as seen in the snap-shot OH images in Figs.3 and 4.

Figure 6a shows the probability density function (PDF) of the leading flame fronts at a given height. As seen the highest PDF of flame front position is around x/D=1.5. The flames are seen to distribute between wide regions, 1<x/D<5. Most frequently the flames are found in a region 1.5<x/D<2. The three flames show similar distribution of the flame front position.

Figure 6b shows the PDF of number of OH signal extinction sites (i.e. of finding flame holes) on the right branches in the OH images for the three L/D cases. As seen, most frequently two flame-holes are found in these flames. The PDF of number of OH extinction sites in the L/D=7 flame is shifted slightly to having more flame holes, corresponding to the fact that the L/D=7 flame is closer to the critical boundary of flame blowout, Fig.2.

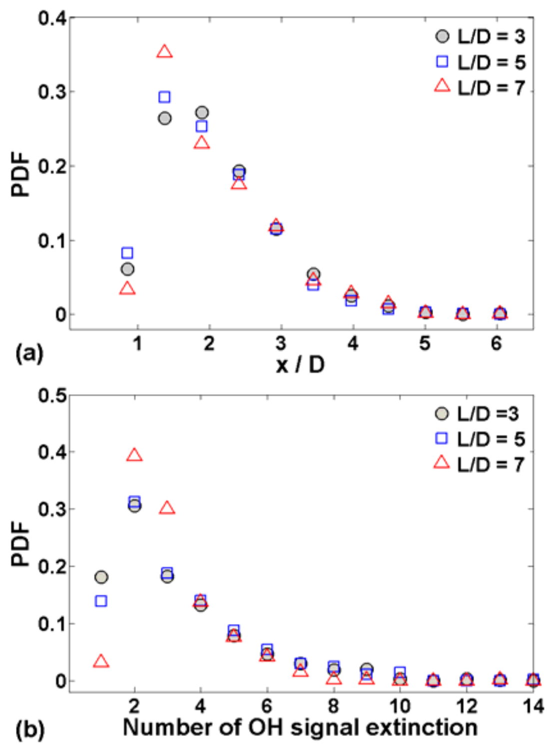

Figure 6. (a) PDF of flame front position and (b) PDF of OH signal extinction holes inside the cone for flames with Φ=3, Re=12000 and different mixing lengths. The OH signal threshold is taken as 5% of the maximum intensity, below which the flames are considered locally quenched.

In Fig.7c, the mean OH distribution from LES is compared with the PLIF measurements. Although they are two different quantities, the shapes of the OH profiles from PLIF and LES can be suitable for comparison. The inner boundary of the mean OH layer predicted in LES agrees well with the OH-PLF measurements. The thickness of the OH layer predicted from LES is larger than the measured ones. This is likely due to the use of stationary flamelet model [12] in the present LES. As discussed earlier, the present LES model could not properly simulate the local flame extinction. This may have contributed the overestimation of the OH concentration in the flames. The present flame offers a challenging test case for validation of partially premixed flames with local extinction.

The mean axial velocity along the axis and along radical direction at two axial positions from the stereo PIV and LES are shown in Fig.7. The velocity is normalized based on the bulk flow velocity at the exit of the mixing chamber (U_0=20 m/s). The axial velocity decreases along the burner axis, due to the expansion of the cone, Fig7a. The radial profile from LES shows negative axial velocity at x/D=2, indicating the flow recirculation, Fig.7b. The PIV could not capture the air entrainment properly due to the lack of seeding in the entrained air streams. In the experiments the axial velocity profile at x/D=4 is slightly asymmetric, due to the imperfection of the cone (it is not ideally axi-symmetric). Despite the discrepancy in the flame structure as seen in the OH layers, the mean flow velocity predicted by the flamelet LES model is in reasonably good agreement with experimental data (in particular the right branch of the profile), showing the relatively low sensitivity of the mean flow field prediction to combustion models.

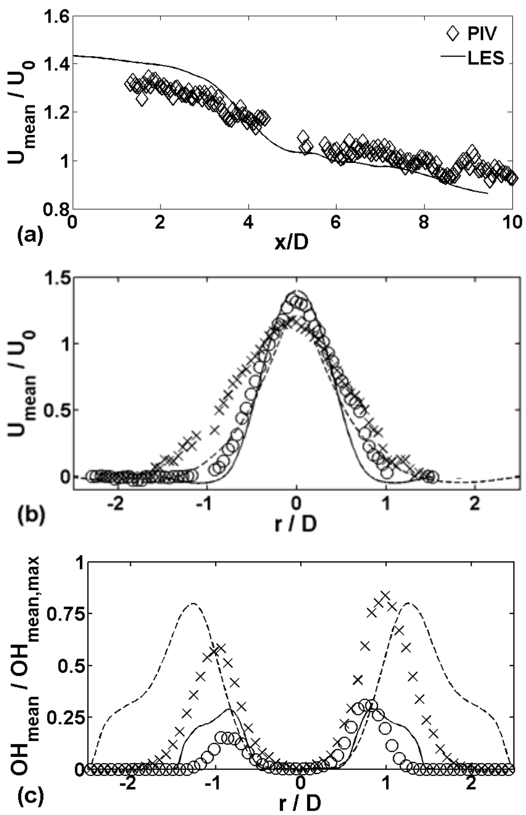

Figure 7. Mean axial velocity along the centre line (a), along radial direction (b), normalized OH-PLIF intensity, and normalized OH mole fraction from LES along radial direction (c), for flames with Φ=3, Re=12000 and L/D=5. Symbol/line notations at x/D=2: Exp (o), LES (solid line), at x/D=4: Exp (×), LES (dashed line).

From the experimental data and LES results an explanation of the flame stability behavior shown in Fig.2 can be made. Essentially, there are two controlling parameters that can be used to explain the flame extinction; one is the degree of partial premixing and the other is the scalar dissipation rate in the reaction zone (i.e. around stoichiometric mixture fraction). In the present flame configuration there are two surfaces with stoichiometric mixture fraction, one inner surface at the shear-layer between the inner airflow and the fuel flow from the annulus, and one outer surface between the fuel flow and the entrained ambient airflow. In our previous work [12] it was shown that the inner stoichiometric surface is not flammable due to too high convective flow. Thus, the scalar dissipation rate and the degree of local partial premixing at the outer stoichiometric surface are the controlling parameters for the present flames.

From laminar flame theory [8] it is known that the critical scalar dissipation rate at which the flame is quenched is a decreasing function of the degree of partial premixing. The flame is easier to quench if the scalar dissipation rate is high or the degree of premixing of air to the fuel flow is high. Increasing L/D would lead to higher degree of premixing and lower gradient of mixture fraction across the outer stoichiometric surface, as such it yields lower scalar dissipation rate. Therefore, it is expected that there is an intermediate L/D, at which both the scalar dissipation rate and the degree of partial premixing are moderate, and the flame is more stable. This is observed in the experiments shown in Fig.2, i.e. the flames with Reynolds number of 8000 and 12000.

For low Reynolds number flames with Reynolds number of 4000, however, the flame is essentially laminar and there is relatively weak flow/turbulence interaction. The scalar dissipation rate is low and the flame is relatively difficult to quench (unless very high degree of partial premixing of air to the fuel stream is made). In such a case, when increasing L/D the level of partial premixing of air to the fuel stream increases (with L/D=0 it is non-premixed flame) and thus, the flame become less stable as it requires lower scalar dissipation rate to quench the flame.

Conclusions

The effect of partial premixing on the stabilization and local extinction of partially premixed methane/air flames is studied in a concentric flow conical burner using stereo PIV, and simultaneous OH-PLIF and planar PIV. The experimental results are compared with model prediction using a two-scalar flamelet LES model. It is found that for a given Reynolds number partial premixing of air to the fuel stream decreases the flame stability. At high Reynolds numbers with a moderate gradient in the composition the flame is more stable, whereas at low Reynolds numbers, the lower the composition gradient the less stable the flame. The stability behavior is related to the OH-radical layer. When the flame is close to the critical condition of flame quenching the OH layer broadens and flame holes appear. The onset of flame holes is shown to be directly coupled to the local flow velocity and thereby the local strain rate. Due to the triple-flame propagation in the recirculation zones the leading flame front position is found to be insensitive to the partial premixing, and the highest PDF of leading flame position is found near the location where the measured mean axial velocity is negative. Although the flamelet LES model predicted rather well the mean flow field and the flame stabilization, it failed to predict the local extinction structures based on the stationary flamelet tabulation method using the scalar dissipation rate. The required critical strain rate for local extinction is likely lower than the one calculated from one dimension stationary laminar flames.

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References

[1] R.W. Bilger, S.B. Pope, K.N.C. Bray, J.F. Driscoll, Paradigms in turbulent combustion research, Proc. Combust. Inst. 30 (2005) 21-42.

[2] C.M. Müller, M. Breitbach, N. Peters, Partially premixed turbulent flame propagation in jet flames, Proc. Combust. Inst. 25 (1994) 1099-1106.
[3] G.R. Reutsch, L. Vervisch, A. Linan, Effect of heat release on triple flames, Phys. Fluids 7 (6) (1995) 1447-1454.
[4] P. Domingo, L. Vervisch, Triple flames and partially premixed combustion in autoignition of non-premixed turbulent mixtures, Proc. Combust. Inst. 26 (1996) 233-240.
[5] N. Peters, Turbulent Combustion, Cambridge University Press, 2000.
[6] V. Favier, L. Vervisch, Edge flames and partially premixed combustion in diffusion flame quenching, Combust. Flame 125 (2001) 788-803.
[7] R. Seiser, L. Truett, K. Seshadri, Extinction of partially premixed flames, Proc. Combust. Inst. 29 (2002) 1151-1557.
[8] K. Seshadri, X.S. Bai, Rate-ratio asymptotic analysis of the structure and extinction of partially premixed flames, Proc. Combust. Inst. 31 (2007) 1181-1188.
[9] F. El-Mahallawy, A. Abdelhafez, M. S. Mansour, Mixing and nozzle geometry effects on flame structure and stability, Combust. Sci. and Tech. 197 (2007) 249-263.
[10] M.S. Mansour, A study of turbulent partially premixed flames based on simultaneous imaging of velocity field and OH radical, Combust. Sci. Technol. 174 (2002) 47-78.
[11] M.S. Mansour, A concentric flow conical nozzle burner for highly stabilized partially premixed flames, Combust. Sci. Technol. 152 (2000) 115-145.
[12] B. Li, E. Baudoin, R. Yu, Z.W. Sun, Z.S. Li, X.S. Bai, M. Aldén, M.S. Mansour, Experimental and numerical study of a conical turbulent partially premixed flame, Proc. Combust. Inst. 23 (2009) 1811–1818.
[13] B. Yan, B. Li, E. Baudoin, C. Liu, Z.W. Sun, Z.S. Li, X.S. Bai, M. Aldén, G. Chen, M.S. Mansour, Structures and stabilization of low calorific value gas turbulent partially premixed flames in a conical burner, Exp. Therm. Fluid Sci. 34 (2010) 412-419.
[14] M. Yaldizli, K. Mehravaran, H. Mohammad, F. A. Jaberi, The structure of partially premixed methane flames in high-intensity turbulent flowsCombust. Flame 154 (2008) 692-714.
[15] K. Bray, P. Domingo, L. Vervisch, Role of the progress variable in models for partially premixed turbulent combustion, Combust. Flame 141 (2005) 431-437.
[16] C. D. Pierce, P. Moin, Progress-variable approach for large-eddy simulation of non-premixed turbulent combustion, J. Fluid Mech. 504 (2004) 73-97.
[17] M. Ihme, C. M. Cha, H. Pitsch, Prediction of local extinction and re-ignition effects in non-premixed turbulent combustion using a flamelet/progress variable approach, Proc. Combust. Inst., 30 (2005) 793-800.
[18] S. A. Ferraris, J.X. Wen, Large eddy simulation of a lifted turbulent jet flame Combust. Flame 150 (2007) 320-39.