Flame Surface Density Measurements in Interacting Premixed Flames Using Experiment and DNS

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1 Introduction

In premixed turbulent combustion, the occurrence of flame-flame interactions marks a departure from the flamelet assumption used in many modelling approaches. In Flame Surface Density (FSD) modelling, where the flame is assumed to approximate a continuous surface subject to stretching and wrinkling by the turbulence, the mean rate of production of progress variable c is assumed to be proportional to the product of the propagation speed of the laminar flame, s_L, and the mean flame surface area per unit volume, or FSD, Σ. In RANS or LES, Σ can be closed algebraically or by solving a balance equation, in which flame interactions are typically incorporated into a destruction term. However, the exact relationship between interactions and FSD has not been fully established and constitutes a gap in the capabilities of such models. Direct Numerical Simulations (DNS) of individual interaction events support the intuitive notion of a net decrease in flame area [1], but relatively little attention has been paid to the cumulative effect of interactions on quantities such as FSD.

In this paper we present results from experimental and numerical work on flame interactions in a twin V-flame configuration (as shown in Figures 1 and 2), and compare FSD estimates to those obtained from non-interacting single V-flames at comparable turbulence intensities.

For a single isosurface of c, the FSD is defined by Pope [2] as $\Sigma_{c=c^*} = \overline{|\nabla c|}_{c=c^*} P(c^*)$, where $\overline{|\nabla c|}_{c=c^*}$ is the conditional gradient magnitude of c and $P(c^*)$ is the probability of finding the c^* isosurface at a particular location. In the thin flamelet limit $\Sigma_{c=c^*}$ is not sensitive to the choice of isosurface, however, an alternative, generalised FSD, $\Sigma_g = \int \Sigma_{c=c^*} dc^* = \overline{|\nabla c|}$, which takes into account all isosurfaces is preferable when this condition is not met. From the definition of $\Sigma_{c=c^*}$ it can be seen that the FSD depends on both the intermittency of the flame front through $P(c^*)$ and on the conditional gradient magnitude $\overline{|\nabla c|}_{c=c^*}$. Theoretical analysis [3] demonstrates that at the point of interaction the scalar gradients go to zero on an isosurface, and so it is expected that this quantity will be lower in interacting flames compared to equivalent non-interacting flames. This expected behaviour is examined in this study using DNS and laser diagnostics.

2 DNS Results

Three DNS cases are considered, as summarised in Table 1, where u'_{in} is the initial rms velocity fluctuation, $\bar{u}_{in}$ is the mean inlet velocity, and l_0 is the integral length scale. The laminar flame thermal

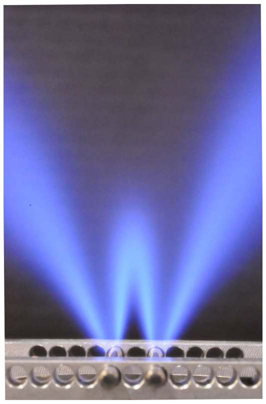

Figure 1: Long Exposure photograph of a twin V flame.

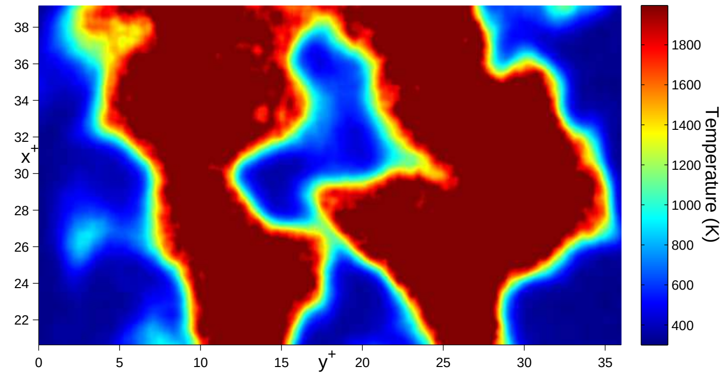

Figure 2: Instantaneous Rayleigh scattering temperature image for the experimental condition as shown in Table 1.

Table 1: Flame parameters for DNS and experiment. Turbulence Reynolds number $\mathrm{Re}_{l_0} = u'_{in} l_0/\nu$, Karlovitz number $\mathrm{Ka} = [(u'_{in}/s_L)^3(\delta_{th}/l_0)]^{0.5}$, and Damköhler number $\mathrm{Da} = (l_0 s_L)/(u'_{in}\delta_{th})$.

Case	Type	u'_{in}/s_L	$\bar{u}_{in}/s_L$	Re_{l_0}	l_0/δ_{th}	Ka	Da
W6	twin V	6.0	16.57	94	3.1	8.35	0.51
W10	twin V	10.0	16.57	114	2.2	21.32	0.22
V6	single V	6.0	24.86	92	3.4	7.94	0.57
Exp.	single+twin V	4.5	30.06	133	3.06	5.46	0.68

thickness, δ_{th}, and laminar flame speed, s_L, are 0.430 mm and 0.603 m/s respectively. Simulations were carried out using the fully compressible DNS code SENGA2, details of which can be found in [4]. A single-step mechanism with preheated reactants is used in all cases, where $T_u = 600\,K$ and the heat release parameter $\tau = 2.51$. At the flame holders, product mass fractions and mean inlet velocity values are imposed through a Gaussian weighting function. Turbulence is supplied at the inflow from precomputed cold-flow simulations of fully-developed homogeneous isotropic turbulence. All reacting flow simulations are run for an initial flow-through time of $\tau_{FT} = L_x/\bar{u}_{in}$ to allow a stationary state to be reached. Following this, the simulations were continued for an additional period of τ_{FT} during which data were collected for analysis. In both cases, the domain configuration is inflow-outflow in the x-direction, outflow-outflow in the y-direction, and periodic in z. Statistics are calculated from an ensemble of all points in the periodic (homogeneous) direction and 10 and 33 regularly spaced snapshots in time for the single and twin V-flames respectively.

Figures 3a and 3b show the domains for the single and twin V-flame simulations respectively, with contours of the Reynolds averaged progress variable $\bar{c}$. Figure 3c relates to the experiments and will be discussed in Section 3. Since the flame brush is continuously developing as it moves downstream from the flame holders, the analysis of FSD is carried out in three discrete sample volumes (A-C) at downstream positions indicated in Figs. 3a and b (positions for W10 are the same as in Fig. 3b). The positions of these sample volumes are selected so that mean convection time from the flame holders is the same for both configurations, thereby eliminating any differences due to temporal development of the flame.

The sensitivity of $\Sigma_{c=c*}$ to the particular isosurface, $c*$, is illustrated in Fig. 4 for Case V6 at position

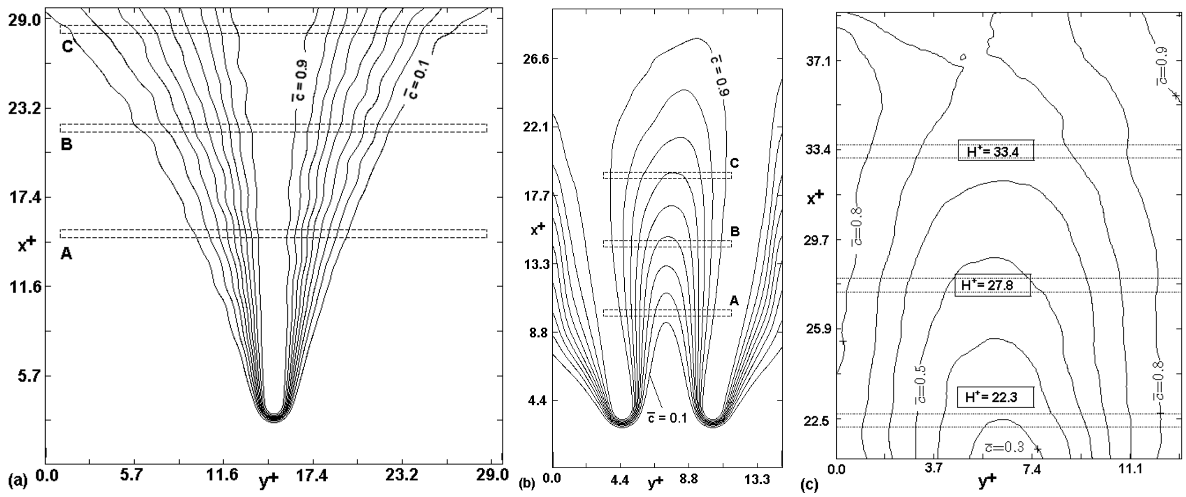

Figure 3: Contours of $\bar{c}$ for V6 (a) and W6 (b) and experimental twin V-flame (c) with locations of sample volumes. Positions x^+ and y^+ are normalised by δ_{th}. Note that the domain in (c) has been truncated to avoid laser reflection from the flame holders.

B, where the generalised FSD, Σ_g, has also been included for comparison. Similar trends are seen in all the other cases and positions.

With the exception of the $c^* = 0.1$ isosurface, all FSD profiles show reasonable agreement in form and magnitude, with more consistent results obtained for higher values of c^*. $\Sigma_{c^*=0.1}$ shows both an increase in magnitude and a shift in the peak towards lower values of $\bar{c}$. These changes are consistent with the expected regime indicated by the Ka numbers in Table 1, which suggest that for all cases small scale eddies are able to penetrate the preheat zone and hence wrinkle the flame more effectively here, but are attenuated by the effects of heat release for positions nearer the reaction layer. For subsequent analysis, therefore, only $\Sigma_{c^*=0.8}$ is considered since it is closest to the point of maximum heat release, and most consistent with Σ_g.

In Figure 5, $\Sigma_{c^*=0.8}$, and its components $P(c^*)$ and $\overline{|\nabla c|}_{c=0.8}$ are shown for all cases and positions. The decay in Σ with downstream positions for all cases is clear, although it should be noted that previous analysis of the single V-flame [4] has shown that since the flame brush thickness is continuously increasing, the turbulent flame speed and fuel consumption rate both continuously increase with downstream position within the range considered here.

3 Experimental Results

Experiments were performed on an axisymmetric cylindrical burner with an inner diameter of 25 mm. The flame was stabilised using stainless steel rods of 2 mm in diameter, and a separation of 5 mm between the centres of the rods. Premixed methane/air flames were studied at an equivalence ratio of 0.8 (s_L = 0.281 m/s, δ_{th} = 0.5391 mm). Mean flow of 8.6 m/s, turbulence intensity $u'_{in}/s_L = 4.5$, and the integral length scale of 1.65 mm were measured by particle image velocimetry (PIV). These parameters are summarised in Table 1.

Planar Rayleigh scattering was used to measure the FSD which consisted of a second harmonic (532 nm) Nd:YAG laser (Continuum Surelite-II) operating at an energy level of 300 mJ/pulse and at a frequency of 10 Hz. A laser sheet of 30 mm high and 350 μm thick was produced using a set of beam shaping optics. The scattering signal was captured using an ICCD (LaVision NanoStar) with a Nikon Nikkor 105 mm

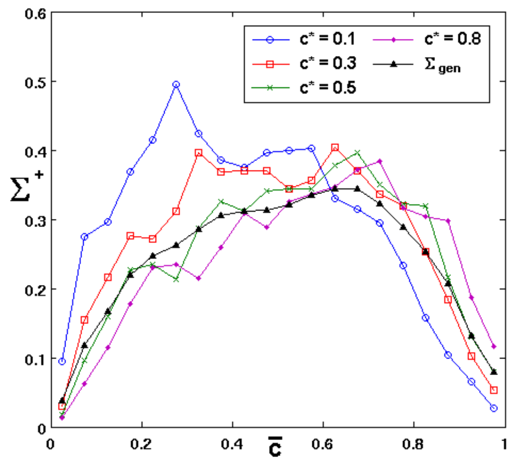

Figure 4: Normalised FSD ($\times\delta_{th}$) for V6 at position B (Fig. 3a). $\Sigma_{c=c^*}$ shown for isosurfaces at c^* = 0.1, 0.3, 0.5, and 0.8, compared to generalised FSD, Σ_g.

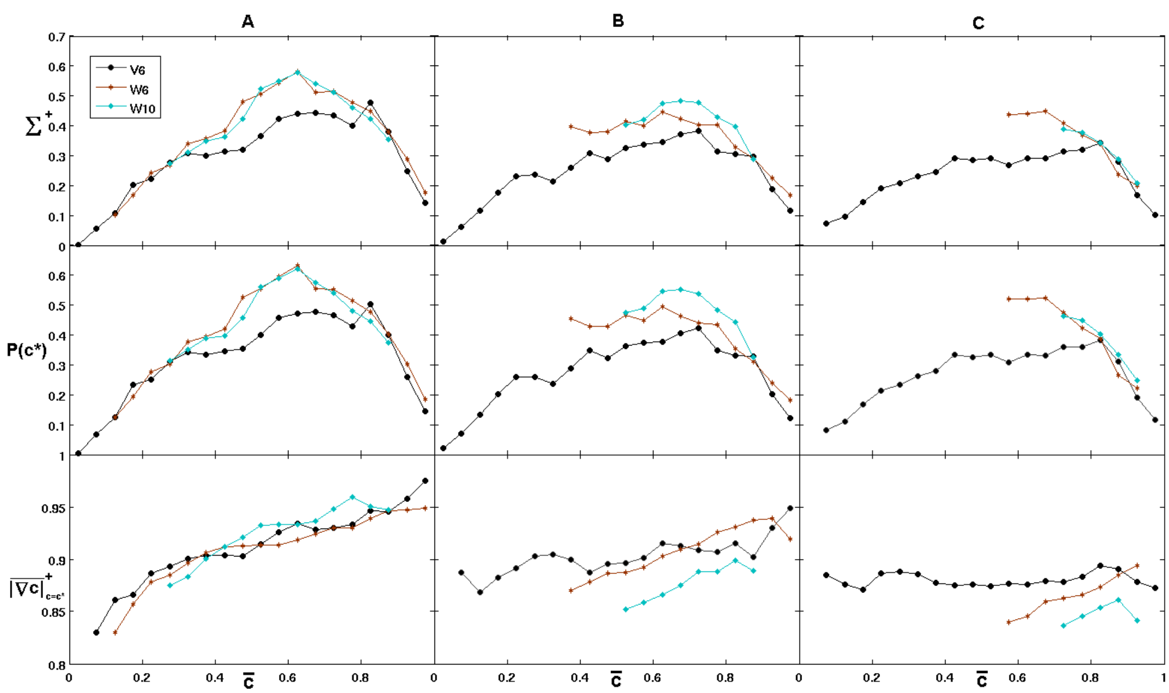

Figure 5: FSD comparison for all DNS cases. From top to bottom: Normalised FSD $\Sigma^+_{c=c^*}$, probability $P(c^*)$, and normalised mean conditional gradient $\overline{|\nabla c|}^+_{c=c^*}$, at positions A-C (left to right). Values shown are averages in bins of $\bar{c}$ from all points within the regions shown in Figs. 3a and b.

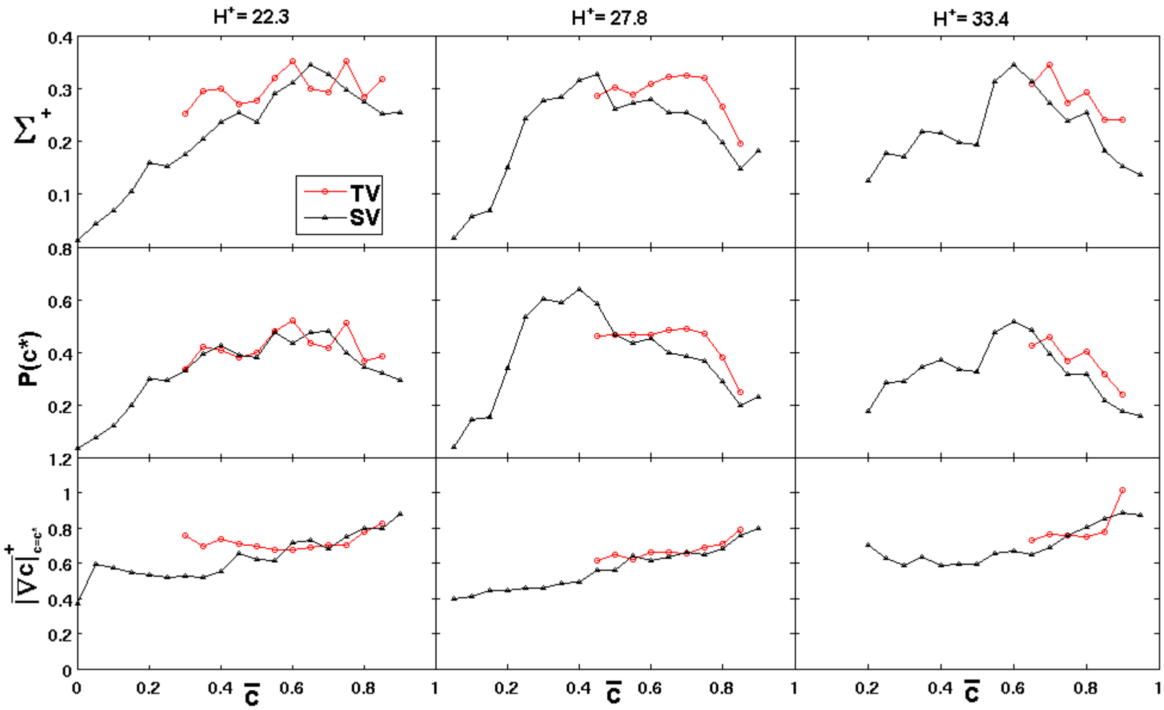

Figure 6: FSD comparison for twin (TV) and single (SV) flames from experiments. From top to bottom: Normalised FSD $\Sigma^+_{c=c^*}$, probability $P(c^*)$, and normalised mean conditional gradient $\overline{|\nabla c|}^+_{c=c^*}$. Values shown are averages in bins of $\bar{c}$ from all points within the regions shown in Fig. 3c.

f/2.8 macro camera lens and a 532 nm bandpass filter. A resolution of 29 μm/pixel was achieved along with a capture area of 10 mm x 7 mm (Fig. 3c).

Rayleigh scattering images were converted from density to temperature and then to gradient of c data. The image processing and temperature conversion techniques are similar to the one used by Knaus et al. [5] and Yuen and Gülder [6]. The uncertainty of the Rayleigh scattering experiment was estimated using the analysis method described by Wang and Clemens [7], in which dissipative structures larger than the laser sheet thickness of 350 μm were found to have a relative error of 7% for the gradient of c. The overall error for the FSD measurement, including the random error and propagation of error, was found to be 13% with a 95% confidence interval.

Σ^+ data for both twin and single V flame (Fig. 6) were subjected to statistical hypothesis tests. The difference between the two data sets was found to be significant and it is 95% confident that they are different by 0.0425 to 0.1119, which means the twin V Σ^+ is 15% to 38% higher than that of the single V flame. This agrees qualitatively with the DNS data although the magnitude of the difference between single and twin flames is reduced. Decay of the FSD magnitude with downstream position is also less evident in the experiments due to the preheating of the reactants in the DNS causing greater dissipation of the turbulence. In addition, no significant change in $\overline{|\nabla c|}_{c=0.8}$ can be observed in any of the sample regions.

4 Discussion and Conclusions

In spite of the reduction in surface gradient magnitude that occurs during individual interaction events, this is not reflected significantly in the mean values. In addition, although flame interactions are known to lead to local reductions in surface area due to the merging of flame elements, a positive correlation exists between FSD and interaction intensity in all cases considered here. This positive correlation can therefore be interpreted as showing that a minimum value of FSD is necessary before any interaction can take place. In the single V-flame this minimum is not met in spite of the intensity of the turbulence, whereas in the twin V-flames, the proximity of the second flame branch increases the probability, $P(c^*)$, beyond a critical value. In this configuration the observed increase in FSD is therefore a consequence of the mean flame geometry, although it should be noted that these results are not necessarily configuration specific since a similar correlation should be expected regardless of the mechanism of FSD production (e.g higher u'/s_L). This interpretation also suggests that the smaller difference in FSD from the experiments may reflect significantly lower interaction activity in the twin flames compared to the DNS. The information needed to verify this is not immediately available from experiment, but attempts to extract it are ongoing.

Finally, it can be observed from the two interacting DNS cases is that the FSD magnitude remains almost unchanged, indicating that a saturation point for FSD may have been reached. The large increase in the number of interactions in W10 compared to W6 (145% increase [8]) appears to cancel-out any expected increase in FSD due to turbulence intensity. This supports the intuitive picture noted earlier of interactions acting principally as a sink term for FSD.

In summary, the results presented here suggest that the observed increase in FSD for interacting flames does not result directly from flame interactions, but is in fact a prerequisite for the occurrence of interactions, and that the interactions themselves play a significant but secondary role in the FSD balance, which at higher turbulence intensities acts to limit the maximum possible FSD magnitude.

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