Flame-Edge Dynamics in Diffusion-Flame/Vortex Interactions

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Introduction

The aim of this work is to describe the dynamics of the triple flames, or flame-edges, that form after the local extinction by a vortex ring of a diffusion flame established between two counterflowing gaseous fuel and air streams of the same density, a configuration sketched in Figure 1. For sufficiently strong vortices, the flame will be locally quenched when the instantaneous value $\chi_s = D_T |\nabla Z|_s^2$ of the scalar dissipation rate at the stoichiometric surface grows above a certain critical value, hereafter denoted as $\chi_{s,e}$ [1]. Here D_T is the thermal diffusitivity and Z is the mixture fraction.

The local extinction of the flame leads to the formation of flame holes (or annulus), where both reactants mix without reaction. Such holes are separated from the diffusion flame by flame-edges that can propagate in either direction—as ignition fronts or failure waves—depending on the local flow conditions [2]. Thus, for values of the scalar dissipation rate smaller than a critical value, $\chi_{\rm s} < \chi_{\rm s,c}$, they propagate along the stoichiometric surface towards the unburned mixture as ignition fronts (triple- or edge-flames with positive velocity, $U_{\rm F} > 0$), while for $\chi_{\rm s,c} < \chi_{\rm s} < \chi_{\rm s,e}$ they behave as failure waves (edge-flames with negative velocity, $U_{\rm F} < 0$) that recede away from the unburned mixture. The detailed analysis of the scalar dissipation rate at the stoichiometric surface is therefore of interest for the subsequent evolution of extinguished holes [3].

The present paper represents an extension of previous work done by the authors on the unsteady response of reacting mixing layers (or diffusion flames) perturbed by vortices [4]. The analysis, confined to the near-stagnation point region—where the strain rate of the unperturbed velocity field, A_0 , is constant—is restricted to cases where the typical vortex ring radius, r_0 , is large compared to both the size, δ_v , of the vorticity core and the characteristic thickness, $\delta_{m,0} = (D_T/A_0)^{1/2}$, of the unperturbed mixing layer (see Reference [4] for details). The dynamics of the flame-edges is modelled using previous numerical results, where heat release effects are fully taken into account, which provide the propagation velocity of triple- and edge-flames in methane-air mixing layers in terms of the local Damköhler number, Da = $1/(\chi_s t_L)$, defined here in terms of the local scalar dissipation rate, χ_s , and the residence time, t_L , in the preheat zone of the stoichiometric premixed flame.



Figure 1: Sketch of the distorted mixing layer perturbed by a vortex ring.

Formulation

After the initial stages of the interaction, the roll-up of the flame sheet around the vortex introduces strong curvature effects and interactions between adjacent flame elements which cannot be studied using boundary layer approximations of the kind performed in [4]. Thus, for an accurate description of the extinction process we must solve the complete conservation equation for the mixture fraction

$$\frac{\partial Z}{\partial \tau} + \mathbf{u} \cdot \nabla Z = \frac{1}{\text{Pe}} \nabla^2 Z,\tag{1}$$

written here in non-dimensional form using r_0 , A_0^{-1} and r_0A_0 as characteristic length, time and velocity scales, respectively. In the above equation $\text{Pe} = r_0^2 A_0/D_{\text{T}}$ is the Peclet number of the unperturbed mixing layer, which is considered to be large but finite.

When the vortex Reynolds number is sufficiently large, $\Gamma/\nu \gg 1$, the axisymmetric velocity field associated with the vortex ring, of circulation Γ and core position $r_c(t)$ and $z_c(t)$, can be added to the unperturbed straining field to obtain the instantaneous velocity field **u** [4]. The nondimensional vortex strength $\tilde{\Gamma} = \Gamma/(2r_0^2A_0)$, which is the ratio of the characteristic strain time A_0^{-1} to the characteristic turn-over time of the vortex r_0^2/Γ , assumed to be of order unity, emerges as the main parameter characterizing the velocity field. Here, the vortex ring is assumed to propagate upwards to match the experimental configurations found in the literature [5–7].

Equation (1) has to be solved with the boundary conditions Z = 0 in the oxidizer stream, coming from $\eta = -\infty$, and Z = 1 in the fuel stream, coming from $\eta = +\infty$, using as initial condition the unperturbed planar mixing layer solution. Then the flame sheet is located at $Z = Z_s = 1/(S+1)$, where S is the overall air-to-fuel stoichiometric ratio.

The diffusion flame will be locally quenched as soon as the instantaneous value of the scalar dissipation rate χ_s exceeds its critical extinction value, $\chi_{s,e}$ [1]. Accordingly, the ratio $\mathcal{R} = \chi_{s,e}/\chi_{s,0}$ of the critical extinction value emerges as an additional nondimensional parameter which measures the robustness of the flame to flow perturbations, indicating how far from extinction the flame is in the unperturbed condition.



Figure 2: Left: velocity of a discrete flame element resulting from the superposition of the convective velocity \mathbf{u}_{d} , imposed by the flow, and the diffusive velocity \mathbf{u}_{d} , which combines the effects of curvature and diffusion along the normal. Right: variation of the front propagation velocity $U_{\rm F}$ with the Damköhler number in a pure methane-air mixing layer.

The dynamics of the flame-edges that appear after the local extinction of the flame is determined by their propagation velocity $U_{\rm F}$ along the stoichiometric surface with respect to the upstream flow, as well as on the velocity $\mathbf{u}_{\rm s}$ of the stoichiometric surface relative to the laboratory reference frame. As illustrated in the left plot of Figure 2, the evolution of a point on the flame sheet is due to the combined effect of convection and diffusion [8]

$$\mathbf{u}_{s} = \mathbf{u} + \mathbf{u}_{d} = \mathbf{u} - \frac{1}{\operatorname{Pe}} \frac{\nabla^{2} Z}{|\nabla Z|} \mathbf{n} = \mathbf{u} - \frac{1}{\operatorname{Pe}} \left[k + \frac{\mathbf{n} \cdot \nabla(\mathbf{n} \cdot \nabla Z)}{|\nabla Z|} \right] \mathbf{n},$$
(2)

where **u** is the convective velocity of the perturbed velocity field, and \mathbf{u}_{d} is a diffusive velocity representing the effects of the curvature $k = \nabla \cdot \mathbf{n}$ and the diffusion along the normal $\mathbf{n} = (\nabla Z / |\nabla Z|)_{s}$.

The propagation velocity of the flame front $U_{\rm F}$, measured with the planar stoichiometric flame velocity $S_{\rm L}$, is known to depend on the local Damköhler number Da of the frozen mixing layer ahead of the triple flame. The ratio $U_{\rm F}/S_{\rm L}$ depends also on the values of the Lewis numbers, on the overall air-to-fuel stoichiometric ratio S, and on the amount of heat release.

The dependence of $U_{\rm F}/S_{\rm L}$ on Da can be obtained numerically as described in [9], leading to the results shown in the right plot of Figure 2 for undiluted methane-air mixtures. For sufficiently large values of Da the velocity becomes weakly dependent on the Damköhler number, growing to an asymptotic value for Da $\gg 1$, which, due to thermal expansion effects in the flame front region, is larger than unity, typically of order 3.

Notice that for the case of strong vortices considered below, the convection velocity imposed by the vortex is typically large compared to the propagation velocity of the front along the stoichiometric surface, and therefore the exact definition of the curve $U_{\rm F}/S_{\rm L} = f({\rm Da})$ is not critical as long as its shape is similar to that of Figure 2. In fact, we can anticipate that the results presented here will be applicable to other fuels not strongly diluted, having values of γ close to that of methane.

After local flame extinction, two flame-edges appear at both sides of the extinguished region. These flame-edges can be characterized by (i) its position $\mathbf{x}_{\mathrm{F}}(\tau)$ on the stoichiometric surface, and (ii) its orientation ϑ_{F} along the surface. For flame-edges propagating in the direction of the tangential vector \mathbf{t} , the orientation is $\vartheta_{\mathrm{F}} = +1$, while for propagations in the opposite direction $\vartheta_{\mathrm{F}} = -1$. Here \mathbf{t} is defined by a 90° clockwise rotation of the normal vector \mathbf{n} . The evolution of each flame-edge is governed by the ordinary differential equation

$$\frac{d\mathbf{x}_{\rm F}}{d\tau} = \mathbf{u}_{\rm s} + \vartheta_{\rm F} \tilde{u}_{\rm F} \mathbf{t},\tag{3}$$

where \mathbf{u}_{s} is the velocity of the stoichiometric surface at \mathbf{x}_{F} given by (2) and

$$\tilde{u}_{\rm F} = \frac{U_{\rm F}}{A_0 r_0} = \left(\frac{S_{\rm L}}{A_0 r_0}\right) \frac{U_{\rm F}}{S_{\rm L}} \tag{4}$$

denotes the front propagation velocity made nondimensional with A_0r_0 . Notice that the factor between brackets appearing in (4) can be rewritten as

$$\frac{S_{\rm L}}{A_0 r_0} = \frac{D_{\rm T}/A_0}{r_0 \delta_{\rm L}} = \frac{\delta_{\rm m,0}^2}{r_0 \delta_{\rm L}} = \frac{\mathrm{Da}_0^{1/2}}{\mathrm{Pe}^{1/2}} = \frac{\mathrm{Da}_{\rm e}^{1/2}}{\mathrm{Pe}^{1/2}} \mathcal{R}^{1/2},\tag{5}$$

where Da_e is the Damköhler number at extinction, fixed for each thermochemical model.

Comparison with experiments

Numerical solutions to Equation (1) are obtained using a fourth degree finite difference method with optimally distributed nodes [10]. A regularized version of the velocity field **u** had to be used to overcome the singularities introduced by the potencial flow assumption. Time integration of the resulting semidiscrete problem is accomplished by a classical fourth order Runge-Kutta method. Spatial and temporal resolutions are chosen fine enough to ensure at least three digits of accuracy. The solution provides the time evolution of the flame sheet, the local value of the scalar dissipation rate χ_s , and the flame sheet velocity \mathbf{u}_s , which are then used to analyze the local extinction of the flame and the resulting flame-edge dynamics.

Figure 3 shows the temporal evolution of a flame sheet, shown in red, on top of the corresponding mixture fraction isocontours: dark gray stands for Z = 0 and light gray for Z = 1. The values Pe = 47, $\tilde{\Gamma} = 20$, and S = 0.7 of the nondimensional parameters have been derived from the experimental conditions of Case 2 in [5]. A good agreement can be observed between the present numerical results and the experimental visualizations given in [5], demonstrating the validity of the assumed velocity field and the applicability of Equation (1). In this case the strength of the vortex ring is not sufficient to trigger local flame extinction, but it is large enough to form an ignited pocket that travels with the vortex and burns completely in times of the order of the diffusion time $r_0^2/D_{\rm T}$.

Figure 4 shows the temporal evolution of an annular extinction event. The values Pe = 40, $\tilde{\Gamma} = 30$, S = 0.77, and $\mathcal{R} = 14.5$ of the nondimensional parameters have been chosen to match the experimental conditions of Flame A in [6] or, equivalently, Flame E



Figure 3: Flame sheet evolution in a flame/vortex interaction with Pe = 47, $\tilde{\Gamma} = 20$, S = 0.7, and $\mathcal{R} \gg 1$. Parameter values derived from the experimental conditions of Case 2 in [5]. The flame sheet is shown in red and the circle marks the location of maximum local scalar dissipation rate.



Figure 4: Flame sheet evolution in a flame/vortex interaction with Pe = 40, $\Gamma = 30$, S = 0.77 and $\mathcal{R} = 14.5$. Parameter values chosen to match the experimental conditions of Flame A in [6] or Flame E in [7]. The flame sheet is shown in red, the region where $\chi_{\rm s} > \chi_{\rm s,e}$ is shown in blue, and the circle marks the location of maximum local scalar dissipation rate.

in [7]. The region where $\chi_s > \chi_{s,e}$ is shown in blue and the location where the maximum scalar dissipation rate χ_s is attained is marked by a filled circle. Again, a good agreement is observed between the present results and the experiments, although later stages of the interaction do not match the experimental observations due to the presence of a jet that follows the (starting) vortex ring in the experimental configuration of [7]. The correct prediction of the annular extinction phenomenon shows that the local flame extinction can be triggered solely by an excess in the local scalar dissipation rate, whose maximum value is in this case attained off the symmetry axis.

Conclusions

Despite the apparent simplicity of the model, the agreement with previously published experimental results is remarkable and shows its potential to describe extinction and reignition phenomena in unsteady non-premixed systems; it captures and clarifies many of the parametric dependencies observed experimentally in non-premixed flame/vortex interactions. The analysis proposed here provides a simple framework to study relevant phenomena such as axial/annular extinction, reignition scenarios, flame-edge dynamics, pocket formation, noise generation, etc. Further work is required to clarify the effect of preferential diffusion and thermal expansion on the predicted results. Similar modelling approaches could also be useful to investigate spray combustion phenomena.

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