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Effects of stratification on locally lean, near-stoichiometric, and rich iso-octane/air turbulent V-flames

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ABSTRACT

The effects of partial premixing on locally rich, near-stoichiometric, and lean flame regions were investigated in stratified, iso-octane/air turbulent V-flames by varying the mean equivalence ratio gradient along the exit plane of a rectangular slot burner. Instantaneous heat release rate (HRR) images were obtained from the product of spatially registered, near-simultaneously acquired OH and CH_2O planar laser induced fluorescence (PLIF) images. HRR data were analyzed within a region of interest (ROI) that was determined from separate 3-pentanone tracer PLIF measurements. The ROI was unique to each gradient flame setting, and was configured to ensure the mean range of equivalence ratios being analyzed was constant among gradient conditions. This allowed distinction of the effects of mean equivalence ratio gradient at the flame front from effects associated with having different ranges of equivalence ratios within the flame zone.

Individual flame realizations were studied for differences in the local peak HRR and instantaneous flame thickness δ_t as they varied with curvature among gradient conditions. While general trends for the fully-premixed cases were consistent with Lewis number theory, subtle changes in the normalized distribution of local peak HRR vs. curvature were observed for locally rich and locally lean flames propagating in different mean ϕ gradients. Negligible changes were observed for near-stoichiometric flames, suggesting that gradient effects may influence the local thermodiffusive stability of off-stoichiometric mixtures more significantly.

Ensemble averages of individual peak HRR and δ_t values within each ROI were separately evaluated, and differences among gradient conditions were greater than those observed for the normalized distributions with curvature. For all flame settings considered, an increase in either of the peak HRR or δ_t led to a decrease in the other. Gradient effects were observed when comparing back- and front-supported locally rich flames, which experienced opposite changes in peak HRR of +10.1% and −5.2% for gradient settings $\partial\phi/\partial y = -0.014$ mm^{-1} and $\partial\phi/\partial y = 0.012$ mm^{-1} respectively, coupled with a thinning and thickening of δ_t of −7.2% and +2.4%. Similar but weaker trends were observed for near-stoichiometric flame regions, with a decrease in peak HRR of up to −3.5% and a thickening up to +2.8% for the steepest gradient $\partial\phi/\partial y = 0.029$ mm^{-1}. Locally lean flames showed small increases in peak HRR of up to +3.8%, and decreases in δ_t of up to −2.1% for back-supported gradient case $\partial\phi/\partial y = 0.024$ mm^{-1}, however, variations were not as significant as those observed for back-supported rich flame regions of equivalent gradients. The presented results show that mean gradients of equivalence ratio can alter the local characteristics of partially premixed flames. Through subtle differences in the local distribution of peak HRR with curvature, more pronounced variations in the magnitude of the mean local peak HRR and δ_t, and opposing effects in both peak HRR and δ_t for back- and front-supported rich flames, the data reveal the specific influence of equivalence ratio gradients in experiments where the mean range of equivalence ratios in the analysis region is fixed.

1. Introduction

Several modern internal combustion devices operate in an intermediate regime in which reactants are partially premixed, or stratified. In this case, the flame propagates through spatial variations in stoichiometry, altering both the *global* behaviour of the combustion system (due to a broader range of equivalence ratios within the overall reactant mixture), and the *local* properties of the reaction zone (due to the presence of a gradient in equivalence ratio at the flame front). As recent experiments [1–7] have shown, both effects may yield different results, and must therefore be approached

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differently. Consideration of the effects of partial premixing on *local* flame properties involves quantifying the interaction between neighbouring flame regions of differing equivalence ratio. Flame configurations in which the local variation in air-to-fuel ratio (A/F) (either normal or tangential to the reaction zone) is precisely controlled have shed light on the underlying physical mechanisms that govern stratified flames. Several authors have approached this problem by devising experiments [8–12] and simulations [13–16] in which an equivalence ratio gradient can be imposed normal to laminar flames propagating in a channel [8–11,14], to spherically-expanding laminar flames [12], or to laminar stagnation flames [13,15,16]. Results of these works have shown that diffusive fluxes of heat/mass from downstream products may back-support weaker flames. Additionally, numerical simulations have demonstrated that tangential variations in mixture composition along the flame front [17–22] can affect local combustion intensity, inducing differences in local flame speed S_L^o. These flame speed variations may further wrinkle the flame front for $u'/S_L^o < 1$ [17,20,22], although this effect is less significant as turbulence increases $u'/S_L^o > 1$ [17–21].

Isolating general effects of stratification from specific effects of equivalence ratio gradients on local flame properties in fully turbulent experimental configurations is inherently more complex. However, recent advances in multi-component optical diagnostics are enabling investigation of the physical mechanisms that may alter stratified, turbulent flame behaviour, as well as acquisition of validation data for numerical models. Working on a co-annular weak-swirl burner, Bonaldo and Kelman [23] separately acquired 3-D velocity data using stereoscopic particle image velocimetry (SPIV), instantaneous temperature data from Rayleigh scattering, and mean local equivalence ratio data using acetone planar laser induced fluorescence (PLIF). They observed a broadening of flame curvature PDFs coupled with a shift towards more positive curvatures with stratification, in addition to a decrease in instantaneous thermal flame thickness. Seffrin et al. [24] introduced a novel axisymmetric stratified burner and fully characterized its turbulent flow field with laser Doppler velocimetry (LDV) and high-speed PIV. In subsequent work, Böhm et al. [25] used Rayleigh scattering and simultaneous OH and acetone PLIF to investigate variations in flame front thickness, curvature, and length with stratification. Kuenne et al. [26] then performed one dimensional Raman/Rayleigh scattering measurements of local temperature and species concentrations to validate large eddy simulations (LES).

Barlow et al. [1] developed a system in which Raman/Rayleigh scattering and CO LIF were used for instantaneous line measurements of temperature and species concentration through the flame. Cross-planar OH PLIF was simultaneously acquired for 3D topology information. They successfully applied their approach to locally lean methane/air turbulent V-flames [1,2] and swirl-burners [3–5], and provided data conditioned on local instantaneous equivalence ratio [2–5] and equivalence ratio gradient [5], reporting instantaneous and mean values of local species concentration, temperature, and three-dimensional flame topology. Among other findings, their results suggest that stratification may lead to differences in local flame structure, which include observed gradients in equivalence ratio within the thermal ramp of the reaction zone.

In our previous work [6,7], we developed a different but complementary approach in which 3-pentanone tracer PLIF is used to identify ensemble-averaged conditioned iso-contours of equivalence ratio (ϕ) up to the mean position of the flame-front at $\langle c \rangle = 0.5$. Subsequent near-simultaneous OH and CH_2O PLIF measurements were used to probe flame topology and heat release rates (HRR) within similar ϕ iso-contours for flame cases of differing mean ϕ gradient. By choosing an analysis region of interest (ROI) such that a constant mean range of ϕ is evaluated as the ϕ gradient is varied, it is possible to isolate specific gradient effects on local flame properties from those of varying equivalence ratio on the global flame system. This ROI approach has been applied to turbulent iso-octane/air V-flames in locally near-stoichiometric [6,7] flame regions. Results showed small but discernible variations in mean heat release rates among gradient conditions, and implied that thermal "back-support" from the heated products within the V-flame decreased with gradient [7], in line with the back-support noted in flames subjected to gradients normal to the flame front in experiments [8–12] and simulations [13–16].

The objectives of this study were to compare the local HRR of rich, near-stoichiometric, and lean V-flames stabilized in progressively steeper equivalence ratio gradients. In addition, differences in behaviour of rich flames propagating in positive, $\partial\phi/\partial y > 0$, and negative, $\partial\phi/\partial y < 0$, gradients of comparable magnitude were specifically investigated. This allowed separate consideration of the coupled effects of back- or front-support (i.e. influence of gradients in equivalence ratio normal to the flame front, where enhanced heat and/or mass transfer from stronger, more stoichiometric mixtures downstream of the flame is commonly termed "back-support", and enhanced heat and/or mass transfer from upstream of the flame is commonly termed "front-support") and effects of transverse equivalence ratio gradients along the flame. The online Supplemental Material includes a brief discussion and diagram further explaining the definition of the terms front- and back-support in the specific context of V-flames.

Local peak HRR intensities and instantaneous flame thicknesses δ_t along individual flame contours were compared among reference-premixed and gradient flame conditions. The thermodiffusive stability of equivalent flame regions was evaluated by plotting relative variations in peak HRR and instantaneous δ_t with local curvature. Measurement uncertainties of the local peak HRR, δ_t, and curvature along the instantaneous flame contours were considered in a Monte Carlo analysis. In addition, relative variations in the ensemble average of the local peak HRR and instantaneous flame thicknesses δ_t (irrespective of curvature) were analyzed. Using the ROI technique to ensure unbiased comparison among reference-premixed and increasingly stratified flame conditions, these experiments provide new insight into the effects of partial premixing on turbulent flames. The results reveal that the local HRR along a stratified flame is modified by gradients in equivalence ratio, that these effects are stronger in off-stoichiometric flames, that front- and back-supported rich flames show opposite effects, and suggest that mechanisms of back-support may differ between rich and lean flames.

2. Methodology

Turbulent stratified iso-octane/air V-flames were stabilized with a 1.5-mm diameter rod above a slot burner described in [6,7]. The burner generates a smooth, transverse gradient in equivalence ratio along the 63 mm × 15 mm rectangular exit by independently manipulating two premixed reactant streams, ϕ_1 and ϕ_2, that enter the base of the burner. Reactant air was pre-heated to 80 °C to aid pre-evaporation of the liquid iso-octane fuel, resulting in a temperature of 55 °C at the exit plane of the burner. The exit nozzle was surrounded by a 4 mm air co-flow.

Instantaneous flame realizations were obtained from the near-simultaneous acquisition of OH and CH_2O PLIF images (subsequently used to obtain HRR images), while tracer PLIF of 3-pentanone (used to characterize the reactant mixture) and biacetyl (used in configuration experiments) were separately acquired. The optical PLIF setup shown in Fig. 1 consisted of a dual head Quanta Ray PIV400 Nd:YAG laser coupled with a Sirah Precision Scan Rhodamine B dye laser. Fluorescence images were acquired using a pair of Princeton Instrument PIMAX 1340 × 1300 pixel intensified CCDs with ST-133 controllers. Images had a projected spatial resolution of 67 μm/pixel. The line spread function of the optical system was 3.91 pixels (equivalent to 263 μm), as determined from the scanning knife edge method [27]