Fuel Effects on the Stability of Turbulent Flames with Compositionally Inhomogeneous Inlets

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Abstract

This paper reports an analysis of the influence of fuels on the stabilization of turbulent piloted jet flames with inhomogeneous inlets. The burner is identical to that used earlier by the Sydney Group and employs two concentric tubes within the pilot stream. The inner tube, carrying fuel, can be recessed, leading to a varying degree of inhomogeneity in mixing with the outer air stream. Three fuels are tested: dimethyl ether (DME), liquefied petroleum gas (LPG), and compressed natural gas (CNG). It is found that improvement in flame stability at the optimal compositional inhomogeneity is highest for CNG and lowest for DME. Three possible reasons for this different enhancement in stability are investigated: mixing patterns, pilot effects, and fuel chemistry. Numerical simulations realized in the injection tube highlight similarities and differences in the mixing patterns for all three fuels and demonstrate that mixing cannot explain the different stability gains. Changing the heat release rates from the pilot affects the three fuels in similar ways and this also implies that the pilot stream is unlikely to be responsible for the observed differences. Fuel reactivity is identified as a key factor in enhancing stability at some optimal compositional inhomogeneity. This is confirmed by inference from joint images of PLIF-OH and PLIF-CH₂O collected at a repetition rate of 10 kHz in turbulent flames of DME, and from one-dimensional calculations of laminar flames using detailed chemistry for DME, CNG and LPG.

Keywords

Turbulent flames, piloted flames, inhomogeneous inlets, flame stability

1. Introduction

Turbulent flames with compositionally inhomogeneous inlets are common in gas turbines due to imperfect mixing between fuel and air [1-4]. This is an issue in non-premixed, as well as premixed, systems where instabilities propagate upstream of the combustor to induce pulsations in the fuel supply [3,4]. Fuel stratification is also induced in modern direct injection reciprocating engines where overall lean operation is sought while rich mixtures are maintained near the spark plug to ensure ignition [5-8]. These issues have prompted extensive research into laminar and turbulent stratified flames to resolve the effects of concentration gradients on the structure and stability of these flames [9-11]. These references as well as others are further discussed in the thorough review of Masri [12]. This work has recently been extended to cover not just flammable mixtures, but the entire mixture fraction space, using the Sydney piloted burner with compositionally inhomogeneous inlets [13-16].

A key feature of the burner is the ability to recess a fuel tube within an air annulus, providing a method of varying the inhomogeneity of the mixture at the jet exit plane. With methane or compressed natural gas (CNG), it was found that flame stability is enhanced significantly at some intermediate recess distance that produces optimal gradients in mixture fraction at the burner exit. Detailed measurements at locations near the pilot have revealed that this enhancement is largely due to the existence of premixed/stratified fuel samples augmenting the stabilizing effects of the pilot [13, 16]. The question addressed in this paper is whether such enhancements may be carried across to other fuels.

In addition to CNG, two other fuels are studied here: dimethyl ether (DME) and liquefied petroleum gas (LPG). DME is one of the simplest oxygenated fuels available for possible use in compression ignition (CI) engines [17]. It has low sooting propensity and lends itself to advanced laser diagnostics [18-20], including laser-induced fluorescence. This is employed here at a high repetition rate of 10 kHz to make joint measurements of formaldehyde (CH_2O) and OH in selected flames of

DME/N₂ (1/1 by vol.). Results from laminar flame calculations and non-reactive RANS simulations for mixtures of DME, CNG, and LPG are used to interpret experimental trends.

2. Stability limits

The burner is similar to that used in [13-16] for the investigation of piloted turbulent CH₄/air flames with inhomogeneous inlets. It includes two tubes surrounded by an annular pilot and an air co-flow, as shown in Fig. 1. The inner tube supplying the fuel can recess within the main tube which supplies air, hence varying the degree of mixing between fuel and air at the burner's exit plane. A recess distance $L_r = 300$ mm results in an almost homogeneous fuel/air mixture, as evidenced by the uniform mixture fraction radial profile, measured for CNG by Rayleigh scattering in [15], and shown in Fig. 2. The other extreme of $L_r = 0$ mm corresponds to the fully non-premixed limit. Intermediate recess distances yield non-uniform mixture fraction profiles with a broad range of equivalence ratios across the jet exit plane as for example case $L_r = 100$ mm, also shown in Fig. 2. A stoichiometric C₂H₂/H₂/air mixture with the same C/H ratio as the main fuel powers the pilot flames stabilized on a perforated plate. The sensitivity of the flame to pilot conditions such as composition, temperature, and velocity has recently been thoroughly studied and is reported elsewhere [29]. The burner assembly is located in a 15×15 cm square wind tunnel, providing a uniform air co-flow at 15 m/s.

Figure 1 goes here

Three fuels are used: DME, LPG which contains 90% C₃H₈ by volume (the balance being 5% butane and 5% other hydrocarbons), and CNG which is 88% CH₄ by volume (the balance being 7.8% ethylene, 1.9% carbon dioxide, 1.2% nitrogen, and 1.1% hydrogen, water, and other hydrocarbons). The mass flow rates are regulated with thermal mass flow controllers (Alicat MC series), with a relative accuracy better than 2%. Table 1 lists relevant properties for the cases studied here, including heat release from the pilot, H_p , and its unburnt velocity, U_{pu} , the volumetric air to

fuel ratio in the main jet, V_A/V_F , its overall equivalence ratio, ϕ_j , and bulk jet velocity ratio of air over fuel, U_A/U_F .

Figure 2 goes here

Table 1: Properties of pilot and jet flames for different fuels examined experimentally.

Fuel	Pilot settings				Jet settings		
	T_{ad} (K)	H_2/C_2H_2 (vol.)	H_p (kW)	U_{pu} (m.s ⁻¹)	V_A/V_F	ϕ_j	U_A/U_F
DME/N ₂	2492	2	1.1	1.5	2.5	2.9	1.1
			2.2	3.0			
CNG	2480	3	1.1	1.5	3.3	2.9	1.5
			2.2	3.1			
LPG	2507	1.67	1.1	1.5	8.3	2.9	3.7
			2.2	2.9			

Figure 3 shows measured bulk jet velocities U_j at blow-off versus recess distance L_r for DME/N₂ (1/1 by volume), LPG, and CNG. Dilution with N₂ was necessary since it was not possible to meter sufficiently high fuel flow rates to drive pure DME flames to blow-off. The air/fuel volumetric ratios used here are $V_A/V_F = 2.5, 3.3$, and 8.3 for DME/N₂, CNG, and LPG, respectively, leading to the same global equivalence ratio $\phi_j = 2.9$. The pilot heat release is $H_p = 1.1$ kW for all the cases shown in Fig. 3. Blow-off is defined here similar to Meares *et al.* [15], and is marked by the velocity U_{bo} at which an audible rumbling is heard, along with an almost non-existent flame just downstream of the pilot. While these limits are obtained from visual inspection, Meares *et al.* [15] found them to be very close to those obtained from thermocouple measurements. The following points are noted:

- At the full diffusion limit ($L_r = 0$ mm), all fuels show somewhat similar values of blow-off around 45 m.s^{-1} , while at the homogeneous limit ($L_r = 300$ mm), the lowest blow-off limit is for CNG at 87 m.s^{-1} , followed by LPG and DME/N₂ at 108 m.s^{-1} .
- The improvement in stability with recess distance varies with fuel and is highest for CNG and lowest for DME/N₂. This is defined by the ratio of the peak blow-off limit over that obtained at $L_r = 300$ mm, $G = U_{bo-max} / U_{bo-300}$. Values of G are $1.29, 1.12$, and 1.06 for CNG, LPG, and DME/N₂, respectively.

- The recess distance yielding peak stability is $L_r \approx 100$ mm for CNG, $L_r \approx 75$ mm for LPG, and $75 \text{ mm} \leq L_r \leq 150$ mm for DME/N₂. For these cases, the contribution of the pilot to the total heat release is 2.8% for CNG and DME/N₂ and 2.3% for LPG.

Figure 3 goes here

The reasons for these interesting differences in stability enhancement are analysed in the remainder of the paper. Detailed measurements performed at Sandia Laboratories with similar flames, but using pure methane as fuel [13, 16] revealed that improvement in stability is largely due to the existence of premixed/stratified combustion in the stabilization zone of the pilot. At the optimum recess distance, near-stoichiometric reactants formed near the pilot result in additional heat release that augments stabilization. While similar measurements are not available for the two other fuels studied here, it is clear from the stability limits shown in Fig. 3 that this effect of heat release augmentation is less evident for DME and LPG fuels.

3. Flame stabilisation effects

Three possible reasons for the differences in the flame stabilization enhancements observed in Fig. 3 are: (i) mixing upstream of the jet exit plane, (ii) effects of the pilot, and (iii) the chemistry of the fuel and its reactivity. Each of these aspects is now analysed separately with respect to the three fuels studied.

3.1 Effects of turbulent mixing

Turbulent mixing inside the injection tube is examined using pipe-flow calculations for non-reactive mixtures of fuel and air. Reynolds-averaged Navier-Stokes (RANS) simulations are conducted for axisymmetric pipe flows employing ANSYS Fluent R16.1 with k- ϵ model for turbulence but with $C\epsilon_1 = 1.6$ instead of 1.44, as is acknowledged for jet flows [21]. Figure 2 shows measured and

computed radial profiles of mean axial velocity and mixture fraction for a CNG/air jet with two recess distances $L_r = 100$ and 300 mm, and a bulk velocity of $U_j = 82 \text{ m.s}^{-1}$. The experimental data in Fig. 2 is taken from [15]. Mixture fraction and velocity were measured under non-reactive conditions with a Rayleigh scattering technique and Laser Doppler Velocimetry, respectively. While measurements are not performed for DME and LPG, the calculations presented here for CNG agree well with measurements and provide the level of confidence required for the comparisons discussed next.

Figure 4 shows the local equivalence ratio computed at $r/D = 0.5$ and $x/D = 0$, as a function of L_r for DME/N₂, CNG, and LPG. Calculations are presented for two bulk jet velocities of 100 and 160 m.s^{-1} . It is evident from the profiles in Fig. 4 that, while the bulk jet velocity has only a minor influence on the axial profile of equivalence ratio, the effects of fuel composition are significant. At $L_r = 300$ mm, the equivalence ratios at the jet exit plane plateau only for LPG, while the other two fuels are gradually approaching the fully mixed limit of $\phi_f = 2.9$. This mixing trend is consistent with the bulk jet velocity ratio between the air and fuel tubes (U_A/U_F), which is 1.1 for DME/N₂, 1.5 for CNG, and 3.7 for LPG. Large velocity ratios increase the shear intensity between the two streams and enhance mixing. This also impacts the recess distance that results in a near stoichiometric mixture near the pilot. Figure 4 shows that a mixture of $\phi = 1.1$ at the exit plane and $r/D = 0.5$ (horizontal dashed line) is formed at recess distances of $L_r = 68$ mm for LPG, $L_r = 112$ mm for CNG, and $L_r = 134$ mm for DME/N₂. These estimates confirm that turbulent mixing patterns for the three fuels are consistent and lead (at the relevant recess distance) to the formation of significant inhomogeneity and hence burnable mixture near the pilot. Yet, this does not lead to the same improvement in stability for all fuels, confirming that mixing alone is not sufficient to explain the differences noted in Fig. 3.

Figure 4 goes here

3.2 Effects of pilot

This section examines the effects of changing the pilot heat release on flame stability. Figure 5 shows stability curves for CNG and LPG for two pilot settings $H_p = 1.1$ and 2.2 kW. Due to limitations in metering high flow rates of DME, it was not possible to reach blow-off for the higher pilot heat release of 2.2 kW and produce the stability curve in Fig. 5. CNG and LPG trend similarly for both pilot settings, but, as expected, the blow-off velocities are higher for $H_p = 2.2$ kW [22]. It is also interesting to note that, when the pilot heat release is doubled, the stability gain G for these two fuels drops from $G = 1.29$ to 1.20 for CNG and from $G = 1.12$ to 1.08 for LPG. Later in the text, this behavior is attributed to the larger strain rate experienced by the flame with $H_p = 2.2$ kW. Figures 2 and 5 clearly show that CNG and LPG feature different stability gains for the same pilot heat release. This, in addition to the fact that the adiabatic flame temperatures T_{ad} of all pilots are similar (see Tab. 1), implies that the pilot flame properties do not explain the different stability gains obtained for the three different fuels.

Figure 5 goes here

3.3 Effects of fuel and its chemistry

Aspects of fuel chemistry and structure of reaction fronts in the stabilization zones are examined here using (i) joint planar imaging of OH and CH₂O performed in selected DME/N₂ flames; these are referenced against earlier measurements in CH₄ flames [13, 16], and (ii) laminar flame calculations using detailed chemical kinetics for DME/N₂, LPG, and CNG over a range of strain rates.

3.3.1 LIF-imaging of OH and CH₂O

The PLIF-OH set-up is standard and described in detail in [23]. Measurements are complemented by simultaneous imaging of PLIF-CH₂O. Formaldehyde is excited by the third harmonic at 355 nm of a Nd:YAG (Edgewave HD30II-E), also fired at a repetition rate of 10 kHz with a power output of approximately 36 W and a pulse duration of approximately 7 ns. While not needed here, high-speed LIF is used instead of low-speed because this work is part of a larger program requiring time resolution. The signal is detected with a 768×768 pixel high-speed CMOS camera (LaVision HSS6), coupled to a two-stage intensifier (LaVision High-Speed IRO), and equipped with a 409 nm longpass filter (Semrock FF02-409/LP- 25) and a 500 nm shortpass filter (CVI SPF-500-50.0M). The signal-to-noise ratio is SNR = 8 in the peak region of a $\phi = 2.2$ laminar Bunsen flame. The image resolution is 57 $\mu\text{m}/\text{pixel}$. Comparing calculated and measured CH₂O layers in the Bunsen flame shows that a Lorentzian function of 0.4-mm full width at half maximum represents well the thickening due to the collection apparatus, giving an idea of the PLIF-CH₂O spatial resolution. Laser sheets have a 30 mm height and a thickness of approximately 200 μm . Ten independent sets of 200 snapshot images of both PLIF-OH and PLIF-CH₂O are recorded for each case investigated. The lasers pulse energies are measured with photo-sensors to correct individual PLIF images for shot-to-shot variations. Mean OH and CH₂O sheet profiles, needed to correct for spatial inhomogeneities, were measured in the burnt gases of a stoichiometric premixed flat flame and in a rich Bunsen flame, respectively.

Figure 6 shows examples of the distribution of LIF-OH and LIF-CH₂O in a DME/N₂/air flame measured downstream of the burner's exit plane for two recess distances $L_r = 100$ and 300 mm and a bulk jet velocity $U_j = 90 \text{ m.s}^{-1}$. These are marked by stars in Fig. 3 and correspond to $U_j/U_{bo-max} = 0.8$ and $H_p = 1.1 \text{ kW}$. The regions of the flow featuring large quantities of CH₂O appear in blue. It is assumed that CH₂O is formed via oxidation of DME and that pyrolysis is negligible. While we cannot fully discount this possibility, PLIF-CH₂O images show that near the burner lip

($x/D < 0.5$), the thickness of the CH_2O layer is small ($\delta_{\text{CH}_2\text{O}} \ll 1$ mm) implying that CH_2O production by pyrolysis due to contact with the hot pilot tube is not significant. Given the large jet velocities examined here, the residence time of fuel in contact with hot surfaces is too short (roughly 100 μs) to allow slow pyrolysis chemical reactions, with a time scale of around 100 ms [24], to occur. It should be noted that the objective is not here to infer the distributions of absolute OH and CH_2O concentrations using PLIF but rather to compare the main features of these distributions when the fuel tube recess distance is varied. The original intention of this experiment was to measure heat release through the product $[\text{OH}][\text{CH}_2\text{O}]$. However, in the transverse direction, the LIF-OH laser sheet energy distribution features a Gaussian-like shape with tails spanning over few hundreds of micrometers. This results in the detection of a weak PLIF-OH signal that originates from OH molecules located outside the central plane of the laser sheet. Often, this unwanted signal overlaps with genuine PLIF- CH_2O , resulting in non-physical but non-negligible $[\text{OH}][\text{CH}_2\text{O}]$ product, which is hard to differentiate from actual heat release, hence the product $[\text{OH}][\text{CH}_2\text{O}]$ will not be used in this paper. This experiment however shows that for the same height above the burner, the CH_2O layer appears to be consistently thicker for the homogeneous case at $L_r = 300$ mm, suggesting that burning conditions at $L_r = 100$ mm are different. This is now confirmed using a statistical analysis of the thickness of measured CH_2O layers.

Figure 6 goes here

Figure 7 (left) shows the probability density function (PDF) of the thickness $\delta_{\text{CH}_2\text{O}}$ of CH_2O layers measured at six heights above the burner's exit plane for the two DME/ N_2 flames studied here. The thickness $\delta_{\text{CH}_2\text{O}}$ is defined as the distance between the two radial positions r where the PLIF- CH_2O signal reaches 10% of the maximum image pixel intensity. A total of 2000 PLIF snapshots were taken at each position and these show that the distribution of $\delta_{\text{CH}_2\text{O}}$ is monomodal. Figure 7 (left)

confirms that δ_{CH_2O} is globally larger for the homogeneous case at $L_r = 300$ mm than for $L_r = 100$ mm, with the difference reaching 34% at $x/D = 4$.

A comparable statistical analysis is conducted in Fig. 7 (right) for the OH layer thickness δ_{OH} . The distribution of δ_{OH} is also monomodal but is overall narrower than the distribution of δ_{CH_2O} . Broadening of distributions is mainly attributed to turbulence, which is lower in the hot burnt gases featuring higher OH concentration and viscosity. Figure 7 (right) also shows that δ_{OH} is globally smaller for the homogeneous case at $L_r = 300$ mm than for $L_r = 100$ mm, following the opposite trend as δ_{CH_2O} . These trends imply that the burning conditions are different for these two recess distances. Measurements are conducted here for a fixed jet velocity $U_j = 90 \text{ m.s}^{-1}$. This suggests that both flames experience comparable strain rates and that the different OH and CH₂O layers thicknesses are attributed to different burning equivalent ratios. This is consistent with previous measurements [15] (see Fig. 2) showing that the mixture fraction near the pilot, $x/D \approx 0.5$, differs for the recess distances $L_r = 100$ and 300 mm. However, insights from qualitative PLIF images alone are not sufficient and confirmation is now obtained by comparing PLIF results to 1-D laminar simulations.

Figure 7 goes here

3.3.2 Laminar flame calculations

Two sets of 1-D laminar counterflow simulations were carried out with the software CHEMKIN and the detailed chemistry mechanism for DME from Zhao *et al.* [24]. First, a DME/N₂/air homogeneous mixture at $T = 298$ K burns in contact with a mixture corresponding to the composition and temperature of the pilot flame burnt gases. Simulations with DME/N₂ are conducted for a range of air to fuel ratios $2.5 \leq V_A/V_F \leq 7.1$ and strain rates $a = [100, 500, 2000] \text{ s}^{-1}$. The cases $V_A/V_F = 2.5$ and 7.1 correspond to equivalence ratios of $\phi = 2.9$ and 1, respectively. Simulations for CNG and LPG are also performed with the AramcoMech-1.3 [25] mechanism. In a

second set of simulations, the DME/N₂/air mixture is opposed to a cold stream of air with $a = [100, 250, 500] \text{ s}^{-1}$. LIF-CH₂O signals were simulated based on the computed temperature and species concentrations, with the Boltzmann fraction population of the ground state and the temperature-dependent quenching rates obtained from [26, 27].

By analogy with PLIF experiments, the calculated δ_{CH_2O} is the separation distance between the two flame coordinates x where the CH₂O simulated fluorescence signal reaches 10% of the peak. Figure 8 plots δ_{CH_2O} versus V_A/V_F for $a = [100, 500, 2000] \text{ s}^{-1}$ in simulations opposing DME/N₂/air homogeneous mixture to hot burnt gases. It is not possible to compute a finite OH layer thickness with these simulations because of the presence of OH molecules in the stream of hot products. Another set of simulations is therefore conducted for mixtures opposed to cold air, for which it is possible to compute δ_{OH} . This choice is justified because the hierarchy between layers thicknesses for different fuel tube recess distances is conserved when the distance x/D is increased and the jet gradually ceases to interact with the pilot stream to the benefit of coflow air (see Figs. 6 and 7). It was also verified that δ_{CH_2O} follows the same trends with equivalence ratio and strain rate in simulations with hot products or cold air, giving additional confidence that either of these simulations can be used to interpret the experimental data shown in Figs. 6 and 7.

Independent of the strain rate, δ_{CH_2O} decreases when V_A/V_F increases, *i.e.* when the equivalence ratio ϕ decreases, while δ_{OH} follows the opposite trend. These opposing trends are also observed in the measured δ_{CH_2O} and δ_{OH} reported in Fig. 7 for cases $L_r = 100$ and 300 mm, which confirms that the different CH₂O and OH layers thicknesses measured at these two recess distances are attributed to different burning equivalence ratios.

Figure 8 goes here

These observations corroborates findings of Fig. 4 showing that decreasing the recess distance below $L_r = 300$ mm allows reducing the local equivalence ratio of the mixture in contact with the pilot towards unity, which benefits stability [13].

Figure 9 plots the normalized integrated heat release versus the equivalence ratio computed in 1-D laminar flames of CNG, LPG, and DME/N₂ counter-flowing against hot burnt gases. Two strain rates of $a = 100 \text{ s}^{-1}$ and 500 s^{-1} are shown for each fuel and the results are normalized by the maximum heat release which occurs at $\phi = 1.1$.

Taking the case of $a = 500 \text{ s}^{-1}$, the equivalence ratio at which 20% of the maximum heat release is reached (dashed horizontal line) occurs at $\phi = 2.1$, 2.7, and 3.0 for CNG, LPG, and DME/N₂, respectively. These trends are also consistent for the lower strain rates of $a = 100 \text{ s}^{-1}$, also shown in Fig. 9. This implies that burning with sufficient heat release can be sustained in much richer mixtures of DME/N₂ (and LPG to a lesser extent) than in CNG. The analogy with the turbulent flames is that a rich homogeneous DME/N₂/air mixture (such as is produced with $L_r = 300$ mm), in contact with the pilot flame, is more likely to sustain combustion than rich mixtures of CNG/air. This also implies that DME/N₂ derives little benefit by further premixing to stoichiometric levels, since it is already reactive, which explains the relatively low gain of stability observed in Fig. 3 for intermediate recess distances. Direct comparisons between measurements in turbulent flames and laminar simulations must always be conducted carefully. However, the reasoning presented in this section is based on the reactivity of the different fuels as a function of the equivalence ratio in laminar simulations. Carrying this conclusion to the turbulent flames studied is not unreasonable since the region of concern is close to the pilot where, locally, the reactive interface of the mixture and the pilot is not unlike a strained laminar flamelet.

Figure 9 goes here

Figure 9 also shows that the normalized integrated heat release curves flatten with increasing strain rates. When a is large, the reaction zone is thinner and the flame front enters the zone of influence of the hot products [28], providing support to the otherwise non-flammable rich mixture. Figure 5 shows that blow-off velocities increase when the pilot heat release increases, leading to a higher strain rate experienced by the flames. Moreover, the stability gain drops when the pilot heat release increases. This is consistent with the observed wider range of equivalence ratios producing a significant heat release when a increases. It also confirms the importance of fuel reactivity in enhancing stability by placing near stoichiometric mixtures close to the pilot.

5. Conclusions

The influence of compositional inhomogeneities on the stability of turbulent jet piloted flames was analyzed for CNG, LPG, and DME/N₂ fuels. After CH₄, it is now confirmed that inhomogeneous inlets allow increasing the flame stability for other fuels. However, the gain of stability is smaller for LPG and DME/N₂ in comparison to CNG or CH₄. It was shown that:

- While the pilot flame settings have a significant influence on blow-off velocities, slight differences in pilot composition cannot explain the different stability gain observed for the three fuels.
- Differences in the mixing patterns in the injection tube exist between the three fuels examined, leading to different optimal recess distances. However, these are not responsible for the variation of the stability gain observed.
- Non-reactive RANS simulations and combined PLIF-OH/CH₂O experiments show that the improvement of stability obtained for intermediate recess distances is attributed to the formation of a near stoichiometric mixture close to the pilot flame, which provides additional

heat release at the base of the flame. These findings corroborate observations based on previous detailed measurements realized in Sandia with inhomogeneous CH₄/air jets.

- Finally, 1-D simulations demonstrate that fuel reactivity is the dominant parameter that dictates the differences noted between fuels. This reactivity, which is a function of equivalence ratio and therefore recess distance in turbulent jet flames, controls the relative gain in stability induced by compositionally inhomogeneous inlets. Rich homogeneous CNG/air mixtures do not burn well in contact with the pilot, leading to a large drop of the blow-off velocity in comparison to inhomogeneous cases with intermediate recess distances, where near-stoichiometric mixtures are in contact with the pilot. Rich homogeneous DME/N₂/air mixtures (LPG/air mixtures to a lesser extent) are more reactive, leading to a higher blow-off velocity for large recess distances and a reduced gain of stability when resorting to inhomogeneous inlets.

6. Acknowledgements

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Table Captions

Table 1: Properties of pilot and jet flames for different fuels examined experimentally.

Figures Captions

Figure 1: Cross-section schematic of burner assembly showing pilot, annulus air, and central fuel streams.

Figure 2: Computed and measured [15] mixture fraction and axial velocity radial profiles at burner exit plane for CNG, $V_A/V_F = 2$, $U_j = 82 \text{ m.s}^{-1}$, and $L_r = 100 \text{ mm}$ (black) and $L_r = 300 \text{ mm}$ (red).

Figure 3: Measured bulk jet velocities at blow-off U_{bo} versus recess distance L_r for DME/N₂ (1/1 by volume), LPG, and CNG and $H_p = 1.1 \text{ kW}$. Stars denote conditions for PLIF experiments.

Figure 4: Computed equivalence ratio along pilot tube wall, $r/D = 0.5$ and $x/D = 0$, as a function of L_r for DME/N₂, CNG, and LPG and two bulk jet velocities $U_j = 100$ and 160 m.s^{-1} .

Figure 5: Measured bulk jet velocities at blow-off U_{bo} versus the recess distance L_r for LPG and CNG and two pilot heat release $H_p = 1.1$ and 2.2 kW .

Figure 6: CH₂O (blue colorbar) and OH (red colorbar) PLIF intensities for two recess distances $L_r = 100$ and 300 mm and $U_j = 90 \text{ m.s}^{-1}$. The three windows separated by horizontal dash-dotted lines are not synchronized.

Figure 7: Measured probability density function of δ_{CH_2O} (left) and δ_{OH} (right) for six heights above the burner's exit plane, two recess distances $L_r = 100$ and 300 mm , and $U_j = 90 \text{ m.s}^{-1}$.

Figure 8: Simulated δ_{CH_2O} (squares) and δ_{OH} (circles) versus V_A/V_F for different strain rates.

Figure 9: Normalized integrated heat release as a function of equivalence ratio for two strain rates $a = 100$ and 500 s^{-1} in 1-D laminar counterflow flames opposing DME/N₂/air, CNG/air, and LPG/air mixtures to hot burnt gases..

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