INVESTIGATION OF FLOW EFFECTS AND EXTINCTION LIMITS OF ETHYLENE- AND METHANE-AIR COUNTERFLOW DIFFUSION FLAMES

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Abstract

Fundamental flame characteristics derived from counterflow flames are routinely used in chemical kinetic model optimization and validation. This paper reports an experimental investigation aimed at characterizing the extinction conditions of low extinction strain rate methane-air flames and high-extinction strain rate ethylene-air flames and identifying the sources of uncertainties associated with such characterizations. In the experiments, convergent nozzles with exit diameters of 7.95mm were used to inject non-premixed fuel and air to establish a planar flame in the counterflow mixing region. Velocity profiles and extinction data were measured using an LDV setup. Experiments were conducted at various separation distances to investigate potential differences in axial velocity profiles along the axial and radial directions and the corresponding local extinction strain rates. The slope of axial velocity in the axial and radial directions at the air outlet boundary was found to increase with decreasing separation distance. The variation of local extinction strain rate with changes in separation distance was within the uncertainty of experimental data.

Introduction

Considerable effort has been devoted to advance the design of scramjet engines including the type of fuels used in the combustion process. Recent interest has focused on the use of liquid hydrocarbons for their relative ease in storage. Several surrogate fuel mixtures have been proposed to represent higher order liquid hydrocarbons in typical jet fuels for numerical modeling purposes. Furthermore, recent studies suggest that heating of the fuel during supersonic flight results in partially reacted or “cracked” fuels of a lower order than their original counterparts. Cracked fuels significantly reduce the complexity of the chemical kinetic models and show the most promise toward modeling complex realistic flows. Fundamental flame properties derived from counterflow flames are routinely used in chemical kinetic model optimization and validation. Two specific flame properties of interest are the burning velocity of premixed flames extracted from twin-premixed flame experiments and the extinction condition of nonpremixed flames. The key experimental uncertainties of premixed flames can be identified as the measurement of (i) local strain rate, (ii) the reference velocity, and (iii) the extrapolation of reference velocity to zero strain rate. In nonpremixed flames the only experimental uncertainty is measurement of the local extinction strain rate. The focus of this paper is on characterizing the extinction conditions, flow effects and corresponding uncertainties of Ethylene-Air and Methane-Air nonpremixed counterflow diffusion flames for validation of reduced reaction models of cracked liquid hydrocarbon fuels.

Measuring the extinction condition of nonpremixed counterflow flames was first addressed by Potter et al. in 1960’s where the global strain rate was characterized for straight tubes and convergent nozzles. The influences of the nozzle exit flow velocity profile, the nozzle diameter, and the nozzle separation distance were documented in this early work. While some of these effects are interrelated, the origin of the uncertainties associated with nozzle separation distance on the nozzle exit velocity profile was first examined by Rolon et al. using an Laser Doppler Velocimetry (LDV) setup. In the computational arena, the influence of actual experimental axial velocity profiles was analyzed by imposing a finite gradient of the radial velocity in the radial direction in quasi one-dimensional flow simulations. Subsequent experimental and computational work has addressed some of the above issues by using 2D PIV techniques and two-dimensional simulations. However, the core issue of uncertainty due to the non-uniform velocity exiting the nozzle has still not been well quantified. Unlike methane-air nonpremixed flames with relatively low extinction strain rates, in high extinction strain rate ethylene-air nonpremixed flames the above effects are exacerbated, hence the motivation to compare the experimental uncertainties in these two flames here.
Experimental Description

A nonpremixed fuel-oxidizer counterflow burner was used to conduct all experiments. The arrangement consisted of two coannular convergent pyrex nozzles with an area ratio of 24 and exit diameter of 7.95mm. The nozzle length was selected to ensure a fully developed flow entered the convergent section. Steel wool was placed at the entrance of the straight sections of both nozzles to diffuse the inlet flow. The design produced a near top hat nozzle exit profile for the opposing fuel and air streams. The fuel, air, and co-flow nitrogen were controlled and metered via Sierra mass flow controllers (series 100 and 860) and a NI LabView interface. All mass flow controllers were calibrated with an uncertainty of ±1.0% of full scale.

Flow velocities were measured via one component LDV consisting of a Ion Laser Technology inc. 100mW 514nm Argon ion laser and TSI beam splitter, TSI photomultiplier, and TSI signal processor. Seeding particles used were 0.25 micron silica spheres from Fiber Optic Center Inc. Analog data from the photomultiplier was converted to digital through the signal processor. The digital output from the signal processor was compiled and analyzed via automated LabView interface to produce one dimensional velocity data. The laser optics were mounted on motor driven Velmex stages to provide independent measurements in both the radial and axial directions. The nozzles were mounted vertically on the cylindrical chamber with a provision for varying the nozzle separation distance. The four two inch windows arranged symmetrically about its circumference allowed access for LDV diagnostics and viewing of the flame.

The experimental procedure was as follows. A chosen separation distance was measured optically through a Basler A602 digital camera, the uncertainty corresponding to ±0.15mm. The chamber was exhausted and held at a pressure of about 0.5 in. water (~0.0012 atm) lower than atmospheric pressure. A co-flow of nitrogen was introduced through the outer annulus of each nozzle to shield the mixing region and avoid secondary flames. Opposed non-premixed fuel and air streams were introduced via the inner annuli of the nozzles, with momenta balanced (\(\rho_{\text{air}} v_{\text{air}}^2 = \rho_{\text{fuel}} v_{\text{fuel}}^2\)) and the mixture was ignited. The alignment of the two nozzles was adjusted until LDV measurements yielded an axisymmetric velocity profile within a tolerance of ±3% of the jet edge velocities. The global extinction strain rate was measured by slowly increasing the fuel, air, and nitrogen flow velocities in small step increments until flame extinction occurred. The global extinction strain rate was calculated via the formula (4\(v_{\text{air,ext}}/L\)), where \(L\) is the separation distance and \(v_{\text{air,ext}}\) a characteristic air nozzle exit velocity. A global extinction strain rate from LDV data was calculated by extrapolating the regression polynomial for velocity to the air nozzle exit. An uncertainty analysis was undertaken and a 95% confidence interval for the uncertainty of the local strain rate measurement was calculated\(^{(8)}\). A Monte Carlo simulation was utilized, generating random data samples from a normal distribution with a mean of the corresponding measured sample and a standard deviation of the total standard uncertainty at each spatial measurement point. Ninety five elements were generated for each sample corresponding to approximately the same number of measured data points remaining in each original sample after trimming. The randomly generated data samples were model fit to the original spatial measurement locations and a 95% confidence interval was calculated for all three polynomial coefficients using Minitab\(^{(9)}\). The spatial location corresponding to the local extinction strain rate and the uncertainty of the first and second degree coefficients were input into the propagation of error equation to estimate the
uncertainty in the local strain rate measured from the regression model. Data was collected for separation distances between 7 and 12mm or normalized L/D (separation distance/nozzle diameter) separations between 0.88 and 1.52.

Results and Discussion

It is well recognized that a single convergent nozzle with a high area contraction ratio produces a top hat velocity profile at the nozzle exit under laminar flow conditions as shown in Fig. 1.

However, as two opposing nozzles are brought within finite proximity to each other, an ellipsoidal static pressure field is produced in response to a decrease in axial velocity when approaching the stagnation plane as described by the Bernoulli Effect. This effect is evident in Fig. 2 which shows axial velocity profiles near extinction measured with LDV 0.4mm from the air nozzle exit for both ethylene-air and methane-air flames at L/D=1.01 and L/D=1.52 separations. The dip is found to decrease with increasing separation distance. The non-top hat nature of the methane-air profile is less pronounced since the flow straining is significantly less than that of the ethylene-air case.

Figure 2: Normalized axial velocity profiles of (a) ethylene-air and (b) methane-air at near extinction conditions and at L/D=1.01 and L/D=1.52. The profiles are measured at 0.4mm from air nozzle exit.

In high-extinction strain rate experiments as reported here, the non top-hat axial velocity profile observed introduces a finite axial velocity gradient in the axial direction (dv/dz=finite) as shown in Fig. 3. Most computations assume this gradient to be zero which is not the case for separation distances where a stable flame can be produced and maintained. For example, in the case of ethylene-air flames near extinction, dv(-L/2)/dz is seen to decrease from 600.6 s^-1 for L=8mm to 294.5 s^-1 for L=12mm. In the limit as L approaches ∞ (or large L/D), dv(-L/2)/dz is expected to approach zero.

Figure 3: Ethylene-air near extinction axial velocity profile measured along the axial direction.
Fig. 4 shows the local and global extinction strain rates calculated from polynomial regressions of measured LDV data for L/D separation distances from 0.88 to 1.52. In the absence of LDV or PIV data acquisition systems, it is routine to assume that the velocity of the air stream in global strain rate formula $4V_{\text{air,ext}}/L$ can be approximated by the volume flow rate (measured by mass flow controllers) divided by the nozzle cross-sectional area $(dV/dt)/A)$. Such an approximation applied to our nozzles under predicts the actual air stream velocity at the center of the jet, as seen from Fig. 2. We introduce two definitions (i) $a_{\text{global,LDV}}$ where $v_{\text{air}}$ is measured by LDV, and (ii) $a_{\text{global,VOA}}$ where $v_{\text{air}}$ is estimated by volume flow rate over nozzle area. A global strain rate data point of 1900 s$^{-1}$ measured at an L/D separation of 1 by Potter et al. is included in Fig. 4 and shows good agreement with the global strain rate data collected. Since LDV systems were not available in 1960’s, we presume that the global strain rates reported in the seminal work of Potter et al. is based on $a_{\text{global,VOA}}$. The local strain rate shows no variation from changes in separation distance within the uncertainty of the data collected for both methane-air and ethylene-air flames. At low L/D separations, the global extinction strain rates calculated from LDV data show a significant deviation from those derived from $a_{\text{global,VOA}}$. These deviations can be attributed to two effects. A dip of the axial velocity profile observed near the axis of symmetry is found to decrease with increasing separation distance. Additionally, a boundary layer evident in Fig. 1 and 2 formed at the nozzle exit leads to an increased axial velocity profile in the radial direction over the theoretical average value. The exact thickness of this boundary layer is considered too significant in our design to be neglected.

The boundary layer effect was decoupled in order to reexamine the global extinction strain rate data. The boundary layer thickness was measured and an approximate apparent nozzle area was used with the measured volume flow rate to recalculate a reference global extinction strain rate, the results of which is shown in Fig. 5. As the non-top hat profile effect diminishes with increasing separation distance, $a_{\text{global,LDV}}$ approaches $a_{\text{global,VOA}}$. Additionally, the global strain rate should approach the measured local strain rate at high L/D. This trend is evident from the global and local extinction strain rate data presented in Fig.s 4 and 5. More importantly, such a trend was first shown by Potter et al. in their original work in 1960. Since the local strain rate shows no consistent variation from changes in separation distance, a mean value could be determined over all samples. The mean of the local extinction strain rate of nonpremixed ethylene-air flames was calculated as 1188.5 ±50.4 s$^{-1}$, and for methane-air flames as 373.7 ±31.6 s$^{-1}$ with 95% confidence.

![Figure 5: Corrected Ethylene-air measured global and local extinction strain rates as a function of the nozzle separation distance.](image)

**Comparison with Numerics**

A preliminary numerical simulation has been performed to better understand the importance of the boundary conditions, as shown in Fig. 6$^6$. As previously described, the non top-hat axial velocity profile observed introduces a finite axial velocity gradient in the axial direction. By mass conservation $2U = -dV/dz$ and the boundary condition for $U$=finite is calculated. For the case where $L/D=1$, when the experimentally determined velocity gradient is imposed in quasi one-dimensional computations, the resulting predicted local extinction strain rate using the USC
Mech II* mechanism (10) is 1238 s⁻¹. On the other hand, a standard counterflow flame calculation with top-hat velocity profile \((U=0)\) yields an extinction strain rate of about 1109 s⁻¹, which is about 10% less compared to the non top-hat velocity profile boundary \((U=\text{finite})\) imposed above. The predicted local extinction strain rate of 1238 s⁻¹ is higher than the experimentally evaluated local strain rate of 1188 s⁻¹. However, when seed particles are introduced for LDV velocity measurements, the global flame strain rate is held at a setting 100 s⁻¹ lower than the actual global extinction strain rate. As a preliminary estimate, an approximate ratio between the global and local strain rate gives a value of 60 s⁻¹ in the local strain rate scale. Thus, the corrected local extinction strain rate from experiments would be 1248 s⁻¹, which is very close to the predicted value using the USC Mech II* model.

![Figure 6: Comparison of Quasi one-dimensional computations for local extinction strain rate imposing \(U=0\) and \(U=\text{finite}\) boundary conditions.](image)

**Conclusion**

A comprehensive experimental and numerical effort was initiated to identify the flow effects and corresponding uncertainties governing nonpremixed counterflow extinction limits for ethylene-air and methane-air flames. The mean of the local extinction strain rate of nonpremixed ethylene-air flames was calculated as 1188.5 ±50.4 s⁻¹, and for methane-air flames as 373.7 ±31.6 s⁻¹ with 95% confidence. Extinction limits of ethylene-air flames obtained from experiments and computations show close agreement when experimentally measured boundary conditions are imposed at the inflow boundaries of the numerical model. Further comparison between numerical simulations and experimental data will be addressed in future work.

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**References**


