FLAME STABILIZATION AERODYNAMICS AND EMISSIONS PERFORMANCE AT STRATIFIED OR FULLY PREMIXED INLET MIXTURE CONDITIONS

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Abstract. The work presents a comparative study of the performance between fully-premixed and stratified propane flames stabilized in a disk burner configuration operating with a swirl coflow over a range of stoichiometric to ultra-lean conditions. Radial equivalence ratio gradients are regulated by staged premixing of propane and air within a double cavity formed along three concentric disks. Measurements of temperatures, OH* and CH* chemiluminescence, FTIR and gas analysis provided information on the impact of the variable inlet fuel-air profile and its interaction with the swirling coflow on flame structure and burner emissions performance.

Keywords: partially premixed, stratified, full premixed, flame stabilization, burner performance, emissions

INTRODUCTION

To extend the environmentally friendly scope of gas turbine operation and their capability to adapt to a wider range of commercial alternative fuel types, investigations into the flame stabilization performance over a range of relevant inlet conditions (e.g. equivalence ratio gradients, preheat) are warranted. The control and extension of the stability margin without compromising emission levels and safety requirements is a key technology issue in the (re-) design and optimization of current combustors along these lines.

Lean premixed conditions have so far become widely exploited to benefit from their potential for an improved trade-off in soot/CO/NOx emissions (Dunn-Rankin et al. 2008). In more recent years controlled partial premixing of the fuel-air mixture has emerged as a promising methodology to mitigate some of the complications that arise in the effort to expand the usefulness of the lean fully premixed concept (Lieuwen and Yang 2005; Stohr et al. 2011; Chaudhuri and Cetegen 2008; Kuenne et al. 2012). In large-scale lean premixed pre-vaporized systems, combustion often takes place under spatially non-uniform stoichiometry (mixture stratification), either by design or due to undesirable limiting operation.

The effects of local equivalence ratio gradients on the turbulent flame structure and propagation under various mixture placements has been studied for both premixed (e.g. Lieuwen and Yang, 2005; Andrews et al. 2009; Stohr et al. 2011) and stratified (e.g. Kuenne et al. 2012; Kamal et al. 2015; Xiouris and Koutmos 2012; Karagiannaki et al. 2014) model flame configurations. These works have highlighted the impact of effectively controlling inlet compositional stratification and its interaction with the main combustion zone on heat release, ignitability limits and emissions performance (e.g. Kamal et al. 2015; Kuenne et al. 2012; Karagiannaki et al. 2014).

Such information is also useful when there are constraints in the use of the fully premixed concept or when existing systems are upgraded, modernized or retrofitted (e.g. Contino et al. 2013; Carrera et al. 2011). Therefore comparative examinations of the structure and performance of the premixed versus the stratified stabilization in practical baffles are required over a variety of flame configurations.

The present work compares the performance characteristics of fully-premixed and stratified propane flames stabilized in an axisymmetric disk burner configuration under the effect of swirl. The inlet mixture conditions can be regulated by staged premixing of propane and air within an upstream double cavity premixer. Measurements of temperatures, OH* and CH* chemiluminescence, FTIR and gas analysis assisted in the interpretation of the variations in flame structure, topology and performance.The present data, complemented by further detailed information could be exploited in the computational modelling of these flames.

FLAME CONFIGURATIONS STUDIED

The premixer/burner and the combustion facility are shown in Figure 1 (Xiouris and Koutmos (2012) and Karagiannaki et al. (2014)). The premixer/burner geometry was made up of three disks connected along their axis with a hollow tube. Under fully premixed operation a mixture of propane and air was supplied through the central tube (Dc=0.052 m) and the flames were stabilized at the afterbody disk recirculation. The stratified flames were obtained by separately feeding the fuel into the hollow connecting tube (Dp=0.01m, Figure 1c) and then injecting it through an annular 1mm slot into the primary fuel-air mixing cavity (Figure 1d). The second cavity promoted partial-premixing with the central air and prevented flashback by balancing mixing and autoignition times.

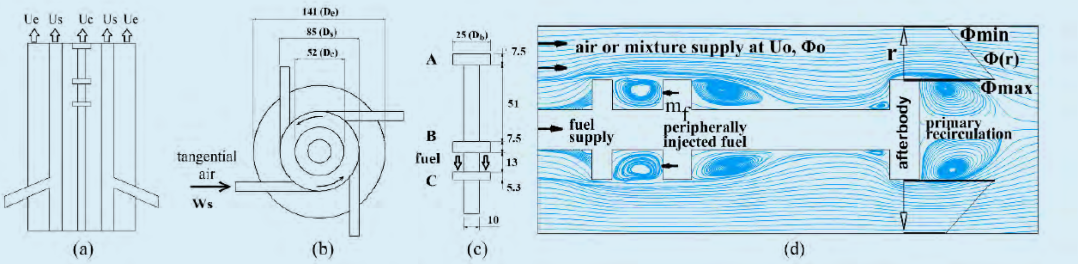

Figure 1. (a and b) Tunnel; (c) burner; (d) fuel placement arrangement

Under each operating condition the afterbody stabilization region can be fuelled, either with a radial equivalence ratio gradient (Figure 1d) regulated via the central air and the primary cavity injected fuel, or with a uniform mixture supplied through the central pipe. The flow topology within the premixer can be better visualized with the help of simulations (Xiouris and Koutmos, 2012) depicted in Figure 1d together with the possible placement of the fuel supply.

Fuel flows were regulated by Bronkhorst MV-304/306 *High-Tech* MFCs with accuracy 1.25% FSD. The burner was surrounded by an annular swirl co-flow (D_s=0.085m, Figures 1a, b) aerodynamically introduced upstream of the premixing plane. The swirl-burner system was shielded by a smooth annulus air co-flow (D_e=141mm, Figure 1a). The Reynolds number, based on the afterbody diameter and the central air velocity (Uc), was maintained at 7985 while the blockage ratio ($BR=(D_b/D_c)^2$) was 0.23. The investigated conditions and parameters are given in Table 1. The stratification at the afterbody exit, could be varied between $\Phi_{min}\approx 0.07/0.03$ and $\Phi_{max}\approx 0.90/0.67$ (Figure 1d). Swirl intensity levels(S=Ws/Us) were varied from 0 to 1.0. The premixed flames are compared against their stratified counterparts on the basis of their proximity to LBO through the parameter, $\delta = (m_{Fuel} - m_{Fuel,\ LBO})/m_{Fuel,\ LBO}$ (%). The relevant range of the operating equivalence ratios that directly correspond to these δ values is given in Table 1.

Table 1. Operating conditions

Case	δ(%)	L_R/D_b		Φ Global		P (kW)	
Swirl		0.00	0.65	0.00	0.65	0.00	0.65
Stratified Conditions							
LS	51	1.06	1.13	0.285	0.31	9.28	10.11
US	24	1.32	1.4	0.234	0.25	7.62	8.31
BS	7	1.56	1.68	0.20	0.22	6.57	7.17
Fully Premixed Conditions							
PLS	51	1.78	2.72	1.04	1.03	35.48	34.93
PUS	24	1.71	2.28	0.86	0.84	29.13	28.68
PBS	7	1.70	2.0	0.74	0.73	25.14	24.75

1. δ (%): percent deviation from Lean Blow Off,

➢ in stratified cases, $\delta=(m_{Fuel}- m_{Fuel, LBO})/m_{Fuel, LBO}$ (%), ($m_{Fuel, LBO}$, Fuel flow at Blow-Off), $U_{Fuel, LBO, S=0} = 0.9$ m/s, $U_{Fuel, LBO, S=0.65} = 0.97$ m/s.

➢ or equivalently in premixed cases, $\delta=(\Phi-\Phi_{LBO})/ \Phi_{LBO}$ (%) (Φ_{LBO}, equivalence ratio at Blow-Off), $\Phi_{LBO, S=0} = 0.69$, $\Phi_{LBO, S=0.65} = 0.68$.

2. LR/ Db: Measured afterbody recirculation length. ($D_b = 0.025$m)

3. Central air supply velocity, U_c=4.87 m/s and Re_{Db}=7980 for all cases, mean coflow velocity in annular swirl stream, U_s=9m/s (Swirl = W_s/U_s, W_s mean tangential velocity at exit from swirl stream), external annular stream velocity, U_e=10m/s.

4. Φ_{Global} : global equivalence ratio, either based on mass flows of injected fuel and central pipe air supply (stratified cases) or on the premixture composition (premixed).

EXPERIMENTAL METHODS

Mean temperatures, OH*/CH* chemiluminescence (CL) images (Figure 2), species concentrations and exhaust major pollutants (Figure 3), were obtained using thin digitally-compensated, high temperature thermocouples, a LaVision® FlameMaster imaging system and a combination of Fourier Transform Infrared Spectroscopy (FTIR, Spectrum TwoTM spectroscopy analyzer, PerkinElmer®) and Kane-May KM9106 Quintox flue gas analyzer (Xiouris and Koutmos, 2012; Karagiannaki et al. 2014).

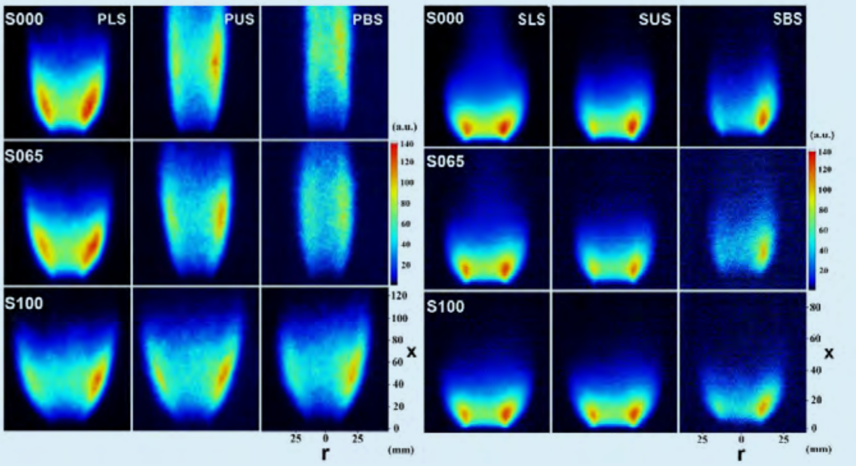

Figure 2. OH* chemiluminescence images for (a) premixed;
(b) stratified flames at three fuel levels and swirl intensities

SUMMARY AND DISCUSSION

The study examined some of the differences and similarities that develop in axisymmetric disk flame stabilization due to variations in the inlet fuel-air mixture profile. A range of topologies of flames sustained under fully premixed or stratified inlet conditions were compared for plane and swirling wake development across the stoichiometric and lean regime. The inlet radial equivalence ratio stratification promoted a wider LBO margin across the range of swirl intensities with respect to the fully premixed configuration. In the present set up fully premixed conditions augmented the primary recirculation by up to 50%, with respect to the stratified conditions, and almost doubled the cold wake vortex lengths, with the larger values pertaining to the higher swirls. For comparable proximities to LBO premixing results in more uniformly distributed temperature regions spread over a greater wake extent. The chemiluminescence images (Figure 2) suggested that stratification produces an overall more compact, frustrum shaped flame that remains well attached to the burner face and is less sensitive to swirl variations or fuel reductions. Close to ultra-lean operation premixed flames detached from the burner face, attained a cylindrical shape and reached lengths of up to seven bluff-body diameters, up to three times the lengths of the stratified cases. Over the full operational range the stratified set up maintained higher efficiency levels (Figure 3). In the present burner configuration the adjustment of the swirling field and the CRZ together with the regulation of the inlet mixture profile seem to allow convenient management of its operating parameters and emission levels.

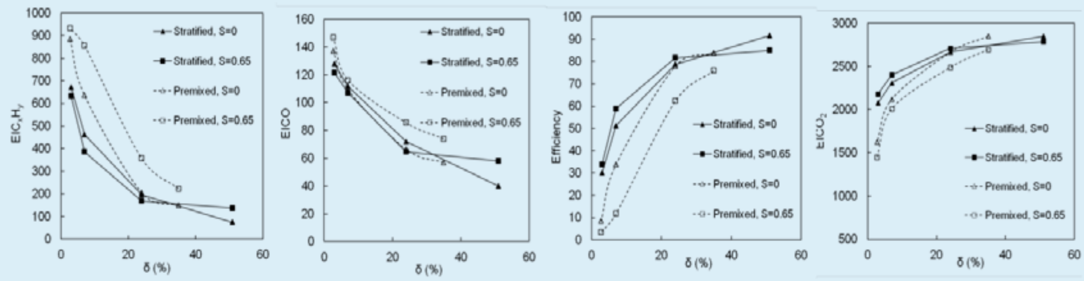

Figure 3. Distributions of the emission indices of, (a) unburned hydrocarbons, (b) CO, (c) CO2 and, (d) the respective combustion efficiencies for the reported cases.

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