Turbulent reacting flow characteristics of axisymmetric disk stabilized propane flames, with inlet mixture stratification and preheat.

K. Souflas[1], P. Koutmos[1]

1. *University of Patras, Department of Mechanical Engineering and Aeronautics, Laboratory of Applied Thermodynamics.*

Introduction

Turbulent partially premixed combustion has evolved into an important research topic in the more recent years owing to its increasing applications in current practical combustion devices. The aim of this work is to investigate the turbulent partially premixed/stratified flame characteristics under stabilization in an axisymmetric bluff body under various inlet preheat levels. Counterpart isothermal flow and mixing field information has been reported in [1].

Experimental set up

The premixer/burner setup, employed within this work, consists of two consecutive fuel-air premixing cavities formed along three concentric disks. Fuel was injected from a 1mm slot into the primary fuel–air mixing cavity and further mixed in the secondary cavity, maintaining a radially stratified equivalence ratio profile at the exit plane of the stabilizer. Flames can be stabilized downstream of the after-body disk, in the vicinity of the shear layer emanating from its rim region. A more detailed description along with the flow patterns and mixing performance of the burner can be found in [1,2].

Instrumentation

Particle Image Velocimetry

For the velocity field measurements, a 2D/2C LaVision® PIV system was employed. The PIV system set up is similar to the configuration presented in [1].

OH Chemiluminescence*

In the present study, the topology of the emitted OH* species was recorded by an Imager E-lite 2M CCD camera via an achromatic triplet lens (f/4, 193 nm–1000 nm) equipped with a narrow band-pass LaVision® filter centered at 307 nm with a full width at half maximum of 10 nm. A thorough description of the measurements set up can be found in [3].

Flame Configurations Studied

The flow fields formed downstream the burner have been investigated for reacting (R) cases at a range of inlet mixture conditions (δ) and preheating temperatures (T_{PR}). The studied cases are presented in Table 1.

Investigated Cases		Φ_{global}	Φ_{peak}	Max mean u (m/s)	Bulk Velocity U_0 (m/s)	MBV (m/s)	RZ length (x/D$_b$)	Re$_D$
R_T_{PR}0	δ=3%	0.239	0.58	8.49	6.77	-4.29	1,113	13936
	δ=15%	0.26	0.65	8.52		-3.43	0.904	
	δ=25%	0.281	0.72	8.48		-2.8	0.649	
	δ=30%	0.294	0.75	8.53		-2.57	0.626	
R_T_{PR}1	δ=3%	0.21	0.5	11.92	9.54	-5.8	1,043	10502
	δ=15%	0.234	0.57	11.88		-4.67	0.942	
	δ=25%	0.253	0.61	11.98		-4.18	0.765	
	δ=30%	0.265	0.65	11.89		-3.69	0.696	
R_T_{PR}2	δ=3%	0.171	0.39	16.24	12.78	-7.48	0.997	8452
	δ=15%	0.191	0.45	16.19		-6.6	0.951	
	δ=25%	0.206	0.49	16.3		-6.12	0.881	

corresponding author: *Souflas Konstantinos, e-mail: souflaskonstantinos@gmail.com*

	δ=30%	0.216	0.51	16.21		-5.67	0.835	
R_TPR3	δ=3%	0.129	0.24	21.36	16.50	-9.37	0.951	7828
	δ=15%	0.144	0.28	21.38		-8.67	0.934	
	δ=25%	0.155	0.31	21.39		-8.27	0.928	
	δ=30%	0.163	0.33	21.37		-7.69	0.904	
	Where:							
	ä (%): percent deviation from Lean Blow Off. defined as ä = (mFuel - mFuel. LBO)/mFuel. LBO (%)							
	TPR0, 1, 2 and 3 refer to preheat temperatures of 300, 423, 573 and 743 K respectively							

Results and discussion (Important physical parameters of preheated stratified flame stabilization)

Lewis number estimations

The effective Lewis numbers, based on the asymptotic theory of the premixed flames, can be expressed as a weighted average of the Lewis numbers of the two reactants as [4]: $Le_{eff} = \begin{cases} \frac{Le_O + ALe_F}{1+A}, \; if\ \Phi < 1 \\ \frac{Le_F + ALe_O}{1+A}, \; if\ \Phi < 1 \end{cases}$ where Le_F and are the Lewis numbers of the fuel and oxygen respectively. A can be defined as: $A = \begin{cases} 1 + Ze(\Phi^{-1} - 1), \; if\ \Phi < 1 \\ 1 + Ze(\Phi - 1), \quad if\ \Phi > 1 \end{cases}$. Ze is the Zeldovich number, [5], which can be expressed with respect to the inner layer temperature T^0 as [6]: $Ze \approx 4\frac{T_{ad} - T_u}{T_{ad} - T^0}$. Based on numerical data of flames with reactant temperatures (T_u) between 300 and 700 K, [6], suggested an approximation of the numerical data by: $3.78 * 10^6 exp\left(-\frac{17300}{T^0}\right) = p \exp\left(\frac{T_{ad}}{1385}\right)$, where p is the pressure. The Lewis numbers for C_3H_8 and O_2 along with the effective Lewis numbers, for the investigated cases, are presented in Fig. 1.

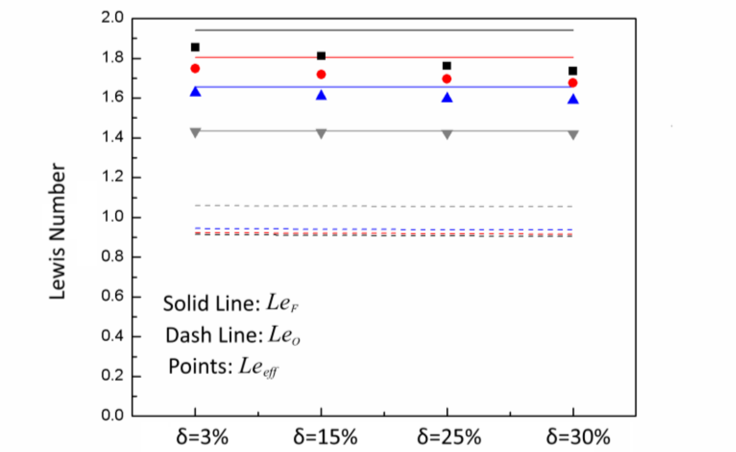

***Figure 1:** Lewis numbers for different mixture compositions and levels of preheat.*

The Lewis number distributions display slightly decreasing trends towards richer mixtures in agreement with previous studies [7,8]. As all the flames investigated within this work lie in the lean regime ($\Phi < 1$), C_3H_8 is the deficient species in the mixture. Le_F values are in close proximity with the Le_{eff} values suggesting that the Lewis number of the deficient species could approximate the effective Lewis number. For higher inlet preheat temperatures, Le_F and Le_{eff} decrease while on the contrary Le_O increase. A maximum decrease, of Le_{eff}, of about 28% has been identified between 300 and 743K. Special care should be given in the interpretation of this trend as for higher preheat temperatures and same δ values the actual equivalence ratio value is decreased. The maximum deviation of Φ values for the investigated cases are of about $\Phi = 0.5$ (from $R\_T_{PR}0$, $\delta = 30\%$ and $R\_T_{PR}3$, $\delta = 3\%$), Table 1. Such variations in Φ values do not account for the trends in the Lewis numbers, which are mainly caused due to the elevated inlet temperatures.

2D Estimates of the hydrodynamic flame stretch.
The points close to the flame anchoring position along the flame mean path length ($s = 0, 0.2, 0.4$), along with PIV data at the equivalent regions, have been chosen to estimate the strain rate information along the flame front. The two-dimensional strain rate was determined using [9]: $\kappa_s = \left({n_y}^2 - {n_x}^2\right)\frac{\partial u}{\partial x} - n_x n_y\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$, where $n_y = 1 - \gamma^2$ and $n_x \approx -\gamma$ and γ is the angle of the flame with respect to the vertical. The above expressions represent the hydrodynamic strain portion of the overall flame stretch. The strain rate statistics were compiled at each individual flame position along the normalized mean path length ($s = 0, 0.2\ and\ 0.4$) for each case. The overall total mean strain rate values (κ_s) are presented in Fig. 2.

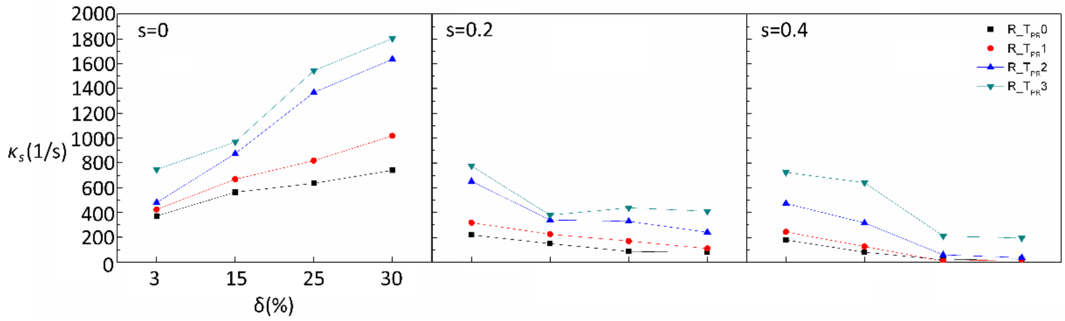

Figure 2: *Mean total aerodynamic stretch rate values induced on the flame for* $s = 0, 0.2$ *and* 0.4 *at different levels of preheat and* δ*'s.*

Close to the anchoring region, ($s = 0$) the increase of the equivalence ratio values resulted in a proportionate increase in κ_s values for all preheat levels and δ values, while further downstream ($s = 0.2$ and $s = 0.4$) the richer flames ($\delta = 15$ to 30%) experienced an overall decrease of the mean strain rates, with the case of $R\_T_{PR}3$ and $\delta = 3\%$ exhibiting minor variations along the normalized path length, s. The richer the flame becomes (up to $\delta = 30\%$) the steeper is the decrease of the strain rate values along s. A significant decrease in mean strain rate values from $1803 s^{-1}$ to $195 s^{-1}$ as we move from $s = 0$ to $s = 0.4$ is displayed for the highly preheated case, $R\_T_{PR}3$, at $\delta = 30\%$. Similar trends have been observed for all levels of preheat and δ's with the $\delta = 3\%$ cases maintaining the lowest strain rate reductions along s. The positively stretched, lean propane/air, flames investigated here are expected to be prone to extinction due to stretch alone, even if complete reactions are still maintained, since its effective Lewis numbers exceed unity $\left(Le_{eff} > 1\right)$, [6,10]. In general, the increase in the inlet temperature of the reactants led to an increase of the mean strain rate values induced on the flame, for each investigated flame position.

Mean Flame brush thickness
Flame brush thickness is an important parameter often used to characterize the spatial boundaries where the turbulent flamelets are situated. It describes the average movement of the flame and it is commonly employed to assess the accuracy of numerical models. For the presently investigated cases, the flame brush thickness was estimated using the mean progress variable gradient ($d\bar{c}/dy_1$), and the axis normal to the flame, pointing towards the reactants (y_1), Figure 3, at different axial distances downstream from the bluff body by using the relation: $\delta_t = \frac{1}{max(|d\bar{c}/dy_1|)}$

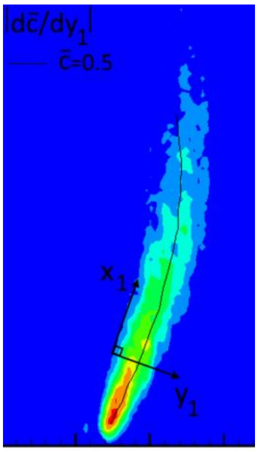

Figure 3: *Coordinate system for the flame brush thickness estimation based on the mean progress variable gradient.*

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